CHALLENGES IN SRF MODULE PRODUCTION FOR THE EUROPEAN XFEL

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Abstract

The internationally organized European XFEL free-electron laser is under construction at the Deutsches Elektronen-Synchrotron (DESY). With an electron beam energy of 17.5 GeV the possible wavelength will be down to below 0.05 nm. The project is the first large scale application of the TESLA technology developed over the last 15 years. The main linac will consist of 100 accelerator modules, i.e. 800 superconducting accelerator cavities, operated at a gradient of 23.6 MV/m. The talk describes the activities with respect to the module production within the international collaboration. The challenges and the status of final prototyping, industrialization and commissioning of new infrastructure will be presented.

INTRODUCTION

The European XFEL [1] is based on a superconducting linac comprising of 100 accelerator modules housing eight TESLA type cavities each (Fig. 1). In order to operate at its design energy of 17.5 GeV, confirmed recently by the XFEL Council, the design gradient of the cavities is 23.6 MV/m. The construction of the cold linac is a common effort of many institutes sharing the responsibility for this superconducting linac. The overall coordination is with DESY leading the XFEL Accelerator Consortium. Table 1 summarizes the major contributions [2].

Table 1: Contributions to the XFEL Cold Linac

Institute	Component / Task
CEA Saclay / IRFU, France	cavity string and module assembly; cold beam position monitors
CNRS / LAL Orsay, France	RF main input coupler incl. RF conditioning
DESY, Germany	Cavities & cryostats; contributions to string & module assembly; coupler interlock; frequency tuner; cold vacuum system; integration of superconducting magnets; cold beam position monitors
INFN Milano, Italy	Cavities & cryostats
Soltan Inst., Poland	Higher Order Mode coupler & absorber
CIEMAT, Spain	Superconducting magnets

CHALLENGES

Key challenge of the accelerator module production is the knowledge transfer to industry and between the collaboration partners. This includes the experience with infrastructure, procedures, handling of critical components as well as dedicated tools. In all of these fields the knowledge established on prototypes and small batches has to be adapted to the series production of cavities, couplers and modules.

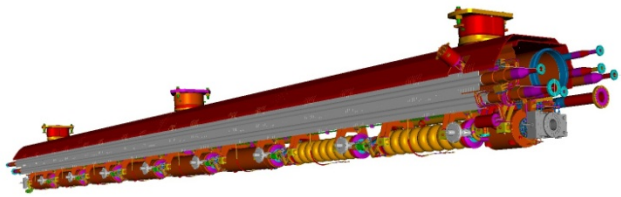


Figure 1: Cold mass with cavity string of European XFEL module.

In contrast to the previous cavity fabrication the cavities for the European XFEL have to be fabricated according to the Pressure Equipment Directive (PED 97/23/EC). This requires a guaranteed "Transfer of Identification" from the material to the final cavity, i.e. a tracking of all relevant parts. The necessary procedures of the PED process are done together with a "Notified Body" (here: German TÜV Nord). After the identification of the classification of the pressure equipment, the "conformity assessment procedure", which defines the adequate PED procedure, was worked out. The so-called modules B and F of PED 97/23/EC have to be applied. Module B includes the EC "type examination" of all relevant documents, vendors, procedures and the fabrication of test pieces for weld qualification (Fig. 2). Module F, the "product verification" for series production, is based on Module B and requires e.g. the pressure test of each individual cavity.



Figure 2: Test piece for weld qualification (Courtesy of RI).

CAVITIES

The European XFEL call for tender [3] was published in July, 2009. Production and surface preparation will be done in industry. After negotiations with the possible

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ADVANCES IN SRF DEVELOPMENT FOR ILC*

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Abstract

The International Linear Collider (ILC) is planned as a next energy-frontier electron-positron collider accelerator, and research and development for the ILC SRF cavity technology has progressed in the Technical Design (TD) phase since 2007. This paper reports advances in the SRF research and development, and discusses preparation for the SRC cavity industrialization.

INTRODUCTION

The International Linear Collider (ILC) is planned as a next energy-frontier electron-positron collider accelerator. The main linac design is based on 1.3 GHz SRF cavity technology, and to accelerate electron and positron beams up to 250 GeV in each positron and electron linac. Based on the ILC Reference Design Report published in 2007, the ILC Global Design Effort (IC-GDE) has progressed the technical design work and R&D programs during the Technical Design (TD) phase to be completed in 2012 [1-4]. The ILC accelerator design has been updated since 2009, so called 'SB2009', with a motivation of 'cost containment'. It contains four major updates: (1) cavity field gradient spread of +/-20% with keeping the averaged gradient at 31.5 MV/m in operation, (2) single tunnel for Main Linac (ML) accelerator, (3) relocation of undulator-based positron source to high-energy end of the electron linac, and (4) a reduced beam-power parameter set with 3.2 km circumference Damping Ring (DR) [5]. Figure 1 shows the SB2009 accelerator layout. Figure 2 shows the SRF R&D plan time-chart in the TD phase with four categories: (1) cavity gradient R&D, (2) cavity-string performance in cryomodules, (3) cryomodule performance with accelerator beam operation, and (4) preparation for industrialization. The following sections describe advances in the R&D efforts.

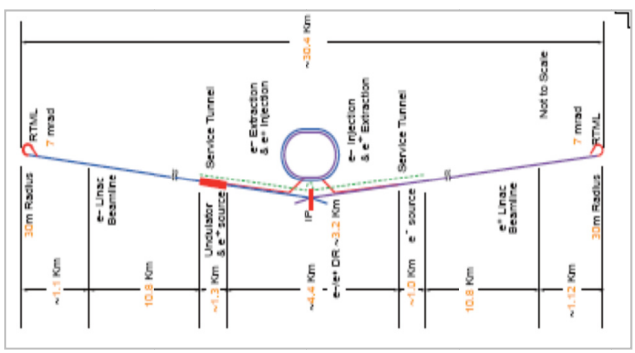


Figure 1: ILC layout updated from RDR to SB2009.

Year	07	2008	2009	2010	2011	2012
Phase	TDP-1			TDP-2		
Cavity Gradient in v. test to reach 35 MV/m	→ Yield 50%			→ Yield 90%		
Cavity-string to reach 31.5 MV/m, with one-cryomodule		Global effort for string assembly and test (DESY, FNAL, INFN, KEK)				
System Test with beam acceleration			FLASH (DESY), NML (FNAL) STF2 (KEK, test start in 2013)			
Preparation for Industrialization				Production Technology R&D		

Figure 2: Global SRF R&D plan for the ILC.

GRADIENT R&D WITH 9-CELL CAVITY

The current ILC SRF cavity design is based on the TESLA-type, 1.3-GHz, 9-cell cavity [6] as the photo shown in Figure 3. The design gradient has been set at 35 MV/m on average with $Q_0 \geq 8\text{x}10^9$ to realize the stable, long-term operation at 31.5 MV/m with Q_0 of $\geq 1\text{x}10^{10}$. The SRF R&D plan is scoping to realize a successful cavity production yield of ≥ 50% as an interim milestone, and to reach a successful production yield of ≥ 90 % by the end of TD phase. To evaluate the progress from a viewpoint of industrialization readiness, a standard process for the cavity fabrication and surface preparation has been settled, as summarized in Table 1, following to a technical assessment given by the Tesla Technology Collaboration [7].

Table 1: Fabrication and surface preparation process for the ILC SRF 9-cell cavity.

Fabrication	- Material purchasing - Sub-component fabrication - Cavity assembly using EBW technology - Acceptance inspection
Surface preparation process (1^{st} & 2^{nd} pass allowed)	- Electro-Polishing: EP1 (~150μm) - Cleaning with ethanol or detergent - High-pressure pure-water rinsing - Hydrogen degassing at > 600 C - (Field flatness tuning) - Electro-Polishing: EP- 2 (~20μm) - Cleaning with ethanol or detergent - High-pressure pure-water rinsing - Antenna assembly - Baking at 120 C
Cold Test	Performance test with temperature and radiation monitoring, and RF mode test

#Work coordinated and supported by ILC Global Design Effort

RECENT SRF DEVELOPMENTS FOR ERLS

G.H. Hoffstaetter, M. Tigner [CLASSE, Ithaca, New York, USA]

Abstract

Research and Development of SRF technology is being advanced around the world. We review developments in Europe, Asia and North America citing specifics from Helmholtz Zentrum Berlin, KEK, JLab and Cornell. These programs are designed in part to improve BBU control, power coupling and Qo which is crucial for minimizing power consumption for operation of ERLs as CW sources of high-current low-emittance beams.

CONTRIBUTION NOT RECEIVED

SRF CHALLENGES FOR IMPROVING OPERATIONAL ELECTRON LINACS*

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Abstract

The performance of the operational SRF-based electron linacs CEBAF, ELBE, and S-DALINAC continues to evolve positively. These facilities are exploiting opportunities to improve operational capability by both remediation of past limitations and also construction of new capacity using state-of-the-art designs and processes. A project to rework the weakest ten cryomodules in CEBAF was completed and enabled robust operation for physics at 6 GeV. The 12 GeV Upgrade of CEBAF is now underway and involves construction of ten new CW >100 MV cryomodules with 80 new 7-cell low-loss cell shaped fine-grained niobium cavities, all electropolished. The technical challenges associated with the preparation of these cavities will be reviewed and their performance in both individual acceptance testing and cryomodule testing to date will be summarized. The ELBE facility at Helmhotz Zentrum Dresden Rossendorf continues to develop its source with an SRF gun system. The long-running S-DALINAC at Technische Universität Darmstadt is operating reliably and is evolving in the direction of reduced energy spread and use of polarized electrons for nuclear physics and astrophysics research.

CEBAF

Historical Context

The construction requirements for a 4 GeV CEBAF in 1987-1993 required 42 cryomodules each providing 20 MV net from eight 0.5 m 5-cell 1.497 GHz niobium cavities. While initial performance requirements were met from the start, the interests of the physics community have maintained pressure to provide the highest 5-pass energy possible for nuclear physics research, well beyond initial specifications. By 2002 CEBAF was operating reliably at up to 5.75 GeV. In 2003 CEBAF performance suffered following an uncontrolled warm-up caused by loss of site power due to Hurricane Isabel.[1] At this time planning was already underway for a project to upgrade CEBAF to 12 GeV. The project, described more below, was to involve population of ten empty zones with a new, higher-capacity cryomodule design. A need existed to strengthen the energy base provided by the original set of cryomodules.

While two cryomodules had small helium leak issues, the principal performance limiting phenomenon was derived from internal field emission from particulate contamination un-removed by the cavity processing methods available circa 1991. Extended operation under field emission conditions produced electrostatic charging of the 2K ceramic rf window on each cavity, which in turn produced an operationally-limiting phenomenon of periodic arcing and the attendant beam delivery interruption.[2] In 2006, a cryomodule refurbishment project was launched to rework the ten weakest cryomodules in order to provide a reliable 6 GeV base for the then-future 12 GeV Upgrade Project. Since the operational target for each cavity in the reworked modules was 12.5 MV/m, the objective for each module was 50 MV, thus the label C50. [3]

Scope of the C50 Project

During the refurbishment process, each cryomodule was disassembled and its cavities removed and subjected to improved processing techniques. The input rf waveguide assembly was redesigned to include a "dogleg" in the waveguide section internal to the helium vessel. The original polyethylene warm RF window outside the cryomodules was replaced with an improved ceramic model. Improvements were made to the mechanical tuners to reduce backlash. Components that were subject to mechanical wear or radiation damage over the years were replaced as well.

In order to eliminate potential vulnerability to hydrogen-induced Q disease, the cavities were vacuum heat treated at 600°C for 10 hours. After a fresh tuning, the cavities were subjected to a 30 µm acid etch followed by high pressure rinsing with ultra pure water, both within a class 100 cleanroom. These processes were designed to greatly reduce particulate contamination on the surface of the cavities and as a result effectively eliminate field emission. As a further safeguard against operational interruptions from arcing, a replacement dogleg waveguide section was designed to reduce or eliminate this type of arcing behavior by eliminating the line of sight from the cavity interior, and generated electrons, to the cold window. (See Figure 1.)

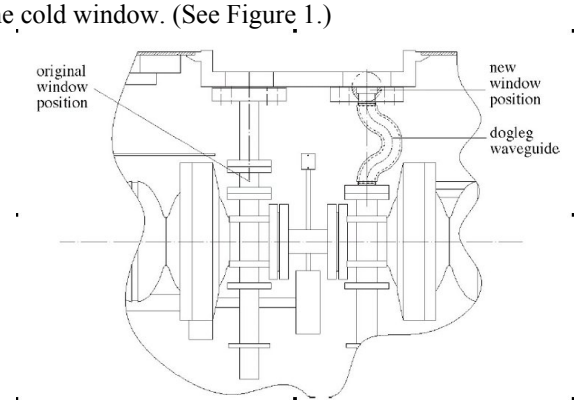


Figure 1: Coupler modifications.

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SRF DEVELOPMENT FOR HIGH ENERGY PHYSICS

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Abstract

Superconducting Radio-Frequency (SRF) technology has become the technology of choice for accelerator-based high energy physics (HEP) research, from the operating Large Hadron Collider to the planned Project X and International Linear Collider. The HEP community has made large investments in recent years in preparation for the construction of a SRF-based project, and the SRF community has grown commensurately. Results and ongoing efforts will be described along with some comparison to the application of SRF technology in non-HEP applications.

CONTRIBUTION NOT RECEIVED

ADVANCES IN SRF FOR LOW BETA ION LINACS

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Abstract

Projects based on ion linacs have multiplied during the last decade to follow the increasing demand of ion beams, either stable or radioactive, for application in nuclear physics or material studies. Thanks to the continuous progress in SRF (Superconducting Radio Frequency) technology, all these linacs are based on low beta superconducting cavities of different type (half-wave, quarter-wave, bulk Nb or Nb/cu) and make this particular field very active in many laboratories worldwide. In this paper, we review the most recent developments in SRF performed in the framework of FRIB, SPIRAL-2, ATLAS, SARAF, IFMIF, TRIUMF and ISOLDE.

CONTRIBUTION NOT RECEIVED

ADVANCES IN SRF FOR NEUTRON SOURCES

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Abstract

There have been studies for applications of superconducting radio-frequency (SRF) technologies to the proton or deuteron accelerators to generate high intensity neutrons. The areas of interests are neutron scattering, material test and accelerator driven systems for nuclear transmutation, energy generation, isotope production, and etc. Advantages of the SRF technology for high power proton/deuteron accelerators include high operating gradient, low beam loss from large aperture size and extremely high vacuum, high RF power transfer efficiency to beam, and operational flexibility. Many technical advances of SRF technologies from various programs have been applied to the high power accelerators for meeting their missions, which enables designs, constructions, and operations of high intensity accelerators at multi-megawatts level or higher. Major large scale operational and future neutron sources using the SRF technologies are presented together with their specific merits, requirements and issues.

CONTRIBUTION NOT RECEIVED

SURVEY OF SRF GUNS*

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Abstract

Developing Superconducting RF (SRF) electron guns is an active field with several laboratories working on different gun designs. While the first guns were based on elliptic cavity geometries, Quarter Wave Resonator (QWR) option is gaining popularity. QWRs are especially well suited for producing beams with high charge per bunch. In this talk we will describe recent progress in developing both types of SRF guns.

INTRODUCTION

Superconducting RF has become the technology of choice for accelerating systems of many high-intensity particle accelerators. As the technology has matured, it is now finding applications other than just accelerating structures. One of such applications is photocathode RF guns. SRF has advantage over other electron gun technologies in CW mode of operation, where it potentially can provide higher rate of acceleration, generating high-charge bunches and high average beam currents.

SRF guns are complex devices merging several technologies: high Quantum Efficiency (QE) photocathodes, superconducting RF, high repetition rate synchronizable lasers. Among the challenges imposed by these technologies are maintaining UHV environment for the cathodes, maintaining cleanliness of the cavity RF surfaces while allowing operation and replacement of the cathodes, designing low RF loss and low heat leak interface between the cold cavities and warmer cathodes, synchronizing high repetition rate lasers with RF.

While SRF guns made excellent progress since previous SRF Conference [1], many issues still have to be addressed. Some of those are outline below. To produce **low emittance** beams, SRF guns have to have high acceleration rate, RF focusing near the cathode, first solenoid as close to the cavity as possible, precise synchronization of a laser with RF, and proper transverse and temporal bunch shaping. For **high bunch charge at high repetition rate** we must develop high QE photocathode with long life time, high average power, high repetition rate lasers. The semiconductor (and other high QE) photocathodes have to be able to operate in the SRF cavity environment. At least one type of photocathodes, Cs_2Te, has demonstrated to have long lifetime in an SRF gun, but more studies needed for other cathode types. **Preparation of cavities** for SRF guns proved to be difficult so far. The cavities either have very small opening to insert a cathode or no opening at all in case of superconducting cathodes. This makes chemical etching and cleaning of cavities challenging. Also, effect of the NC cathodes on SRF performance is still unclear. Finally, SRF guns have to **demonstrate stable operation in accelerators**. This includes handling of high average RF power, managing parasitic kicks from input power couplers, and effective damping of higher-order modes.

This paper is focused on reporting recent progress in the field. A more comprehensive description of the SRF guns can be found in [1].

TYPES OF SRF GUNS AND PHOTOCATHODES

In [1], SRF guns are classified by cavity/cathode type. The first SRF guns were based on elliptic cavity geometries – conventional shapes of high-β SRF cavities. While guns to be installed in accelerators use normal-conducting photocathodes, small R&D guns utilize superconducting (Nb or Pb) photocathodes. Quarter Wave Resonator (QWR) option is gaining popularity. QWRs are especially well suited for producing beams with high charge per bunch. QWRs can be made sufficiently compact even at low RF frequencies (long wavelengths). The long wavelength allows to produce long electron bunches, thus minimizing space charge effects and enabling high bunch charge. Also, such guns should be suitable for experiments requiring high average current electron beams. More details on QWRs can be found in [2]. One more type is a hybrid DC-SRF gun.

Semiconductor photocathodes are the preferred option for many projects. They can provide very high QE, up to 0.1 or even higher. However, these cathodes are very sensitive and require very good vacuum. The most developed semiconductor materials are GaAs(Cs), Cs_2Te, and CsK_2Sb. Gallium arsenide is the only photocathodes suitable for producing polarized electrons, but is more sensitive to ion back-bombardment than others, requires extremely good vacuum and has short lifetime. Cesium telluride is the most robust of the three, but requires UV lasers, which makes it more difficult to use for high bunch charge: more laser power needed for the same QE than at longer wavelength, optics and pulse shaping is more difficult as well. Cesium potassium antimonide can be used with green lasers and is the most preferred at present. Metal cathodes, while much more robust, have low QE and suitable only for use in the initial phases of SRF gun development. However, special coating of metals can increase QE up to 7×10^{-3} [3]. Finally, diamond can be used to boost current by a factor of ~100 and is very promising for high charge applications. We refer the readers for more details to the recently published review of photocathode R&D for future light sources [3].

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE.
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OPERATIONAL EXPERIENCE WITH SRF CAVITIES FOR LIGHT SOURCES

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Abstract

Third generation light sources require modest accelerating voltages, however this is offset by a need for high reliability, to serve users on a continual basis with minimal interruption. The high Q of the superconducting (SC) cavities means that cavities are designed such that higher order modes are effectively damped using external loads, offering stable high current, multi-bunch operation. Fundamental mode SC cavities for light sources were initially used in CESR and KEKB, followed by Taiwan Light Source and Canadian Light Source and third harmonic systems are used for bunch lengthening at SLS and ELETTRA. The successful operation of those machines led to the choice of SC cavities in the design of Soleil, Diamond Light Source and Shanghai Synchrotron Radiation Facility, all now in operation. Additionally, Taiwan Photon Source, Pohang Light Source II and National Synchrotron Light Source II are currently in construction and all employ SC cavities. In this paper we will review recent operational experience of SC cavities in light sources and will describe recent developments related to the cavities and their auxiliary systems.

INTRODUCTION

For nearly 40 years light sources have attracted enormous interest and funding and the design and development has resulted in light sources of exceptional brightness, stability and reliability. More than 50 light sources have already been built and since the mid 1980s, the focus has been on third generation light sources. Third generation light sources are generally considered to consist of a low emittance electron storage ring with insertion devices. Recent upgrades and new light sources have tended to push the beam current up to the point where beam instabilities caused by parasitic higher order cavity impedances of normal conducting cavities can limit the stored current. It is the modest requirement for accelerating voltage, high beam power and the higher order mode absorbers which makes superconducting (SC) cavities particularly attractive. The fact that a smaller amount of valuable straight section space is needed is another important factor. For these reasons, many of the latest electron storage rings (SR) have been designed with SC cavities. The early development of SC cavities for use with light sources has been reviewed previously, see for example [1, 2, 3] and the references within.

RECENT OPERATIONAL EXPERIENCE

There are three distinct designs for fundamental frequency SC cavities in use in SR light sources. They are the CESR single cell 500 MHz cavity developed at Cornell [4], the two-cell 352 MHz cavity developed at SOLEIL [5] and the single cell 508 MHz KEK cavity [6]which has been adapted to operate at 500 MHz. In addition, there are SC third harmonic cavities for bunch lengthening in order to improve the beam lifetime and reduce instabilities They are in use at SLS and ELETTRA [7] and are under consideration and fabrication for TPS and NSLS-II [8].

The CESR Style Cavity

Cornell developed the single cell 500 MHz cavity in the late 1980s to early 1990s for the proposed B-factory. This cavity is aperture coupled to the RF waveguide which results in a fixed Q_{ext}. HOM damping is by means of ferrite absorbers on the beam pipes. The first module was incorporated in the CESR luminosity upgrade, CESR-III, with the first cavity in 1997 and in 1999 CESR became the first SR to operate entirely with SC cavities. CESR has been operating successfully since then and currently typically operates the SR at 400 mA. A three stub tuner is used to provide an optimum match for the various operating conditions. The forward power is typically 180 kW per module with one module being operated at 110 kW due to a higher trip rate. Only one persistent cavity trip mechanism exists: a window trip, which occurs on one module, which is mitigated by weekly pulsed RF conditioning.

In 2003, the Canadian Light Source (CLS) became the first dedicated light source to use a SC cavity. CLS operates using a single cavity with a second module available as a spare and future upgrade. The cavity typically operates at relatively high field for these cavities at 2.2 – 2.4 MV, 8 MV/m with forward power around 229 kW. Operation is generally reliable although a rupture on a bellow on the multi channel line (MCL) has occurred twice. Now the MCL is normally kept cold at all times and only warmed to LN2 temperature during maintenance periods. The CLS modules do however suffer with a gradual reduction in the Q_0. After a warm up and conditioning the dynamic loss is 40-50 W rising, after 2 weeks operation with beam, to 90-100 W. Operation is maintained by regular pulse conditioning and partial warm ups to release hydrogen. The pulse conditioning takes around 4 hrs. In the longer term, the plan is to install the second cryomodule to allow an increase in beam current to 500 mA.

TLS became the next light source to upgrade the existing normal conducting (NC) cavities, and the first SC module was successfully installed in 2004 and has been in continuous operation since 2005 [9]. A second module was also procured and is available as a spare. The upgrade

HOT TOPICS: SOURCE OF QUENCH PRODUCING DEFECTS

R.L. Geng [JLAB, Newport News, Virginia, USA]

Abstract

Recent efforts in pushing the performance of superconducting RF niobium cavities for the International Linear Collider have resulted in two-fold progresses: reduced field emission and improved quench limit in real 9-cell cavities. RF testing at cryogenic temperatures assisted with quench-detection instrumentation reveals that quench happens often times at highly localized areas inside or near the equator weld of a cavity cell, which is also the high surface magnetic field region. High-resolution optical inspection of the identified quench location makes it possible to correlate the cavity quench limit with certain types of defects. Several sources of quench producing defects are being explored. We will discuss the experimental evidence in supporting each of these sources. We will also discuss the methods of curing or preventing these defects for improved gradient limit and reduced gradient spread.

CONTRIBUTION NOT RECEIVED

COMMERCIAL SUPERCONDUCTING ELECTRON LINACS

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Abstract

Industry now has the capability to design, build and commission superconducting electron linacs. This capability includes the integration of the liquid helium refrigerator and the license to operate a radiation generating device. Niowave offers a broad range of commercial turnkey superconducting electron linacs with beam energies from 0.5 to 50 MeV and average beam powers from 1 W to 1 MW. The commercial linacs operate at 4.5 K with helium refrigerator loads typically less than 100 W. Operation at 4.5 K uses niobium cavities with frequencies less than about 700 MHz. The types of electron source used depend on the application and include DC, copper RF and SRF guns with cathodes based on photoemission, thermionic and field emission. There are many applications with a diverse range of uses from ultrafast electron microscopes to free electron laser to advanced x-ray sources and isotope production. Commercial developments and plans to date will be presented.

CONTRIBUTION NOT RECEIVED

650 MHZ CRYOMODULES FOR PROJECT X AT FERMILAB – REQUIREMENTS AND CONCEPTS*

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Abstract

Cryomodules containing 650 MHz superconducting niobium RF cavities and associated components (input couplers, tuners, instrumentation, etc.) will be developed for Project X, a high intensity proton accelerator facility based on an H- linear accelerator at Fermilab. This paper describes the requirements of the 650 MHz cryomodules and the implications of those requirements for the cryomodule design. Cryomodule string segmentation, integration with the cryogenic system, features for maintainability and access, piping and emergency venting considerations, pressure vessel issues, and thermal and mechanical design concepts will be described.

INTRODUCTION

Project X will be a multi-MW proton accelerator facility based on an H- linear accelerator using superconducting RF technology [1]. The Project X 3 GeV CW linac will employ 650 MHz cavities [2] to accelerate 1mA of average beam current of H- in the energy range 160 – 3000 MeV. We describe the requirements of the 650 MHz beta = 0.9 cryomodules (see Figure 1) and implications of those requirements for the design concepts.

The baseline design concept includes cryomodules closed at each end, individual insulating vacuums, with warm beam pipe and magnets in between cryomodules such that individual cryomodules can be warmed up and removed while adjacent cryomodules are cold. The cryostat must:

- Provide the required insulating and beam vacuum
- Minimize cavity vibration and coupling of external sources to cavities
- Provide good cavity alignment (<0.5 mm)
- Allow removal of up to 250 W of heat at 2 K per cryomodule
- Protect the helium and vacuum spaces including the RF cavity from exceeding allowable pressures
- Intercept significant heat loads at intermediate temperatures above 2 K to the extent possible in full CW operation
- Provide high reliability in all aspects of the cryomodule (vacuum, alignment stability, mechanics, instrumentation) including after thermal cycles
- Provide excellent magnetic shielding for high Q0
- Minimize cost (construction and operational)

* Work at Fermilab supported by the U.S. Department of Energy under contract No. DE-AC02-07CH11359.

The focus in this report will be on some of the unique features which result from the continuous wave (CW) operation and resulting heat loads of as much as 30 W per RF cavity.

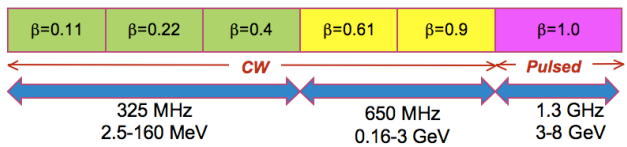


Figure 1: Project X incorporates six types of cryomodules, shown in this map. This paper describes the requirements for 650 MHz, beta = 0.9 cryomodules.

CRYOMODULE MECHANICAL COMPONENTS

The cryomodule consists of various subassemblies and components which are integrated into one vacuum jacketed vessel. These include:

- Eight (8) dressed RF cavities [1,2]
- Eight RF power input couplers
- One intermediate temperature thermal shield
- Cryogenic piping, connections to supply and return lines, and valves
  - 2 K liquid level control valve
  - Cool-down/warm-up valve
  - 5 K thermal intercept flow control valve
- A heat exchanger will be incorporated into the cryomodule design which precools helium from approximately 4.5 K to 2.2 K upstream of the cryomodule liquid level control valve.
- Pipe and cavity support structure
- Vacuum vessel, external supports with features for positioning the cryomodule, and alignment fiducials on the vacuum shell with reference to cavity positions
- Instrumentation
- Beam tube connections at the cryomodule ends with beam vacuum isolation valves.

The lattice developed for Project X assumes eight RF cavities per 650 MHz high energy (HE650) cryomodule. Cryomodule linac lattice dimensions and spacing [3] are shown in Figure 2.

MODIFIED SRF PHOTOINJECTOR FOR THE ELBE AT HZDR

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Abstract

The superconducting radio frequency photoinjector (SRF photoinjector) with Cs2Te cathode has been successfully operated under the collaboration of HZB, DESY, HZDR, and MBI [1]. In order to improve the gradient of the gun cavity and the beam quality, a new modified SRF gun (SRF-gun 2008) has been designed.

The main updates of the new cavity design for the new photoinjector were published before. (ID THPPO022 on the SRF09 Berlin) This cavity is being fabricated in Jefferson Lab.

In this paper the new ideas of the further parts of the SRF-gun 2008 will be presented. The most important issue is the special design of half-cell and choke filter. The cathode cooler is also slightly changed, which simplifies the installation of the cathode cooler in the cavity.

The next update is the separation of input and output of the liquid nitrogen supply, for the purpose of the stability of the nitrogen pressure as well as the better possibility of temperature measurement.

Another key point is the implementation of the superconducting solenoid inside the cryomodule. The position of the solenoid can be accurately adjusted with two stepmotors, which are thermally isolated to the solenoid itself.

INTRODUCTION

For ELBE LINAC (**E**lectron **L**inear accelerator with high **B**rilliance and low **E**mittance) a new SRF-gun has been redesigned (see Figure 1). This paper presents the revised design and discusses the advantages.

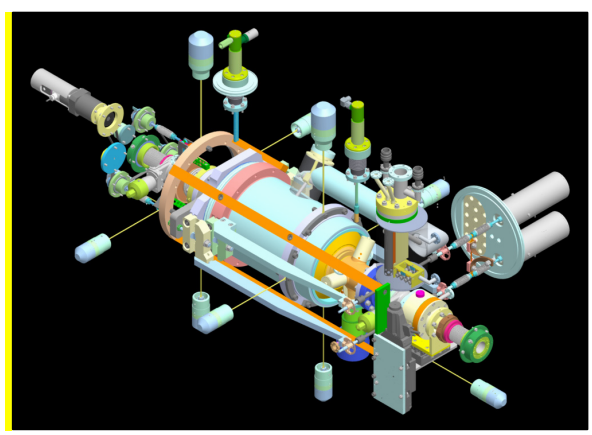


Figure 1: View of the inside parts.

SPECIAL DESIGN OF HALF-CELL AND CHOKE FILTER

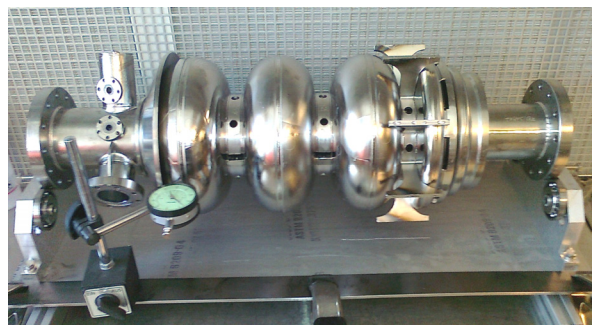


Figure 2: The status of the cavity fabrication.

The Figure 2 is the latest photograph of the new cavity, which is currently produced and assembled in Jefferson Lab. There, the whole process, including production, tuning and welding in the tank will be done [2][3]:

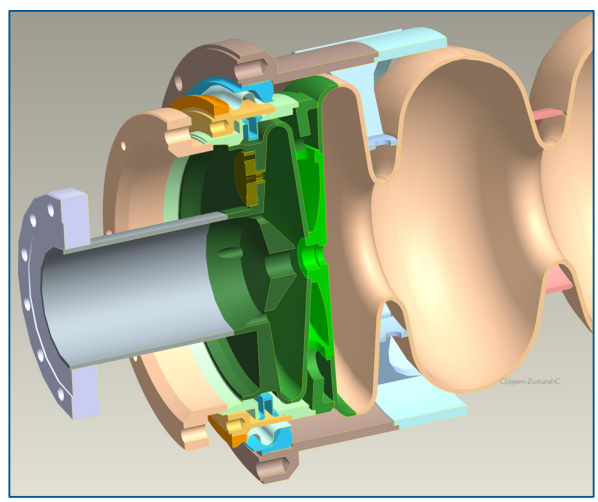


Figure 3: New cathode opening design.

CONCEPTUAL DESIGN OF THE SUPERCONDUCTING PROTON LINAC SHORT CRYO-MODULE

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Abstract

The Superconducting Proton Linac (SPL) is an R&D effort conducted by CERN in partnership with other international laboratories, aimed at developing key technologies for the construction of a multi-megawatt proton linac based on state-of-the-art Superconducting Radio Frequency technology, which would serve as a driver for new physics facilities such as neutrinos and radioactive ion beams.

Amongst the main objectives of this effort, are the development of 704 MHz bulk niobium β=1 elliptical cavities, operating at 2 K and providing an accelerating field of 25 MV/m, and testing of a string of cavities integrated in a machine-type cryo-module. In an initial phase only four out of the eight cavities of an SPL cryo-module will be tested in a ½ length cryo-module developed for this purpose, and therefore called the Short Cryo-module.

This paper presents the conceptual design of the SC, highlighting its innovative principles in terms of cavity supporting and alignment, and describes the integration of cavities and their main equipment (RF couplers, helium vessels, tuners) inside the cryo-module and possible assembly methods.

INTRODUCTION

A first proposal for building a superconducting proton linac (SPL) at CERN to replace some of the existing accelerators was reported about 14 years ago [1], with the potential for evolving towards very high beam power, which would support new physics facilities for neutrinos and/or radioactive ion beams [2]. Later, the design of the SPL evolved towards a low-power 4 GeV version (LP-SPL), with potential use in a new injector chain for the LHC, together with Linac4, presently under construction, and having the potential to be up graded to a multi-MW proton injector [3]. Following recent changes in the mid-term plan strategy at CERN, the construction of the LP-SPL has been stopped, but the continuation of the R&D effort towards a high-power version of the SPL has been endorsed. As one of the priorities of this program, 704 MHz bulk niobium β=1 elliptical cavities are to be developed and tested in collaboration with the European Spallation Source (ESS). The main cavity and cryogenic design parameters are summarised in Table 1, for a 50 Hz pulsed operation, 20 mA current and 0.8 ms beam pulse length.

Machine architecture and integration studies made for the SPL at CERN, featuring 60 β=0.65 cavities, and 184 β=1 cavities in an SRF linac of about 500 m length, led to the choice of housing 8 β=1 cavities in standalone cryo-modules, individually connected to a cryogenic distribution line cryostat running parallel to the linac (Figure 1).

Table 1: β=1 cavity, main parameters

Property	Units	Value
Cavity material	-	bulk niobium
Gradient	MV/m	25
Quality factor Q_0	-	$5 \cdot 10^9$
R/Q	-	570
Operating Temp.	K	2
Cryo duty cycle	%	8.22
Dynamic heat load	W	20.4

This cryo-module will therefore feature two cryostat end closures, equipped with Cold-To-Warm transitions (CWT) for the beam tube, as well as a connection to the cryogenic distribution line for the feeding of helium at cryogenic temperatures.

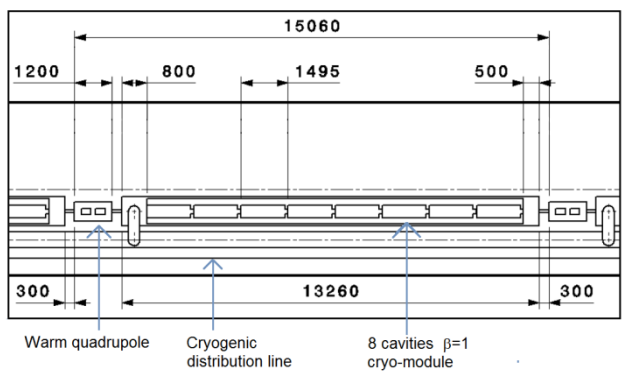


Figure 1: Layout (top view) of the SPL cryo-module.

Considering that in an initial phase only four out of the eight cavities will be made, and will need to be tested together as they would operate in a machine-type cryo-module, a ½ length cryo-module, the so-called Short Cryo-module (SC), has to be designed and constructed. This cryo-module will serve primarily as a test-bench for RF testing of the cavities, powered by specifically developed RF couplers, but will also provide the opportunity of developing a first prototype of a machine-

STATUS AND PLANS FOR AN SRF ACCELERATOR TEST FACILITY AT FERMILAB*

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Abstract

A superconducting RF accelerator test facility is currently under construction at Fermilab. The accelerator will consist of an electron gun, 40 MeV injector, beam acceleration section consisting of 3 TTF-type or ILC-type cryomodules, and multiple downstream beam lines for testing diagnostics and performing beam experiments. With 3 cryomodules installed this facility will initially be capable of generating an 810 MeV electron beam with ILC beam intensity. The facility can accommodate up to 6 cryomodules for a total beam energy of 1.5 GeV. This facility will be used to test SRF cryomodules under high intensity beam conditions, RF power equipment, instrumentation, and LLRF and controls systems for future SRF accelerators such as the ILC and Project-X. This paper describes the current status and overall plans for this facility.

FACILITY DESCRIPTION

Figure 1 shows the overall layout of the new facility. The existing New Muon Lab building (NML) is 70 m in length and was previously used to house a high energy fixed target experiment. This building has been completely refurbished to accommodate the upstream end of the beamlines and supporting infrastructure. Starting from the lower left in the figure are the RF gun, injector, and 1st 3 SRF cryomodules, all housed in the original building. A 70 m tunnel extension has been built to house the high energy end of the beamlines and high power beam dumps. The cryogenic plant currently consists of 2 Tevatron-style satellite refrigerators and does not have the capacity to cool all 3 cryomodules at full beam intensity and at full pulse repetition rate. Also shown in Figure 1 is a new refrigeration plant (CMTF) [1] which is being built with capacity to deliver 600 W of 2 °K helium. CMTF will also have multiple horizontal cryomodule test stands to test 325 MHz, 650 MHz, and 1.3 GHz SRF cryomodules in CW mode.

Photocathode Laser

An enclosed, temperature-controlled laser hut is being built inside the NML building to house the photocathode laser. The seed laser is a fiber optic laser (from Calmar Laser) operating at 1.3 GHz with Ytterbium as the lasing element and output at 1060 nm. A Pockels cell reduces the pulse rate to 81.25 MHz and further amplification and an additional Pockels cell reduces the rate to 3 MHz and increases the pulse energy to ~1 mJ/pulse. Two doubling crystals then decrease the wavelength to 265 nm which is used to excite the Cs_2Te photocathode in the RF gun. This laser will be capable of producing 10's of nC of charge per pulse with rms pulse lengths of 2 ps – 20 ps. In addition, there will also be a TiSa laser housed in the same laser hut capable of exciting the photocathode with pulses of rms pulse length of 100 fs.

RF Electron Gun

The RF electron gun is identical to the guns recently developed at DESY Zeuthen (PITZ) for the FLASH facility [2]. It is a 1½ cell L-band gun capable of operating at up to 5 MW peak power and DC power dissipation of ~20 KW. We expect to operate the gun routinely at peak gradients of 45 MV/m, and output kinetic energy of ~5 MeV. The photocathode is Cs_2Te with 5 mm diameter sensitive area. These photocathodes are coated at a separate facility on the Fermilab site and transferred to the gun under vacuum. The photocathode preparation facility was developed by D. Sertore at INFN Milano. The gun is surrounded by 2 solenoid magnets for emittance compensation, and ASTRA simulations indicate that transverse normalized transverse emittances of 5 μm can be attained at a bunch charge of 3.2 nC. RF windows are currently being conditioned and gun commissioning will commence in late 2011.

Booster Cavities

The electron gun is followed by two SRF cryomodules to accelerate beam to 40 – 50 MeV. Each cryomodule contains a 9-cell L-band cavity operating at 1.3 GHz. One cavity is currently in use at the Fermilab A0 Photoinjector [3] operating at a peak gradient of 12 MV/m and will be refurbished with a higher gradient cavity in the Fall of 2011 before installation at NML. The other cavity is currently installed at NML and operates at a peak gradient of 25 MV/m.

40 MeV Injector Line

Downstream of the SRF booster cavities is the 40 MeV injector beamline whose primary purpose is to deliver appropriate beam to the SRF cryomodules. This beamline will have adequate instrumentation to fully characterize beam parameters – toroids for intensity, BPMs for position, OTR and YAG screens for beam size, slit masks for transverse emittance, spectrometer magnet for energy and energy width, phase monitors for timing jitter, and streak camera and interferometer for bunch length. There is a 4-dipole chicane for bunch compression, and there will eventually be a 3.9 GHz SRF cavity for bunch linearization. A 3.9 GHZ normal conducting transverse mode cavity [4] will be installed to measure longitudinal phase space (in conjunction with the spectrometer magnet).

*Operated by Fermi Research Alliance, LLC, under Contract No. DE-AC0207CH11359 with the United States Department of Energy
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TEST OF COMPONENTS FOR THE S-DALINAC INJECTOR UPGRADE*

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Abstract

In 2009 a vertical bath cryostat was commissioned at the S-DALINAC. Since then, components for the new cryostat module within the framework of the injector upgrade have been tested. Measurements have been performed to check the leak rate of "Quick-CF" UHV flanges. Furthermore, the performance of piezo actuators in superfluid helium has been investigated. To extend the range of possible measurements at the vertical bath cryostat, systems for measureing the quality factor via the decay-time method and for quench localisation via second sound will be implemented this year.

INTRODUCTION

The superconducting Darmstadt linear accelerator S-DALINAC [1] is a recirculating electron linac, using twelve superconducting niobium cavities at a frequency of 2.9975 GHz. It was first put into operation in 1987. Running at a temperature of 2 K the main acceleration is done by ten 20 cell elliptical cavities with a design accelerating gradient of 5 MV/m. The S-DALINAC uses cryostat modules containing two cavities per module. The first module is used in the injector section of the machine. Behind this section, the beam can be transported into an experimental area where nuclear physics experiments at a maximum energy of 10 MeV are performed, or transferred to the main linac for further acceleration.

The injector upgrade project [2] aims at a beam-energy and current increase from 10 MeV with 60 µA up to 14 MeV with 250 µA in the injector section. Therefore, it was necessary to construct a modified cryostat module to replace the existing one. Furthermore, new cavities had to be built, providing a good quality factor to achieve the higher accelerating gradient of 7 MV/m with acceptable power transfer to the helium bath. A vertical bath cryostat was used to test the components for the new cryostat module and is still being improved to provide a larger range of measurements for new test projects.

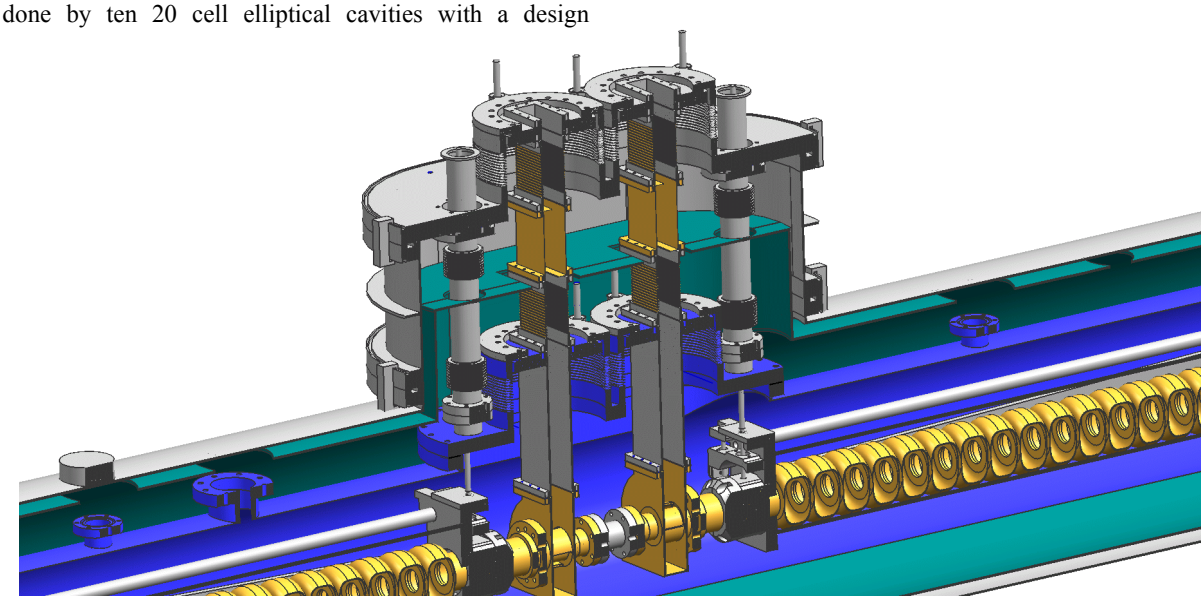


Figure 1: 3-D design of the new injector module. RF input and output couplers, together with the 20 cell cavities and their frequency tuners are shown inside the helium vessel. These inner parts are surrounded by a thermal shielding made of aluminium and cooled with liquid nitrogen. The outer pressure vessel is made of stainless steel. In the center, the waveguides and their transitions through the different vacuum/pressure stages in the so-called tower section are shown. Each transition line consists of two custom-made flexible waveguides with a special waveguide in between to intercept heat radiation. For a better view the carriage which supports the tuners and the beam line, several lines for nitrogen and helium, the magnetic shielding and the multi-layer-insulation are hidden.

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RF AND SRF COMPONENTS FOR B*ERL*INPRO*

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Abstract

The Energy Recovery Linac (ERL) project B*ERL*inPro is funded as of January 2011 and is now in the design phase. B*ERL*inPro should demonstrate the feasibility to use ERL technology for next generation light sources and other ERL applications. The planned SRF layout is described including the RF transmitter, the couplers and the configuration of the SRF modules. The project has been reviewed by a machine advisory committee (MAC).

INTRODUCTION

In the search for the next generation light source, the ERL (energy recovery linac) principle seems to be a promising candidate. The characteristic parameters for such a light source will be a beam current of 100 mA or more, an emittance of 1 mm mrad and bunch length in the ps-range or in special modes even in the 100 fs-range. The ERL principle has been demonstrated [1][2][3], but the high current and low emittance in combination has not been shown yet. To demonstrate that an ERL-based accelerator can achieve these parameters, the B*ERL*inPro project has been approved by the Helmholtz-Gemeinschaft and the BMBF and will be built at the HZB.

BASIC LAYOUT OF BERLINPRO

The layout of B*ERL*inPro is shown in Figure 1. There will be a superconducting (sc) 1.3 GHz photo-injector cavity that delivers an energy gain of 1.5-2 MeV. The booster section consists of three-two cell cavities which envisioned to accelerate the beam up to an energy of 6.5 MeV. Both sections form the injector. The merger magnets connect the injector to the recirculating ERL ring. To minimize costs, the main linac consists only of three seven-cell strongly higher order mode (HOM) damped cavities. The energy of B*ERL*inPro is not a critical parameter that has to be demonstrated. It is rather the emittance and the beam current. In the future more cavities may be added in the opposing straight section or the building needs to be expanded. The main parameters of B*ERL*inPro are listed in Table 1. Due to the fact that B*ERL*inPro is a development project and costs have to be minimized, there are some reduced parameters (e.g. transmitter power) in the start phase with room for subsequent upgrades given in brackets.

Table 1: Basic Parameters of B*ERL*inPro

Energy	~ 50 MeV
Merger energy	~ 6.5 MeV
Beam current	100 mA
Emittance	1 mm mrad (normalized)
Electron source	superconduncting RF photoinjector
Gun transmitter	270 kW 1.3 GHz
Booster cavities	3 x 2-cell
Booster transmitter	2 x 200 (270) kW + 1x 15 (200) kW
Linac cavities	3 x 7 cell
Linac transmitter	3 x 15 kW

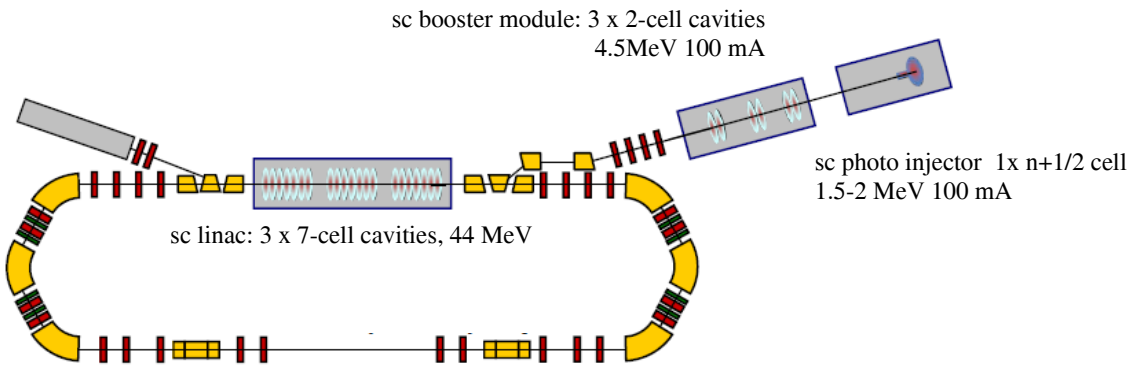


Figure 1: Layout of *BERL*inPro

*Work supported by Bundesministerium für Bildung und Forschung and Land Berlin
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DESIGN STATUS OF THE SRF LINAC SYSTEMS FOR THE FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) will utilize a powerful, superconducting heavy-ion driver linac to provide stable ion beams from protons to uranium, at energies of >200 MeV/u at a beam power of up to 400 kW. ECR ion sources installed above ground will be used to provide highly charged ions that will be transported into the linac tunnel approx. 10 m below ground. For the heaviest ions, two charge states will be accelerated to about 0.5 MeV/u using a room-temperature 80.5 MHz RFQ and injected into a superconducting cw linac, consisting of 112 quarter-wave (80.5 MHz) and 229 half-wavelength (322 MHz) cavities, installed inside 51 cryomodules operating at 2K. A single stripper section will be located at about 17 MeV/u (for uranium). Transverse focusing along the linac will be achieved by 9 T superconducting solenoids within the same cryostat as the superconducting rf accelerating structures. This paper describes the matured linac design, as the project is progressing towards a Department of Energy performance baseline definition in 2012. Development status of the linac subcomponents are presented with emphasis on the superconducting RF components.

INTRODUCTION

Michigan State University is currently designing a U.S. Department of Energy (DOE) Office of Science national user facility for research with rare isotope beams. This accelerator facility for basic nuclear science research, the "Facility for Rare Ion Beams (FRIB)", will provide intense beams of rare isotopes produced by fast fragment separation. The rare isotope beams will be created from high-current beams of stable isotopes (from He to U) accelerated in a superconducting radio-frequency linear accelerator to kinetic energies above 200 MeV/u for all ions with beam powers of up to 400 kW. As a comparison, MSU's current state-of-the-art rare isotope user facility, the National Superconducting Cyclotron Laboratory (NSCL) supported by the National Science Foundation, can provide 1 kW of beam power on target. On the scientific side, FRIB will incorporate the significant experimental infrastructure available at NSCL. A full set of already developed scientific instruments for fast, stopped, and re-accelerated radioactive beams will make FRIB immediately available for rich scientific output. A facility layout, an architectural rendering, and a functional system diagram of the FRIB facility are shown in figure 1, figure 2, and figure 3 respectively.

In December 2008 DOE has selected MSU to establish FRIB. A corresponding cooperative agreement has been signed between DOE and MSU in June 2009 with an expected project cost of $614.5M ($520M DOE-funded, and $94.5M MSU-funded). CD-1 approval (Conceptual Design Complete) has been granted by DOE in September 2010. The project is currently pursuing CD-2 (Accelerator and Experimental Systems Preliminary Design Complete) and CD-3a (Conventional Facility Detail Design Complete) approvals for May 2012. Pending DOE approval, the project will start tunnel construction in 2012.

SUPERCONDUCTING DRIVER LINAC

The FRIB accelerator systems are based on a heavy-ion, superconducting driver linac capable of achieving a minimum energy of 200 MeV/u for uranium (higher for lighter ions) at beam power of up to 400 kW. Charge stripping at about 17 MeV/u energy (for uranium) is needed to reach the final energy for the heaviest ions. In

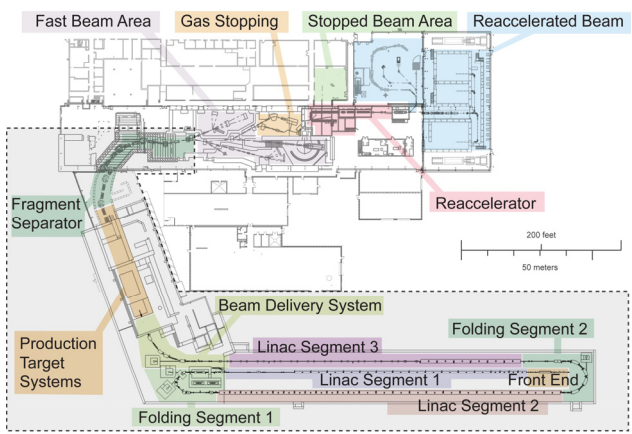


Figure 1: The FRIB facility layout includes the driver linac, a 400 kW nuclear production target, a radioactive in-flight fragment separator, and scientific instruments for fast, stopped, and re-accelerated radioactive beams [1].

*This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

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UPDATE ON MODULE MEASUREMENTS FOR THE XFEL PROTOTYPE MODULES

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Abstract

The Cryo Module Test Bench (CMTB) at DESY is used since several years for the SRF module tests [1], [2]. Three XFEL [3] prototypes modules, PXFEL1,2,3, were tested on this facility. An update on the SRF modules testing activities since PXFEL1 test [2] is presented (see Table 1).

XFEL PROTOTYPE MODULES AND TESTS

Table 1: Module Tests on CMTB at DESY

Date	Module	Comment
Jun.2009	**PXFEL1**	first test
Oct.2009	**PXFEL2**	first test
Aug.2010	**PXFEL3**	first test
Feb.2011		after disassembly at DESY: single cavities tests
Mar.2011	**PXFEL2_1**	after reassembly at CEA Saclay

Table 1 summarizes the XFEL prototypes test sequence so far, next test (PXFEL3_1) is planned for the end of 2011.

MODULE TEST STAND

CMTB layout and infrastructure was already described in [1], [2].

General Description

CMTB features the following:

- Single SRF accelerating 8 cavities cryo-module test stand in a radiation shielded area.
- Cryogenic system to cool down the cavities to 2K.
- Multibeam 8 MW klystron with tunable waveguide RF distribution.
- Advanced LLRF subsystem (see Fig. 1) featuring SimCon FPGA based DAC, 3x8 channels 1 MHz ADCs for the RF signals, cavity frequency tuner and fast piezo tuner controllers.
- 5x8 channels calibrated RF power measurement (see Fig. 1) for all module RF signals.
- Vacuum subsystem (TSP / IGP / TMP pumps).
- Gamma radiation measurement (both module ends).
- Personal interlock subsystem.
- Input RF power coupler diagnostics and technical interlock subsystem.
- Computer (LabVIEW, DOOCS) control system.

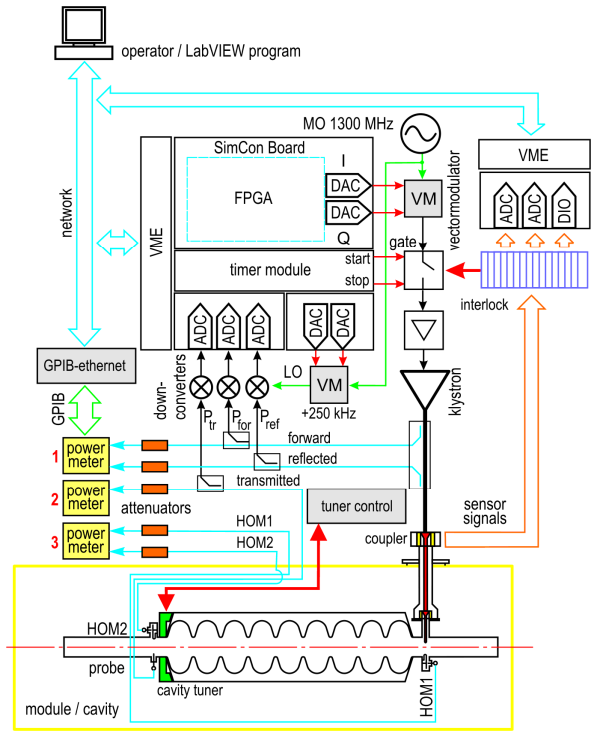


Figure 1: CMTB LLRF and RF system.

Test Procedure

Following test sequence is used to test the module:

1. RF cables (re)calibration.
2. Warm input RF couplers conditioning.
   - Up to 800kW at 20..400μs, 600kW at 1.3ms
3. Cool down to 2K.
4. Cavities Spectra measurements.
   - Fundamental / HOM spectra.
   - Cold RF cables calibration.
5. Cavities Tuners Test.
   - Tune the cavities to the 1.3GHz ± 5kHz using the Network Analyzer.
6. Couplers Q_{load} measurement.
   - Set $Q_{load} = 3\times10^6$ for each coupler.
7. Cavities on-resonance fine tuning.
   - Cavities fine-tuning to the 1.3 GHz ± 50 Hz using LLRF system (phase-tuning).
   - Q_{load}, k_t calibration ($E_{acc}=k_t\times(P_{trans})^{1/2}$).
8. Cold input RF couplers and cavities on-resonance conditioning.
   - Short RF pulse test at 2K on resonance: 100..500 μs pulse lengths up to 700kW, input coupler and cavity conditioning.

STATUS OF SARAF SUPERCONDUCTING ACCELERATION MODULE

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Abstract

Soreq Applied Research Accelerator Facility (SARAF) is based on a 176 MHz superconducting RF light ions linac, currently under commissioning at Soreq NRC [1]. At present, the accelerator includes a Prototype Superconducting Module, containing 6 half wave resonators. In this work we present measurement results of various mechanical properties of the resonators. Beam operation results are also discussed, including a new technique for the calibration of the cavity pickup probe by operating the Linac using two RF sources. Lastly, simulation results obtained using CST MWS for present and future cavities are presented as well.

LORENTZ COEFFICIENT MEASUREMENTS

The electromagnetic field contained in a superconducting cavity exerts a force on the surface charges and currents developed in the conductor. This force - the radiation pressure - slightly deforms the cavity shape, thus producing a shift of the resonance frequency. That frequency shift is proportional to the square of the field and is always negative, so the resonance frequency is reduced. The proportionality constant is defined as the Lorentz coefficient K_L, so $\Delta f_c = -K_L E_a^2$, where E_a is the accelerating field and Δf_c the resonance frequency shift.

Dynamically, the radiation pressure may couple to a mechanical resonance of the cavity structure. This situation is described by the following second order differential equation:

$$\frac{d^2(\Delta f_c(t))}{dt^2} + \frac{\Omega_m}{Q_m}\frac{d(\Delta f_c(t))}{dt} + \Omega_m^2 \Delta f_c(t) = -K_L \Omega_m^2 E_a^2$$

With Ω_m, Q_m being the mode's frequency and quality factor respectively. The left hand side describes the mode of vibration and the right hand side is the Lorentz force driving term [2,3].

By linearization of the above equation around steady state values, $E_a = E_{a,0}(1 + \delta E_a)$, and application of a Laplace transformation the Lorentz Transfer Function is obtained:

$$\delta f_c(s) = \frac{-2K_L \Omega_m^2 E_{a,0}^2}{(\Omega^2 + s^2) + \frac{\Omega_m}{Q_m} s}\delta E_a \qquad (1)$$

Where $s = jw$ is the Laplace variable. This equation has a complex pole and we therefore expect a peak in the magnitude plot, accompanied by a π phase shift when crossing the resonance in frequency.

Measurement Using NWA

The Network Analyzer (NWA) is a 2-port device capable of measuring the scattering parameters (transmission, reflection) in each of its ports.

In this setup, one port of the NWA was used to drive the high power amplifier connected to one of the cavities (via a directional coupler and a circulator). The second port was connected to the cavity pick up antenna which couples to the electromagnetic field in the resonator. By generating frequency sweeps using the NWA the cavity resonance curve (transmission between the driving and pickup signals) was measured. This was done at different levels of power incident to the cavity. As can be seen in Figure [1] the high power resonance curves are 'tilted' towards the left as a result of the resonance frequency being reduced by the Lorentz force.

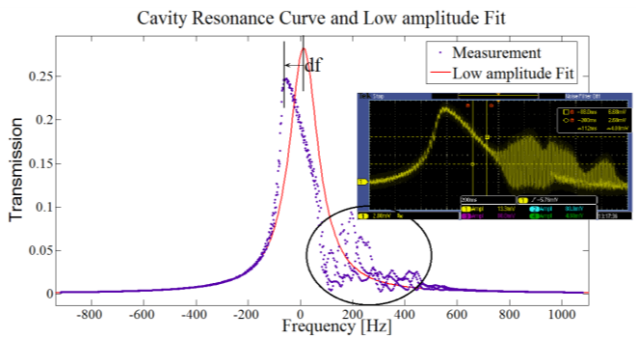


Figure 1: The cavity resonance curve measured at ~150W incident power (dots) and a fit to the low amplitudes part of the curve (Red). Marked by a circle - ripples caused by 200 Hz pondermotive oscillations observed in the scope screenshot as well.

For each resonance curve a fit was made to the low amplitudes part of the curve, to determine the resonance frequency of the cavity without the effects of the Lorentz force. Then the shift of the actual resonance frequency from that value was calculated. The amplitude of the field in the cavity was also calculated based on the pickup signal amplitude. A plot of the frequency shift Vs. the square of the accelerating field is presented in Figure [2]. This method Thus yields $K_L \sim 11.2 \pm 1.1 \frac{Hz}{(MV/m)^2}$.

OVERVIEW OF ILC HIGH GRADIENT CAVITY R&D AT JEFFERSON LAB*

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Abstract

We report on the progress of ILC high gradient cavity R&D at Jefferson Lab since the Berlin conference. The optimal cavity processing recipe has been developed and applied for reproducible high gradient and high Q_0 results in real 9-cell cavities. An example of 90% gradient yield at >35 MV/m is demonstrated based on 10 cavities built by an experienced vendor. JLab qualified 9-cell cavities are sent back to FNAL, contributing to the first ILC cryomodule CM2 in the US. Advanced quench studies of 9-cell cavities are enhanced by new instrumentations. Besides the main work with the ILC baseline cavities, we have also processed and tested ILC alternate cavities including 9-cell large-grain niobium cavities and 9-cell low-loss shape cavities in collaboration with Peking University, KEK, and IHEP. A 9-cell seamless cavity from DESY has completed EP processing and RF testing. To date, more than 50 9-cell cavities have been processed and/or tested at JLab under the American Regional Team program in support of ILC. More than 110 ILC cavity EP cycles have been accumulated, corresponding to more than 330 hours of active EP time. More than 150 ILC cavity RF tests at cryogenic temperatures have been completed including cavity qualification tests and instrumented studies for understanding of quench limit.

INTRODUCTION

The accelerating gradient choice has a significant impact to the project cost for the International Linear Collider (ILC). The baseline ILC design requires a cavity accelerating gradient of 31.5 MV/m in average with an allowable spread of < ±20% (TESLA-shape cavity) to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs. The vertical test acceptance specification is 35 MV/m at Q_0 8E9, with an allowable gradient spread of < ±20% [1]. The ILC cavity gradient R&D program is a global effort with major contributions from DESY, JLab, FNAL, KEK and Cornell [2]. A major focus is to improve the gradient yield. In the mean time, a broader range of SRF cavity R&D topics are being addressed in support of ILC, such as alternative cavity shapes, large-grain niobium material, mechanical polishing for bulk removal and seamless cavity fabrication. The alternatives are relevant to the ILC gradient goal in terms of reaching higher ultimate gradient, improving gradient reproducibility or reaching the same gradient at potentially lower cost. In this paper, an overview of high gradient SRF R&D at JLab will be given for baseline ILC cavities, alternative cavities as well as focused R&D with 1-cell cavities. JLab collaborates with FNAL, KEK, Cornell, DESY, PKU and IHEP and cooperates with the cavity fabrication industry in many activities reported herein.

The high gradient cavity processing and handling procedures have been established, standardized, and routinely applied. The repeatable processing has shown to result in reproducible high gradient and high Q_0 results. Nine out of ten 9-cell cavities manufactured by ACCEL/RI achieved a gradient of more than 38 MV/m at Q0 of more than 8E9 up to a second-pass processing. Four out of six 9-cell second production batch cavities manufactured by AES achieved a gradient in the range of 36-41 MV/m, validating the vendor to become the first "ILC certified" manufacturer in the US industry.

The cavity quench studies are further enhanced by adopting the Cornell OST's and the KEK replica technique, in addition to the existing JLab fixed thermometry system and JLab high-resolution optical inspection machine. Advanced quench studies through dual-mode excitation and high-resolution local thermometry have resulted in new insight into the nature of cavity quench behaviors at low as well as at high surface magnetic fields. First results have been obtained in studies of a 1-cell cavity with controlled geometrical defects, elucidating the initiation of phase transition due to local magnetic field enhancement and the interplay with the heat generation and conduction. We have also EP processed and tested alternative cavities, including low-loss (ICHIRO) shape 9-cell cavities, large-grain niobium 9-cell cavities and seamless 9-cell cavities, in collaboration with KEK, PKU and DESY.

Up to now, more than 50 9-cell cavities have been processed and/or tested at JLab under the America Regional Team program in support of ILC. More than 110 ILC cavity EP cycles have been accumulated, corresponding to more than 330 hours of active EP time. More than 150 ILC cavity RF tests at cryogenic temperatures have been completed including the cavity qualification tests and instrumented studies for the understanding of quench limit.

BASELINE CAVITY RESULTS

Standard Cavity Processing and Handling Procedure

The standard procedures of ILC high gradient cavity processing and handling are described in Ref. [3]. The procedure includes optimized electropolishing, streamlined post-EP cleaning, updated vacuum furnace

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

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RF TEST RESULTS FROM CRYOMODULE 1 AT THE FERMILAB SRF BEAM TEST FACILITY*

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Abstract

Powered operation of Cryomodule 1 (CM-1) at the Fermilab SRF Beam Test Facility began in late 2010. Since then a series of tests first on the eight individual cavities and then the full cryomodule have been performed. We report on the results of these tests and lessons learned which will have an impact on future module testing at Fermilab.



Figure 1: View of CM-1 from upstream to downstream with the waveguide distribution installed.

INTRODUCTION

CM-1 is the first Tesla Type III Cryomodule to be placed into operation in the United States and the first multi-cavity cryomodule of any type to become operational at Fermilab. It was provided to Fermilab as a 'kit' from DESY in exchange for a 4-cavity 3.9 GHz module, ACC39, which was designed and assembled at Fermilab and is now in operation at DESY's FLASH facility. Assembly of the module has been documented previously [1]. Plans for a fully-utilized facility are described elsewhere at this conference. [2]. Table 1 highlights the major steps in bringing CM-1 into operation from its final installation in January 2010 to the present. Figure 1 shows CM-1 installed in the cave at the SRF Beam Test Facility.

*Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
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Table 1: CM-1 Commissioning Milestones

Milestone	Date
Cryomodule moved into final position and aligned	22 January 2010
Permission to initiate RF commissioning and warm coupler conditioning	11 June 2010
5 MW RF/Klystron commissioning	June - July 2010
Warm coupler conditioning - one cavity at a time (4 - 14 days/cavity)	August – October 2010
Cryogenic and vacuum connections, leak check	October – November 2010
Cool down from room temperature to 4 then 2 Kelvin	17 – 22 November 2010
Approval to initiate cold RF operation	10 December 2010
Cavity 1/Z89 cold conditioning and evaluation	17 December 2010 - 26 January 2011, 18-22 March 2011
Cavity 8/S33 cold conditioning and evaluation	28 January 2011 - 7 March 2011
Cavity 2/AC75 cold conditioning and evaluatio	7 - 16 March 2011
Cavity 3/AC73 cold conditioning and evaluation	26 March - 4 April 2011
Cavity 4/Z106 cold conditioning and evaluation	20 April - 19 May 2011
Cavity 5/Z107 cold conditioning and evaluation	20 - 25 May
Cavity 6/Z98 cold conditioning and evaluation	3 - 9 June

DESIGN OF THE FUNDAMENTAL POWER COUPLER AND PHOTOCATHODE INSERTS FOR THE 112 MHZ SUPERCONDUCTING ELECTRON GUN*

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Abstract

A 112 MHz superconducting quarter-wave resonator electron gun will be used as the injector of the Coherent Electron Cooling (CEC) proof-of-principle experiment at BNL [1]. Furthermore, this electron gun can be the testing cavity for various photocathodes. In this paper, we present the design of the cathode stalks and a Fundamental Power Coupler (FPC) designated to the future experiments. Two types of cathode stalks are discussed. Special shape of the stalk is applied in order to minimize the RF power loss. The location of cathode plane is also optimized to enable the extraction of low emittance beam. The coaxial waveguide structure FPC has the properties of tunable coupling factor and small interference to the electron beam output. The optimization of the coupling factor and the location of the FPC are discussed in detail.

INTRODUCTION

A 112 MHz superconducting quarter-wave resonator electron gun had been built under cooperation between Brookhaven National Lab and Niowave Inc. This gun will be used as the injector of the Coherent Electron Cooling experiment in BNL. Besides that, this gun can also be used as the testing facility for various photocathode. However, two major modifications have to be done to make the gun suitable for the tasks mentioned above. First, the original cathode holder, which had also been used as a fundamental power coupler has to be replaced by a newly designed cathode stalk. The new stalk is specially designed for the test of Diamond Electron Amplifier which will multiply the primary electron current by a factor of nearly 200. Meanwhile, this stalk is compatible for the test of other photocathode such as the metal and multi-alkali cathode, one only have to change the insertion of it and the outer shield can be kept untouched. Secondly, the fundamental power coupler has been redesigned. Since the length of new cathode stalk has been made half wave length in order to optimize the field on cathode, it is not applicable as a power coupler any more. Therefore a new FPC which couples the RF power into cavity from the exit of cavity has been designed. Moreover, by adjusting the penetration of the Coupling Tube one can tune the frequency of cavity as well as adjust the coupling strength. The layout of the cavity including the cathode stalk and FPC is shown in Figure 1.

DESIGN OF CATHODE STALK

As mentioned above, for the future application of 112 MHz electron gun in CEC project as well as the testing experiments on different photocathodes the original stalk has to be replaced by a new one which can be used to mount a much larger cathode and also have enough space inside for the primary DC gun in the Diamond Amplifier experiment. The general considerations in the design of cathode stalk are discussed below.

Large Cathode Surface-half Wave Length Design

The cathode that is going to be tested in this gun has the diameter as large as 2 cm. This requirement leave only 4 mm gap between the stalk and nose cone at the entrance of the cavity. If we still use the original length of stalk which was selected as quarter wave length for the sake of power coupling, the voltage drop between the cavity and stalk will be more than 5.6 kV if a reasonable acceleration field is assumed. Therefore, we applied a half wave length design here to minimize the voltage drop between stalk and cavity.

According to the general equation of impedance of transmission line [2]:

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} , \quad (1)$$

here $Z_0 = 60\, ln\frac{b}{a}$ where b and a and the radius of outer and inner conductor respectively.

$$\gamma = \alpha + j\beta , \quad (2)$$

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IHEP 1.3 GHz SRF TECHNOLOGY R&D STATUS*

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Abstract

1.3 GHz superconducting radio-frequency (SRF) technology is one of the key technologies for the ILC and future XFEL and ERL projects in China. With the aim to develop 1.3 GHz SRF technology, IHEP has started a program to build an SRF Accelerating Unit. This unit contains a 9-cell 1.3 GHz superconducting cavity, a short cryomodule, a high power input coupler, a tuner, a low level RF system etc. This program also includes the SRF laboratory upgrade, which will permit the unit to be built and tested at IHEP. The unit will be used for the 1.3 GHz SRF system integration study, high power horizontal test and possible beam test in the future. In this paper, we report the recent R&D status of this program. The first large grain low-loss shape 9-cell superconducting RF cavity made by IHEP reached 20 MV/m in the first vertical test. The prototype tuner and LLRF system were tested. The first 1.3 GHz high power input coupler fabrication was finished and the cryomodule is under fabrication. Several key SRF facilities (CBP, BCP, HPR, optical inspection camera, pretuning machine etc.) for 9-cell cavity processing were successfully commissioned and in operation.

INTRODUCTION

1.3 GHz superconducting radio-frequency (SRF) technology is one of the key technologies for the International Linear Collider (ILC) and future XFEL and ERL projects of China. With the aim to develop this technology, IHEP has started a program to build an SRF Accelerating Unit within ILC collaboration [1, 2, 3].

The SRF Accelerating Unit contains a 9-cell 1.3 GHz superconducting cavity, a short cryomodule, a high power input coupler, a tuner, and a low level RF (LLRF) system. The unit can undergo beam tests and can be used as the booster for an SRF linac.

The R&D goals of the program are:

- Cavity gradient of 25-35 MV/m with $Q_0 > 8\times10^9$ for the vertical test, and 20-31.5 MV/m with $Q_0 > 1\times10^{10}$ for the horizontal test;
- 1 MW (5 Hz, 1.5 ms pulse, TW) power through the high power input coupler in conditioning tests; 300 kW (5 Hz, 1.5 ms pulse, SW) power for the horizontal test;
- LLRF phase stability 0.1°, amplitude stability 0.1 %;
- Labs and facilities capable of the 9-cell cavity processing, pretuning, vertical tests and horizontal tests.

LOW LOSS LARGE GRAIN CAVITY

The combination of the low-loss shape and large grain niobium material is an alternative to achieve higher gradient and lower cost for ILC 9-cell cavities, and will be essential for the ILC 1 TeV upgrade.

Recently, a KEK low-loss shape fine grain 9-cell cavity reached 40 MV/m [4] and a DESY TESLA large grain 9-cell cavity reached 45 MV/m [5]. 45-50 MV/m gradient demonstration of the electro-polished low-loss shape 9-cell cavity, especially with large grain material, is foreseen in the next few years.

A low-loss shape 9-cell cavity (IHEP-01, Figure 1) without HOM couplers using Ningxia large grain niobium was fabricated and processed (CBP + BCP) at IHEP. The first vertical test was made at KEK. 20 MV/m was achieved with strong field emission [6]. After removing almost all the defects with CBP (tumbling) machine, the second test was performed at JLAB [7].

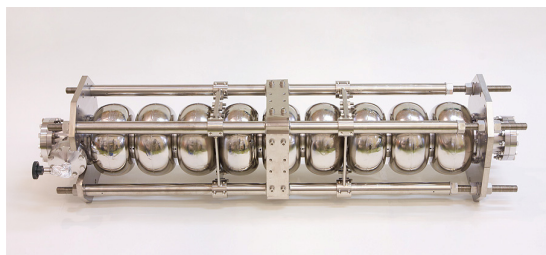


Figure 1: IHEP-01 low-loss large grain 9-cell cavity.

The low-loss shape large grain 9-cell cavity with full end groups (IHEP-02) is also under fabrication. We will test it at FNAL in early 2012. This cavity will be installed into the cryomodule to make horizontal test at IHEP.

HIGH POWER INPUT COUPLER

With the successful fabrication technologies developed for the high power input coupler of the BEPCII 500 MHz superconducting cavity, the 1.3 GHz high power input coupler is designed based on the KEK STF baseline coupler [8] with two TRISTAN type windows.

After careful RF, thermal and mechanical simulation and design, we finished brazing the warm and cold windows and other parts (Figure 2) and finally the whole coupler (Figure 3). The high power test and conditioning will be done soon. In the fabrication, plating copper on bellows was the most difficult. The plating usually volatilized or some bubbles appeared on the plating layer after brazing in the furnace.

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SUPERCONDUCTING RF FOR THE CORNELL ENERGY-RECOVERY-LINAC MAIN LINAC *

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Abstract

Cornell University is developing the superconducting RF technology required for the construction of a 100 mA hard X-ray light source driven by an Energy-Recovery Linac. Prototype components of the 5 GeV cw SRF main linac cryomodule are under development and fabrication. This work includes an optimized 7-cell SRF cavity, a cold frequency tuner, a broadband HOM beamline absorber, and a 5 kW cw RF input coupler. A Horizontal Test Cryostat (HTC) is also under design, and will be used for a first horizontal test of the ERL main linac cavity in 2012 and later for a beam test of the cavity at high beam current. In this paper we give an overview of these activities at Cornell.

INTRODUCTION

Continuos progress in Superconducting Radio-Frequency (SRF) technology during the last three decades had transformational impact on particle accelerators for many different applications. Multi-GeV SRF linacs running in CW mode and supporting beam currents of tens of mA are now coming into reach, which will enable novel high current accelerators like an x-ray light source based on the Energy-Recovery-Linac (ERL) principle. Such an accelerator is currently under development at Cornell University's Laboratory for Accelerator based Sciences and Education [1].

After fabrication and successful commissioning and testing of a short SRF linac section in the ERL injector prototype at Cornell [2], the main focus is now on developing the SRF technology for the 5 GeV ERL main linac, supporting beam currents exceeding 2 x 100 mA (100 mA in the accelerated beam and 100 mA in the decelerated beam). Fig. 1 shows the layout of the Cornell ERL design and Table 1 summarizes the specifications for the SRF main linac. After fully developing and testing the individual main linac beam line components, a single cavity test cryomodule will be fabricated and tested first before a full main linac prototype cryomodule hosting six 7-cell cavities will be fabricated at Cornell.

ERL MAIN LINAC

The 5 GeV Cornell ERL main linac will have 384 7-cell SRF cavities, running CW at 16.2 MV/m accelerating gradient. Each main linac cryomodule will host 6 SRF cavities; see Fig. 2 and Tables 1 and 2. Key challenges that need to be addressed in the main linac cryomodule include: (1) Support of CW cavity operation with high dynamic cryogenic loads, (2) supporting high beam current ERL operation up to 2 x 100 mA with short (2 ps) bunches, and (3) operating the SRF cavities at a high loaded quality factor $Q_L \geq 6.5 \times 10^7$ while still achieving excellent RF field stability.

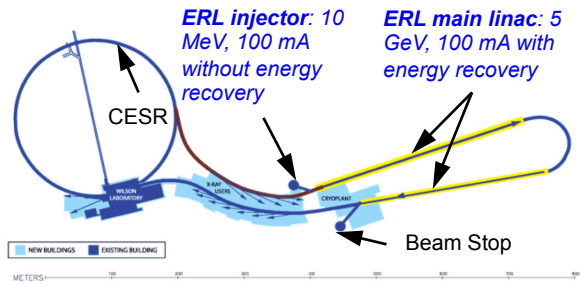


Figure 1: Layout of the Cornell ERL. The 5 GeV main linac would consist out of two continuous linac sections located in a new tunnel which would extend the existing CESR tunnel.

ERL MAIN LINAC CAVITY

The 7-cell main linac cavities are optimized for a high R/Q of the fundamental mode of 387 Ω (circuit definition) and for strong HOM damping by optimizing the shape of the end cells [3]. Fig. 3 shows the optimized cavity, and Table 3 lists some of its parameters. HOMs up to 10 GHz

Table 1: Cornell ERL main linac specifications

Parameter	Value
Total energy gain	5 GeV
max. beam current	100mA
Bunch charge	77pC
Bunch length	2ps
Number of linacs	2
Modules per linac	35 (linac A); 29 (linac B)
Linac length	344 (linac A); 285 (linac B)
Cavities per module	6
Total number of cavities	384
Linac fill factor	49%

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PERFORMANCE LIMITATION STUDIES ON ISAC-II QWR'S AND E-LINAC ELLIPTICAL CAVITIES AT TRIUMF

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Abstract

TRIUMF has been operating successfully for several years numerous 100MHz class superconducting quarter wave resonators on the ISAC-II heavy ion linac [1] and is now developing a 1.3 GHz activity to build the e-linac, a 50 MeV superconducting electron linac to produce radioisotopes by photofission [2]. Several studies on cavity treatments are ongoing to both enhance ISAC-II QWR performances and to meet the requirements on the e-linac elliptical cavities. This paper will summarize the main development efforts to understand performance limitations in these cavities.

INTRODUCTION

Two spare Quarter-Wave Resonator (QWR) built for ISAC-II upgrade are available to perform additional studies to improve their performance. These 141 MHz QWR have been repaired after a first etching as they both revealed a leak at the welding joint between the inner conductor and the drift tube (donut). The unique difference between a repaired and non-repaired cavity is that the inner conductor is cut out of the upper flange, repaired and then welded back into place.

A study loop [3] has been performed after repair that consists in sequencing a BCP etching, two tests at 4.2K, two 100K soaking and an in-situ baking at 120C for 48h as sketched on Figure 1. This loop has been repeated three times.

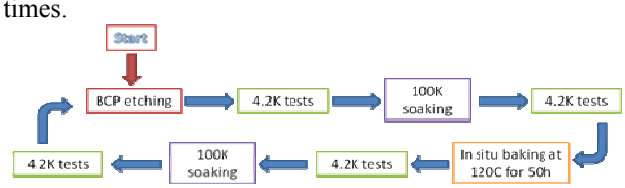


Figure 1: One loop study layout.

The cavity performances have barely improved and is still performing under the ISAC-II requirements (Qo of 3E8 corresponding to 7W dissipations at 6 MV/m). Some interesting observations have been made during this study and will be described here.

TRIUMF is also working on the development of 1.3 GHz nine cell elliptical cavities and the construction of the infrastructure to support 1.3 GHz activities for the ARIEL facility [4]. Two single cell cavity prototypes have been built by PAVAC Industries of Richmond, BC and are processed and tested at TRIUMF [5]. After several etching iterations, the cavity performances have been gradually improved but the requirements have not been reached yet (Qo of 1E10 corresponding to 10W dissipations at 10 MV/m for 9 cells). Several technical issues like leak opening after etching or "super-leaks" have significantly delayed our progress. The results will be exposed in this paper.

Recently, in collaboration with Fermilab, one QWR and one 1-cell cavity have been degassed above 600C and tested back at TRIUMF. These last results will be included in this paper.

RESULTS ON 141 MHZ QWR

Preparation

The surface conditioning of the cavity for each loop is the following:

- Etching is about 80 microns in high magnetic field regions and 20 microns near the beam tube. The acid temperature is kept below 13C. Some agitation is provided during the etching. The cavity is then rinsed thoroughly with deionised water and left for drying in a fume hood after an alcohol rinsing.
- The cavity is High Pressure Rinsed in a class 100 clean room and dried over night after some alcohol rinsing.
- The cavity is loaded in the cryostat in a class-1000 environment and pumped down to 1E-6 torr. A 24h drying at 50C is done in all cases before a 4.2K test. In some cases a 120C bake for 48 hours is done
- The cavity is cooled down as fast as possible to spend less than 30 min between 150K and 50K.
- After a test, the cavity is warmed to spend at least 2h between 80K and 110K to trigger Q-disease. The cavity is then tested at 4.2K
- During an in situ baking, the cavity is kept between 100C and 120C during 40h under vacuum.

Results and Observations

This cavity shows significant improvements between the first and second loop. Q-curves measured look all "Q-diseased" [3] meaning a significant Q-slope at low field even after a fast cooling down (see figure 2).

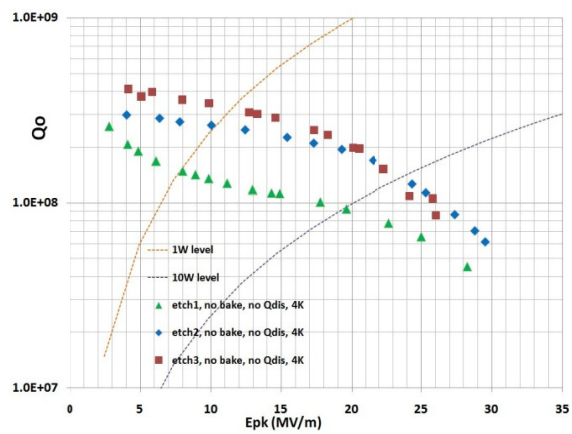


Figure 2: Q curves measured after each additional etching steps (86 µm, 74 µm and 78 µm).

THE UPGRADED INJECTOR CRYOSTAT MODULE AND UPCOMING IMPROVEMENTS AT THE S-DALINAC*

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Abstract

Since 1991 the superconducting Darmstadt linear accelerator S-DALINAC provides an electron beam of up to 130 MeV for nuclear and astrophysical experiments. The accelerator consists of an injector and four main linac cryostats, where the superconducting 3 GHz cavities are operated in a liquid helium bath at 2 K.

For the injector upgrade program, the RF power delivered to the beam had to be increased from 500 W to 2 kW. Therefore, the coaxial power couplers have to be replaced by new waveguide couplers introducing only small transversal kicks to the beam. Consequently, modifications to the cryostat-module and had become necessary. We review on the design of the module and some interesting features and give details on the tuning of the newly built 20-cell cavities. The paper will close with an outlook towards the installation of an additional recirculation path planed in 2013.

INTRODUCTION

The superconducting Darmstadt linear accelerator S-DALINAC [1] is a recirculating electron linac, using twelve superconducting niobium cavities at a frequency of 2.9975 GHz. It was first put into operation in 1987. Running at a temperature of 2 K the main acceleration is done by ten 20 cell elliptical cavities with a design accelerating gradient of 5 MV/m. The S-DALINAC uses cryostat modules containing two cavities per module. The first module is used in the injector section of the machine.

Behind this section, the beam can be transported into an experimental area where nuclear physics experiments at a maximum energy of 10 MeV are performed, or transferred to the main linac for further acceleration. Here, eight additional cavities are installed, providing an energy gain of 40 MeV. The final design energy of the machine (130 MeV) is obtained when the electron beam is recirculated twice.

An active experimental program around the machine, supported by the DFG within the framework of a collaborative research centre (CRC/SFB) leads to a continuous upgrade program around the machine, two of which will be described within this article.

INJECTOR UPGRADE

The injector upgrade project aims at an energy and current increase from 10 MeV with 60 µA up to 14 MeV with 250 µA in the injector linac, requiring a major modification of the cryostat module.

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The cryostat modules in operation so far use a coaxial RF transition line to deliver the RF power to the cavities. This transition line has a diameter of only 21 mm (7/16''), limiting the power transferable to the couplers and the cavities to 500 W [2]. For the beam energies and currents in the injector upgrade project new power couplers capable of up to 2000 W were designed. These power couplers feature a RF transition line now being a rectangular WR-284 (cross section 72×34 mm^2) waveguide (see [3] for more details).

Because of the increased spacious demands of the RF transition, the cryostat design had to be changed considerably [4, 5] leading to interesting features. As the WR 284 waveguide has a large aperture, resulting in excessive heat transfer by radiation from ambient to the cold, special precaution for a thermal intercept was taken. We designed a waveguide with two bars as a barrier for the heat radiation (as shown in Figure 1), connected to the 80 K radiation shield. The distance between the bars chose to give minimum reflection at the operation frequency. The RF simulations were done using CST-MWS microwave. Figure 1 also shows the RF measurement on a warm prototype of this waveguide intercept indicating that less than 1% of the RF power is reflected. The shrinkage during cool-down and thus the frequency shifting of the minimum has been taken into account. Even though the bars do not cover the complete waveguide cross section, at least 70% of heat radiation can be intercepted, reducing the heat transfer from radiation to the 2 K part to some 500 mW.

Since the design was finished, finding vendors for all the components were an issue. Especially, the flexible RF waveguides transitions from the helium vessel at 2 K to the parts at room temperature were commercially not available. Finally, an industrial R&D program was launched to build the parts as rectangular bellows out of stainless steel (see Figure 2). They were delivered a few

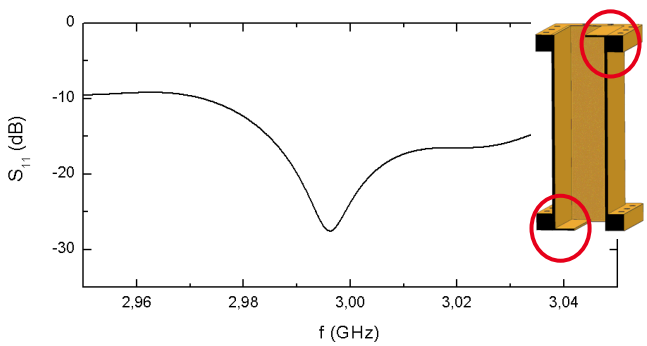


Figure 1: Heat radiation intercept of the RF waveguide at 80 K (schematic layout and RF properties).

MINIMIZING MICROPHONICS DETUNING BY OPTIMIZATION OF STIFFENING RINGS*

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Abstract

Maintaining a constant gradient in a superconducting cavity requires much more power if the cavity is not driven on resonance. Significant cost savings in both power consumption and power supplies can be realized by minimizing the detuning of the cavity away from the drive frequency. One of the largest contributions to detuning is microphonics. In this paper, simulations of microphonics detuning by LHe bath pressure fluctuations in a Cornell ERL cavity are presented, and the effect of varying stiffening ring radius is investigated. The consequences of using optimal stiffening ring radii are explored as well, including bandwidth limitations in active detuning compensation due to mechanical resonances and requirements for the frequency tuner.

INTRODUCTION

Several proposed accelerator facilities such as the Cornell ERL, the KEK ERL, and Project X, plan to use SRF cavities in continuous wave (CW) operation with low effective beam loading. At small cavity bandwidths, even a few hertz difference between the cavity frequency and the drive frequency can require significantly more than the on-resonance drive power to maintain a constant gradient.

Studies [1] have shown that careful cryomodule design can successfully decouple ground vibration from cavities. This leaves fluctuations in the helium bath pressure as likely the main source of microphonics detuning for CW operation, when Lorentz force detuning is not relevant. The detuning Δf depends on the product of the helium pressure deviation Δp and the cavity pressure sensitivity df/dp. The pressure stability depends on the pumping system, where the peak, not average, pressure deviation is the important measure of its stability. The cavity sensitivity depends on the design of the cavity and its helium vessel frequency tuner assembly. Careful design through simulation can reduce this factor to a tolerable level.

This paper presents efforts to reduce the pressure sensitivity of the Cornell ERL main linac cavity, shown in Figure 1, through optimization of the stiffening ring radius. The analysis benefits from the work of Zaplatin et al. [2], Conway et al. [3], and Schappert et al. [4].

SIMULATIONS

A technique was developed to simulate the full 3D cavity including helium vessel and tuner. The engineering simulation package ANSYS [5] was used, which is capable of performing both high frequency electromagnetic eigenmode analyses and structural analyses on the same model. The ANSYS modules used were APDL and Workbench. APDL is the older module, capable of high frequency analysis, but with limited ability to interface with CAD geometries. Workbench is more user-friendly, is able to work with more geometry file types, and has more functionality when handling complicated geometries. Images from the two programs are shown in Figure 2.

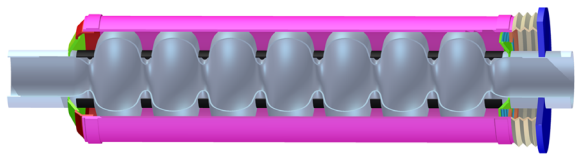


Figure 1: 3-quarter section view of a CAD model of the ERL main linac cavity cryomodule.

To determine the pressure sensitivity, first the CAD file was imported into Workbench. A pressure load was applied to the appropriate areas and the cavity was fixed as it would be in normal operation by supports in the helium vessel. The resulting length change of the cavity was the output of the Workbench analysis. Then a simple quarter model of just the cavity and enddishes was input to APDL, and a conformally meshed vacuum volume was generated. To duplicate the deformation of the cavity found in Workbench, it was subjected to a displacement constraint using the length change found earlier, along with a pressure load on the relevant areas and a symmetry constraint on the quartered faces. An update was performed on the FEA model to reflect the resulting geometry change. A high frequency eigenmode analysis was performed both before and after the model was updated to determine the frequency shift. By performing the analysis in this way, the strengths of both Workbench and APDL were exploited.

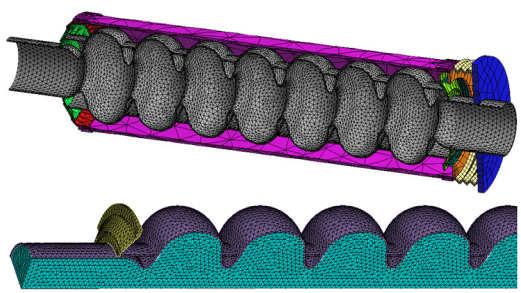


Figure 2: ANSYS Workbench model (top) and APDL model (bottom).

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NINE-CELL ELLIPTICAL CAVITY DEVELOPMENT AT TRIUMF

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Abstract

The superconducting e-Linac project at TRIUMF requires a new nine cell elliptical cavity at 1.3GHz of TESLA influenced design capable of providing a CW accelerating voltage of 10MV at 10mA of beam intensity. This corresponds to a challenging 100kW of beam loaded rf power and a Beam Break-up (BBU) threshold in multi-pass mode of $R_d/Q*Q_L$=10MOhm. For this purpose we use two opposed CPI 60kW CW rated couplers. Another challenge is to provide HOM damping for the possibility of multi-pass ERL operation by means of end cell optimization and higher order mode (HOM) dampers. Results of the cavity design work including developments toward a passive HOM damper will be discussed.

INTRODUCTION

TRIUMF eLinac project requires 50MV acceleration effective voltage [1]. It was decided to build this voltage with 5 nine cell 1.3GHz elliptical Tesla/ILC cavities operating at 2K. Each cavity will operate for 10MV or E_a=10MV/m acceleration gradient. It's quite realistic goal for production. This class of cavities, achieved operation gradients of 25-30MV/m.

The challenges for these cavities are related with 10mA beam current at 10MV which require:

- 100kW CW rf power in the cavity
- suppress HOM to below BBU threshold

ERL operation mode for last 4 cavities are under consideration and it will require additional attention for HOM damping.

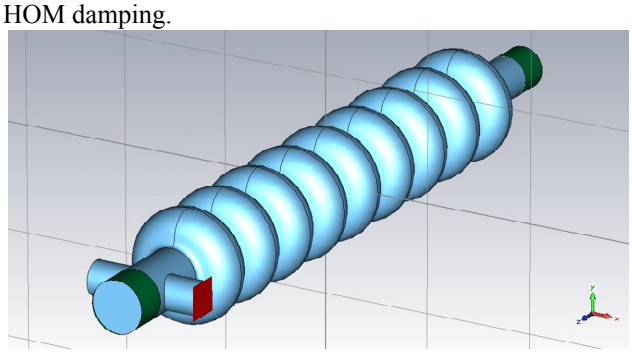


Figure 1: 9 cell TRIUMF cavity CST MWS model with input couplers and HOM damping rings

Two single cell elliptical test cavities have been built by PAVAC Industries of Richmond, BC [2] and are processed and tested at TRIUMF [3, 4]. Current TRIUMF results for these cavities didn't reach design goal of $Q_o=10^{10}$ at 10MV/m. Meantime PAVAC made the same 6 cavities. Processing and testing of these cavities in Fermilab show good results [5].

RF DESIGN

The cavity rf design is a combination of borrowed solutions for the project requirements:

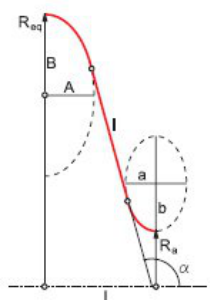
- 9 cell TESLA superconducting cavity [6] operating at 2K was chosen to get 10MV acceleration voltage at 10W power dissipation
- coupler section of 2 cell Cornell ERL cavity consisting of 2 CPI couplers [7] delivering 100kW rf power in CW
- HOM damper rings similar to Cornell ERL HOM load [8] to be simple solution

The cavity rf 3D CST MWS [9] model was used for design (Fig.1). It consists of 9 elliptical cells, 2 symmetrically opposed couplers and beam pipes with rings of rf absorber material for HOM damping.

Cavity

The cavity shape is mainly the same as 9 cell TESLA cavity with the difference in end cell iris radius adjacent to coupler beam pipe to put 2 CPI coupler ports. Such a way coupler beam line has radius 48mm (like Cornell did) and tuner beam line (opposed to coupler) - 39mm (the same as TESLA). Cavity cell geometric parameters were tuned to get flat distribution of accelerating component in CST model and presented on Table 1.

Table 1: TRIUMF 9 cell cavity geometry (in mm)



Dimension	Inner cell	Coupler end cell	Tuner end cell
Length L	57.692	56	57
Iris Radius R_a	35	48	39
Equator Radius R_{eq}	103.3	103.3	103.3
Iris half axis a	12	10	9
Iris half axis b	19	13.5	12.8
Equator half axis A	42	45	42
Equator half axis B	42	40.5	42.275

RF parameters of the cavity in comparison with 9 cell Tesla (DESY) cavity [6] are presented in Table 2. We can see that rf parameters of TRIUMF cavity are very close to TESLA (DESY). R_{sh}, E_p/E_a and B_p/E_a are ~3-5% worse because of coupler end cell iris increase. Geometric factor

SPL 704MHz β = 0.65 CAVITIES MECHANICAL DESIGN FOR EUCARD

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Abstract

Within the framework of EUCARD (European Coordination for Accelerator Research&Development), supported by European Union, IPN Orsay is in charge of the design of a 704 MHz 5-cell elliptic superconducting cavity for the intermediate energy section (β = 0.65) for accelerating high intensity proton beams in pulsed mode. This study offers a new option to replace the injector of the Large Hadron Collider at CERN with SPL (Superconducting Proton Linac) project.

For this cavity's design, a compromise between the requirement of high technological performance and the constraint of the cavity's cost should be found. As middle β elliptical cavities have a big ratio between equator radius and iris radius, the Lorentz forces detuning factor is higher than for a high β elliptical cavity. As a consequence, the cavity wall thickness should be increased and one or two stiffening rings between cells are necessary. Both increase the cost of cavity which should be imperatively minimized since more than fifty β 0.65 cavities are considered for SPL linac.

To do these optimizations, the simulation of Lorentz forces detuning has been carried out first since the operating mode is pulsed. Finite Element Method (FEM) models have been developped in Cast3m, aiming to reduce frequency shift by optimization of stiffening rings. Thanks to the platform developed at IPN Orsay, the 3D modeling for mechanical calculations are performed on the set which includes coupler and high mode ports and helium vessel. The final design of 704 MHz β 0.65 niobium cavities with optimized wall's thickness according to mechanical constraints imposed by SPL specifications are presented in this paper.

INTRODUCTION

Based on SPL superconducting linac design parameters, the electromagnetic design is optimized first with Superfish [1]. Then 3D modeling with Microwave Studio has been performed in order to optimize coupler port position. The maximum peak surface electric field is 50 MV/m , the maximum peak magnetic field is 100 mT. Other essential parameters are given in table 1.

The principal challenge is the high accelerating gradient for middle β. As the frequency shift due to Lorentz forces increases with square of the accelerating gradient, for E_{acc} = 19 MV/m, and Q_{ext}≈10^6, the frequency shift must be kept less than bandwidth δf:

$$\delta f = f_0(\frac{1}{Q_0} + \frac{1}{Q_{ext}}) \quad (1)$$

As $Q_0 \gg Q_{ext}$, $\delta f = f_0 \frac{1}{Q_{ext}}$ the frequency shift should not exceed 704 Hz. In other term, the Lorentz detuning coefficient $K = \Delta f/(E_{acc})^2$ should be smaller than 1.9.

Table 1: Some SPL superconducting linac design parameters

Parameter	Values
Frequency	704.4 MHz
$\beta = v/c$	0.65
R/Q	290 Ω
Q_0	$> 10^{10}$
Accelerating gradient	19 MV/m

LORENTZ FORCES DETUNING AND CAVITY STIFFENING

First, FEM modeling of the cavity shape is performed in Cast3m, [2]. Then, the electromagnetic fields on the cavity's wall, simulated with Superfish, have been interpolated on Cast3m modeling. Figure 1 shows the vector representation of radiation pressure on the cavity wall.

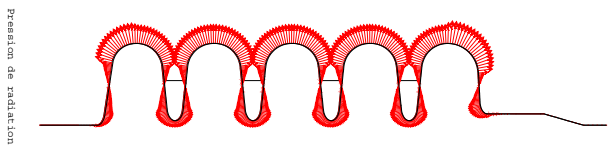


Figure 1: Radiation pressure on β0.65 cavity.

The resulting cavity shape change under radiation pressure while cavity is totally fixed is computed. Finally the frequency shift Δf_0 is computed thanks to a specially developed module according to Slater's formula:

$$\frac{\Delta f_0}{f_0} = -\frac{1}{4W} \iiint_{\Delta V} (\mu_0 H^2 - \epsilon_0 E^2) dV \quad (2)$$

where: W is the total electromagnetic energy stored in the resonator, E and H are the electromagnetic surface fields and ΔV the cavity volume variation due to deformation, f_0 is the fundamental mode of the unperturbed cavity.

A very high numerical precision is required at this step because the cavity deformation (Δl = 0.2 μm) is very small compared to the cavity scale (1 m).

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HIGHER ORDER MODE PROPERTIES OF SUPERCONDUCTING TWO-SPOKE CAVITIES

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Abstract

Multi-Spoke cavities lack the cylindrical symmetry that many other cavity types have, which leads to a more complex Higher Order Mode (HOM) spectrum. In addition, spoke cavities offer a large velocity acceptance and can be used over a wide velocity range, which means we must perform a detailed analysis of the particle velocity dependence for each mode's R/Q. We present here a study of the HOM properties of two-spoke cavities designed for high-velocity applications. Frequencies, R/Q and field profiles of HOMs have been calculated and are reported.

INTRODUCTION

Superconducting, TEM-class two-spoke cavities, for 352 MHz and 325 MHz, are being considered for high-velocity applications. The diameter of spoke-loaded cavities is on the order of λ/2, which implies lower operating frequencies for a given size and therefore a larger velocity acceptance. Another of the advantages over conventional elliptical TM-class cavities includes increased longitudinal acceptance, lower surface resistance and thus lower heat load allowing for the possibility of 4 K operation [1]. The description and optimization procedure of the 352 MHz cavity has been previously reported [2]; table 1 presents the main characteristic properties of the 325 MHz two-spoke cavities [3].

Table 1: RF parameters for 325 MHz 2-spoke cavity

Parameter	$\beta_0 = 0.82$	$\beta_0 = 1$	Units
Frequency fundamental mode	325	325	MHz
R/Q	543	621	Ω
Geometrical factor	167	188	Ω
E_p / E_{acc}	2.49	2.27	
B_p / E_{acc}	5.4	5.32	mT/(MV/m)
B_p / E_p	2.17	2.34	mT/(MV/m)

At E_{acc} = 1 MV/m and reference length = $\beta_0\lambda$

Even for velocity-of-light cavities the fundamental accelerating frequency mode in two-spoke cavities is the lowest order mode. Excitation of higher-order modes (HOMs) by a high-current beam can lead to subsequent beam instabilities and should therefore be damped by appropriate HOM couplers. In this paper, we report a detailed study of longitudinal and transverse HOMs. A CST Microwave Studio picture of the 325 MHz, $\beta_0 = 0.82$ cavity is shown in figure 1.

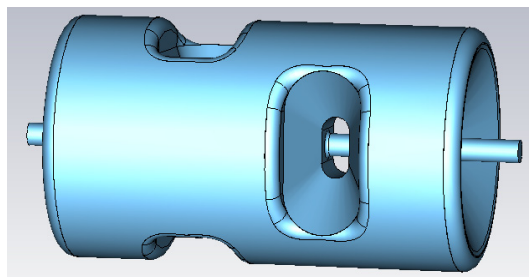


Figure 1: CST Microwave Studio picture of the 325 MHz, $\beta_0 = 0.82$ two-spoke cavity.

HOM PROPERTIES

The mode types can be classified as accelerating, deflecting, or TE-type (meaning a strong H_z field component along the beam axis and negligible transverse electric field). If we define the longitudinal direction (that which the beam propagates in) as *z*, then one of the spokes is oriented parallel to the x-axis, while the other is oriented parallel to the y-axis. Deflection occurs in both the *x* and *y* directions because the fields throughout the cavity are not strictly in either the x- or y-directions but rather contain components in both (see figure 2). This requires us to calculate separate, direction-specific [R/Q] for each deflecting mode.

The longitudinal [R/Q], which applies to accelerating modes where the electric field is along the beam axis, is given by:

$$\left[\frac{R}{Q}\right] = \left.\frac{\left|\int_{-\infty}^{\infty} \vec{E}_z(z,r=0)e^{i\left(\frac{\omega z}{\beta c}+\varphi\right)}\right|^2}{\omega U}\right|_{\max\varphi} \quad (1)$$

where ω is the angular frequency of the mode, βc is the particle velocity, and *U* is the stored energy in the cavity. On the other hand, for deflecting modes, where we have deflection with E_x and H_y in addition to E_y and H_x for the same mode, the transverse $[R/Q]_T$ is calculated by direct integration as,

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LOW TEMPERATURE TEST OF A LOW-BETA ELLIPTICAL CAVITY FOR PEFP LINAC EXTENSION*

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Abstract

For the future extension of the PEFP (Proton Engineering Frontier Project) proton linac, a study on the SRF technology has been performed including a prototype cavity development to confirm the design of the cavity and fabrication procedures and to check the RF and mechanical properties of a low-beta elliptical cavity. The geometrical beta and resonant frequency of operating mode are 0.42 and 700 MHz, respectively. The cavity is a five-cell structure stiffened by double-ring structure to increase mechanical stability. For the vertical test of the cavity, RF system based on PLL (phase locked loop) has been prepared. If there is no magnetic shielding and operating temperature is 4.2 K, the required RF power to generate the design accelerating field of 8 MV/m is estimated to be about 320 W at critical coupling. In case single RF amplifier cannot deliver sufficient RF power, a coaxial type two-way RF combiner is under consideration. The details of the cavity test setup and results will be presented in this paper.

PEFP LINAC EXTENSION PLAN

The proton linac for PEFP is a 100-MeV machine. To extend the output beam energy up to 1 GeV, SRF technology is under consideration. The overall parameters of the PEFP SRF linac are like followings.

- Input proton energy: 100 MeV
- Output proton energy: 1000 MeV
- Peak beam current: 20 mA
- Beam duty factor: 5 %
- Beam power: 1 MW
- Frequency: 700 MHz
- RF source: 150 kW IOT
- Cavity structure: Elliptical cavity
- Number of cavity group: 2
- Beam focusing: SC solenoid

Preliminary study on the beam dynamics shows that two cavity groups (β_g = 0.50 and β_g = 0.74) can provide the required beam energy. The cavity geometrical beta is defined by the cell length of $\beta_g \lambda/2$, where λ is the RF free space wavelength. The operating frequency is determined to be 700 MHz because the operating frequency of the RFQ and DTL is 350 MHz. Beam focusing will be provided by superconducting solenoid magnets installed between every two cavities, which means single cryomodule will host 4 cavities and 2 solenoid magnets.

Figure 1 shows the cavity geometry of two groups. Number of cells per cavity is 6 for both groups. The RF power requirement for each cavity is shown in Fig. 2. An inductive output tube (IOT) is chosen for the RF source due to its low operating voltage and economic reasons. The output RF power of single IOT is limited to about 150 kW, therefore, two IOTs per cavity are going to be used if the required RF power per cavity is more than 150 kW. No cavity requires more than 300 kW.

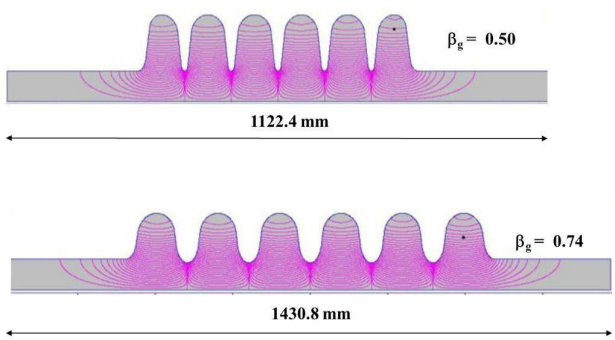


Figure 1: Cavity geometry for PEFP SRF linac.

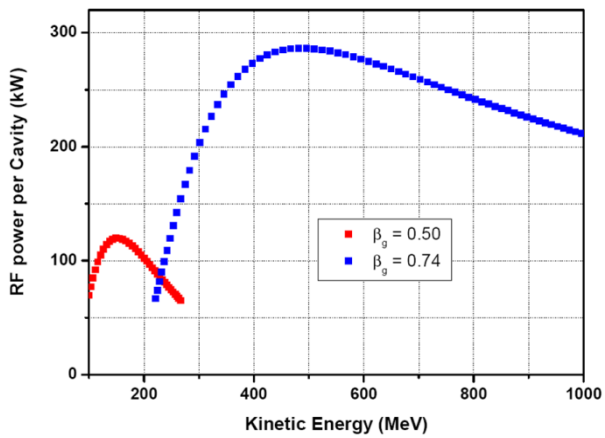


Figure 2: RF power requirement for each cavity.

PROTOTYPE CAVITY

To gain an experience and check the design concept, we developed the prototype cavity which has following design parameters [1].

- Frequency: 700 MHz
- Operating mode: TM010 PI mode
- Cavity shape: Elliptical
- Geometrical beta: 0.42
- Number of cells: 5
- Accelerating gradient: 8 MV/m @2.0K
- Epeak/Eacc: 3.71
- Bpeak/Eacc: 7.47 mT/(MV/m)

*Work supported by MEST of the Korean Government.
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DESIGN OF SINGLE SPOKE RESONATORS FOR PROJECT X*

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Abstract

Project X is based on a 3 GeV CW superconducting linac and is currently in the R&D phase awaiting CD-0 approval. The current proposal for the low-energy section of the Project X H- linac includes three types of super-conducting single spoke resonators (SSR0, SSR1 and SSR2) operating at 325 MHz and accelerating the beam from 2.5 MeV to 180 MeV. Single spoke cavities are being favored for the linac in virtue of their higher r/Q values compared to standard Half Wave Resonators (HWR). At the moment, the use of HWR is still considered an option for the SSR0 section. Quarter Wave Resonators were not considered for such a high frequency. The β values for SSR0 and SSR1 are 0.115 and 0.215 respectively. For the SSR2 section an iterative RF optimization has been performed recently to take into consideration several changes in the lattice and characteristics of the linac such as the introduction of a low-β (0.6-0.9) section operating at 650 MHz replacing the Triple Spoke Resonator section. The study shows that the geometrical β of SSR2 should be changed from 0.414 to 0.480. Among other benefits, this new beta value allows to use a smaller number of cavities.

In this paper we present the decisions and analyses that lead to the final RF/Mechanical design of SSR0 which is currently finalized and awaiting approval for fabrication. Electro-magnetic and mechanical finite element analyses were performed with the purpose of optimizing the electro-magnetic design, minimizing frequency shifts due to helium bath pressure fluctuations and providing a pressure rating for the resonators that allow their use in the cryomodules.

SSR1 prototypes were originally developed for the HINS R&D linac [1] and were successfully tested as bare resonators in the FNAL Vertical Test Stand and in the test cryostat at the FNAL Superconducting Cavity Test Facility [2, 3] after the installation of the helium vessel and two tuners. With Project X being a CW machine, (HINS was a pulsed machine) a redesign of the helium vessel of SSR1 resonators was necessary to address frequency stability issues due to helium pressure fluctuations.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [4]. It enables a world-leading program in neutrino physics, and a broad suite of rare decay experiments. The facility is based on a 3 GeV, 1 mA, CW superconducting linac (see Figure 1). After the linac, about 5-9% of the H- beam is accelerated in an SRF pulsed linac to the Recycler/Main Injector. The main portion of the H- beam from the 3 GeV linac is directed to three different experiments.

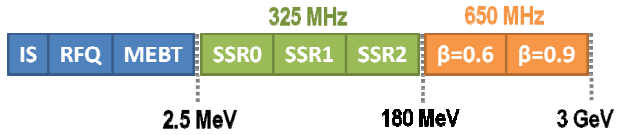


Figure 1: The Project X CW linac.

The beam originates from a DC H- source. The beam is then bunched and accelerated by a CW normal-conducting RFQ to 2.5 MeV and the bunches are formatted by a chopper following a pre-programmed timeline. From 2.5 MeV to 3 GeV the H- bunches are accelerated by a CW super-conductive linac. The CW linac consists of a low-energy 325 MHz SCRF section (2.5 - 180 MeV) containing three different types of single-spoke resonators (SSR0, SSR1, SSR2) and two types of 650 MHz elliptical cavities (180 MeV - 3 GeV). The feature of the linac is small beam loading, and thus narrow cavity bandwidth. In Table 1 it is shown for each section the number of cavities, the maximal H- energy gain for zero synchronous phase, and the bandwidth of the matched cavity.

Table 1: Cavities for the Project X linac. Two options are shown for the SSR2 section, the decision between the two designs has not been made yet.

	SSR0	SSR1	SSR2 A	SSR2 B
β optimal	0.115	0.215	0.414	0.480
CMs x Cavities	2 x 9	2 x 10	4 x 10	4 x 8
Design Eacc [MV/m]	9	11	10	10
Max surf Field [mT]	61	64	56	59
Q_0	> 6.5E6	> 6.5E6	> 6.5E6	> 6.5E6
Bpeak/Eacc [mT/MV/m]	6.83	5.81	5.64	5.9
Epeak/Eacc	5.66	3.84	3.78	3.5
Leff (2*βλ/2) [mm]	106	198	382	443
G [Ω]	51	84	109	119
R/Q_0 [Ω]	109.2	242	247	304
TOT FE length [m]	59/54.3	59/54.3	59	54.3

Since the bandwidth of the matched SSR cavities is only 20-40 Hz, microphonics are an issue. In order to mitigate microphonics, several means are typically used. First of all one can over-couple the cavity in order to

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HIGH-FREQUENCY AND MECHANICAL BASIC ANALYSIS OF CONICAL HALF-WAVE RESONATOR*

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Abstract

A cylindrical Half-Wave length Resonator is a proved superconducting structure in the low energy part of accelerators. Accelerating efficiency in such resonator is limited by the peak RF magnetic field on the inner cavity surface. An enlargement of the dome cavity volume containing RF magnetic field reduces the cavity peak surface magnetic field. Additionally, this results in the power dissipation reduction. The paper reports results of cavity shape optimization and structural analyses of conical Half-Wave Resonators for β=v/c=0.11 and two resonance frequencies 325 MHz and 162.5 MHz.

INTRODUCTION

The main purpose of this work is to investigate the possibility using of Half-Wave Resonator (HWR) for β=0.11 that provides substantially lower the peak magnetic field by the same accelerating rate. Additionally, an alternative to the standard beam port deformations option for the cavity frequency adjustment should be developed.

Several resonator design parameters based upon the requirements of the Project X low-β part of accelerator at Fermi National Laboratory have been chosen.

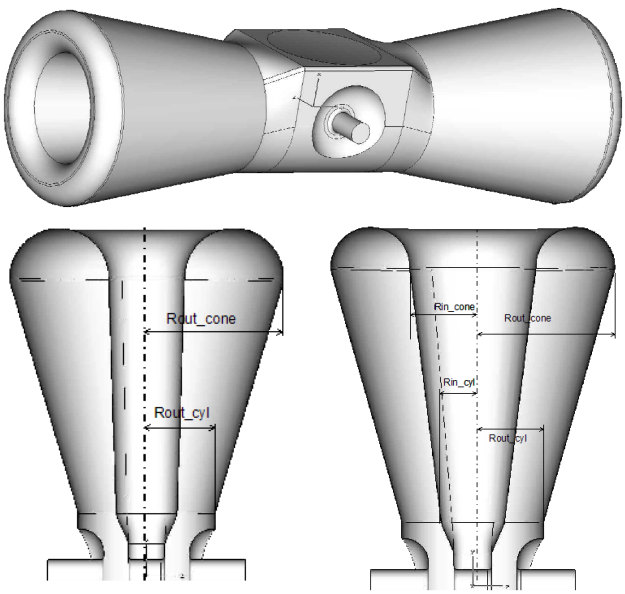


Figure 1: HWR with enlarged outer conductor dome diameter.

To reduce substantially B_{pk}/E_{acc} the conical Half-Wave Resonator (cHWR) [1] can be used.

*Work supported by the DOE SBIR Program, contract # DE-SC0006302.

CAVITY RF DESIGN

162.5 MHz, β=0.11 cHWR

A straight circular IFMIF 175 MHz, β=0.094 half-wave resonator ([2]) has been used as a basis for a 162.5 MHz, β=0.11 HWR developments. The cavity geometry has been modified to get the design frequency 162.5 MHz and β=0.11 and to minimize values of peak electrical and magnetic fields on the cavity surface relative to the accelerating electrical field on the cavity axes (B_{pk}/E_{acc} and E_{pk}/E_{acc}).

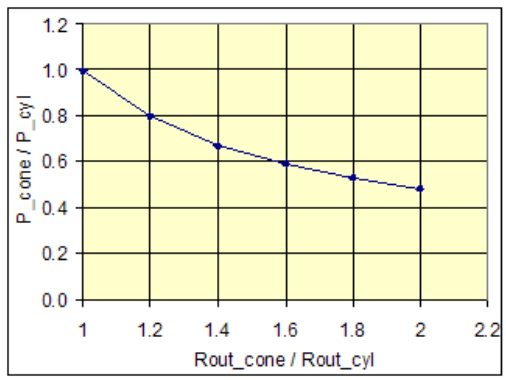


Figure 2: Power dissipation in conical HWR relative to cylindrical shape.

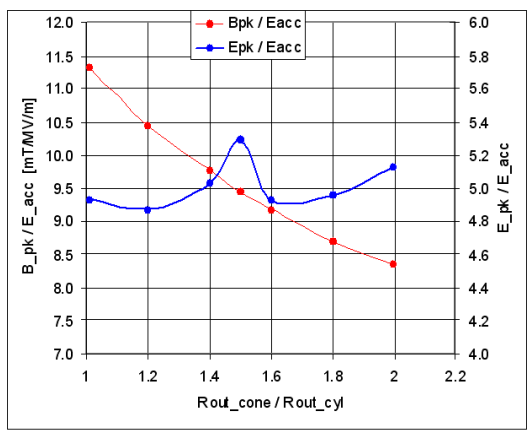


Figure 3: Peak magnetic and electrical fields in conical cavity.

At the cavity dome region there is a space for the peripherical cavity volume enlargement containing RF magnetic field to get the conical cavity shape (Fig. 1). This results in decreasing the cavity peak surface magnetic field B_{pk}/E_{acc}. For the cHWR geometry optimisation we used the same procedure discussed elsewhere [3].

β=0.285 HALF-WAVE RESONATOR FOR FRIB*

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Abstract

We have developed an optimized electromagnetic and mechanical design of a 322 MHz half-wave resonator (HWR) suitable for acceleration of ions in the post-stripper section of the Facility for Rare Isotope Beams (FRIB). The cavity design is based on recent advances in SRF technology for TEM-class structures being developed at ANL. Highly optimized EM parameters were achieved using an "hourglass" cavity shape for the HWR. This new design will be processed with a new HWR horizontal electropolishing system after all mechanical work on the cavity including the welding of the helium jacket is complete. Recently, this procedure was successfully tested on a quarter wave resonator developed for the ATLAS upgrade which achieved peak surface fields of 70 MV/m and 105 mT. Following these results we propose to operate the HWR with a 2.5 MV accelerating voltage per cavity at the optimal ion velocity of β_{OPT} = 0.285. Fabrication of the cavity can be started immediately as soon as funding is available.

INTRODUCTION

In the early stages of the FRIB driver linac design it was decided to use HWRs in the post-stripper section for the energy range from 16 to 55 MeV/u. The original design uses 72 HWRs with β_{OPT} = 0.285 [1]. This paper reports on an advanced HWR design developed for this energy range. To improve accelerator performance and decrease cost, the following main design goals were pursued in the cavity development [2]:

- 40-mm aperture diameter to avoid beam losses and facilitate beam centroid tuning;
- Higher accelerating gradients (voltages per cavity) to reduce the cavity count and, consequently, the cost;
- Reduced cryogenic load by applying advanced RF design and surface processing techniques.

OPTIMIZED EM DESIGN

The electromagnetic (EM) design of the cavity was performed using MWS software and detailed results are reported elsewhere [3]. The EM design of the HWR is primarily based on a successful 72.75 MHz β_{OPT} = 0.077 quarter-wave resonator (QWR) recently tested to 4.4 MV of accelerating voltage [4,5]. To increase the available accelerating voltage, the cavity shape is highly optimized reducing both B_{PEAK}/E_{ACC} and E_{PEAK}/E_{ACC} [3]. The final cavity shape looks like an hourglass as shown in Fig. 1. A cavity shape with tapered central and outer conductors was proposed and studied in earlier publications [6,7]. Only recently, the fabrication technology became available to build such cavities [8,9]. The confidence in the proposed HWR design and predicted performance is based on the very successful design, construction and testing of a conical QWR for the ATLAS upgrade [4,8]. Optimization of the cavity shape was performed taking into account die-forming fabrication technology available from industry. For example, the same toroid die as for 72 MHz QWRs [8] will be used. This allows us to reuse the fixturing hardware developed earlier. The results of the EM optimization are summarized in Table 1. We have noticed an appreciable effect of the coupling ports (pos. 2 in Fig. 1) on the peak magnetic field as is shown in Table

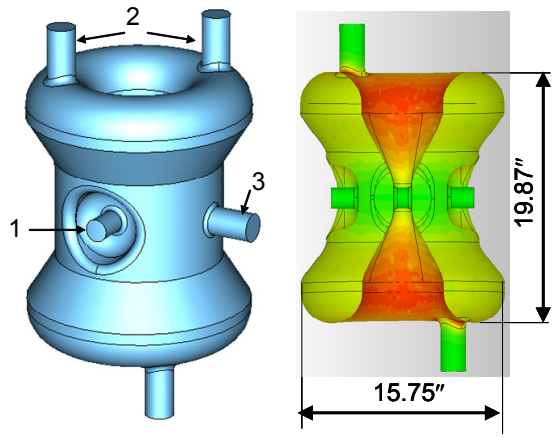


Figure 1: 3D view (on the left) and cross-section (on the right) of the cavity. 1-beam port, 2- coupling ports, 3- RF coupler port.

Table 1: Cavity RF parameters

Port's blending radius	No ports	0.25″	0.5″
Frequency, MHz		322	
Optimal beta, β_{opt}		0.285	
$L_{EEF}= \beta_{opt}\lambda$, cm		26.6	
$G = Q_0R_s$, Ω	97	97	97
R/Q_0, Ω	194	194	194
E_{pk}/E_{acc}	4.38	4.49	4.49
B_{pk}/E_{acc}, G/(MV/m)	71.2	104	79.5
U_0/E_{acc}^2, J/(MV/m)^2	0.175	0.175	0.175

*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and WFO 85Y64 Supported by Michigan State University
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ANALYSIS OF HOM PROPERTIES OF SUPERCONDUCTING PARALLEL-BAR DEFLECTING/CRABBING CAVITIES*

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Abstract

The superconducting parallel-bar cavity is currently being considered for a number of deflecting and crabbing applications due to improved properties and compact design geometries. The 499 MHz deflecting cavity proposed for the Jefferson Lab 12 GeV upgrade and the 400 MHz crab cavity for the proposed LHC luminosity upgrade are two of the major applications. For high current applications the higher order modes must be damped to acceptable levels to eliminate any beam instabilities. The frequencies and R/Q of the HOMs and mode separation are evaluated and compared for different parallel-bar cavity designs.

INTRODUCTION

In the proposed LHC luminosity upgrade the crab cavities will be used at two interaction points (IPs) in the LHC collider ring operating in a local crabbing scheme. At one of the interaction points the beam will be crabbed horizontally and in the other in vertical direction. One of the requirements in the cavity design is the dimensional constraint of 194 mm separation of the two parallel beam lines of 84 mm beam aperture diameter. This restricts the cavity diameter to be 300 mm or less. The crabbing system is required to deliver a peak transverse kick of 10 MV per beam at each side of the IP.

The 400 MHz superconducting parallel-bar cavity [1] proposed for LHC luminosity upgrade has been modified from the initial rectangular shaped geometry in to the cylindrical geometry as shown in Fig. 1, with improved electromagnetic and mechanical properties; to meet the design requirements.

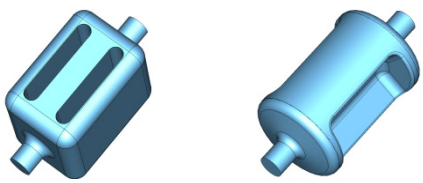


Figure 1: Rectangular shaped (left) and cylindrical shaped (right) parallel bar cavities.

The higher order modes (HOMs) in any cavity geometry may get activated when the harmonics of the beam current coincide with HOM frequencies of the cavity. The wake fields generated with the activation of HOMs may act upon single or multiple bunches depending on the decay time of the HOMs. These effects may lead to beam instabilities and further into beam losses and can be minimized to an acceptable level by damping using couplers and filters.

The study HOM properties are equally important as the cavity properties in applications like LHC with higher average beam current (~500 mA). In this paper different geometries of the 400 MHz parallel-bar cavities are analyzed to determine the evaluation of modes, mode separation and corresponding R/Q values for the modes.

PARALLEL-BAR DESIGN GEOMETRY

Parallel-bar geometries with a cylindrical outer wall are analyzed for different orientations of bar shapes as shown in Fig. 2.

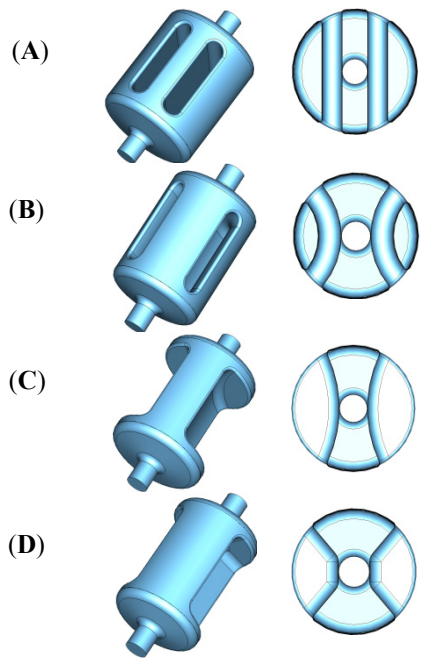


Figure 2: Cylindrical shaped parallel-bar geometries (left) with (A) straight bars (B) curved bars (C) bars merged to the side walls and (D) trapezoidal bars with the corresponding vertical cross sections (right).

The designs are compared to determine a compact design with improved properties such as lower and balanced peak surface fields, higher shunt impedance, and mechanical stability. The properties of each design are listed in Table 1.

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
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DESIGN OF CW SUPERCONDUCTING BUNCHER FOR RIKEN RI-BEAM FACTORY *

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Abstract

Design of rebuncher cavity for uranium beams withβ = 0.303 has been studied. The estimated peak voltage is rather high as 3 mega-voltages (MV). Superconducting radio frequency (SRF) technology is necessary for the effective operation of a rebuncher resonator. Therefore, we studied the design of an SRF resonator that would operate at a velocity of β = 0.3027. Several structures were simulated and discussed using the Microwave Studio code (MWS) in this initial design study, and the performances and field patterns of these structures were compared.

INTRODUCTION

At the RIKEN RI-beam factory (RIBF) [1], very heavy ions such as uranium can be accelerated up to very high energy. There are two charge-stripping sections in this accelerator chain which consists of a new linac named RILAC2 and four booster cyclotrons (RRC: K = 540 MeV, fRC: K = 570 MeV, IRC: K = 980 MeV, and SRC: K = 2600 MeV), as shown in Fig. 1 [2, 3]. This RILAC2 is equipped with a powerful superconducting ECR ion source [4]. As shown in Fig. 1, there are two charge-stripping sections in this acceleration mode. One is located after RRC (β = 0.16), and the other is after fRC (β = 0.3027). Stripping causes an increase in the phase width of the beam in the subsequent cyclotrons, which should be reduced by using a rebuncher with a longitudinal focusing function. Therefore, we studied the design of a new rebuncher to be placed between fRC and IRC.

The rf frequency of the rebuncher was chosen to be 219 MHz, which is the 12th harmonic of the fundamental frequency of 18.25 MHz, as shown in Fig. 1. This frequency gives the cell length of βλ/2 = 207 mm at β = 0.303. Although a higher frequency helps to reduce the cavity length, the beam phase at the rebuncher becomes too large to be well bunched. The total voltage required for the rebuncher is estimated to be 3 MV at this frequency and use of superconducting rf technology is necessary for the effective operation of the rebuncher resonator.

There are few designs and researches for the SRF cavities at this frequency and velocity region. Therefore, we compared several structures by computer simulations to look for the best candidate for the initial research of cavity: the quarter-wavelength resonator (QWR), triple-spoke structure, coupled-TE structure, and ladder structure, as shown below. We paid attention to the value of Ep/Eacc, where Ep and Eacc are the peak of the electric field and the total voltage of the gaps, respectively, in an effort to increase the voltage gain with minimum risk of rf-breakdown. We also considered the possibility of cleaning the cavity after assembly.

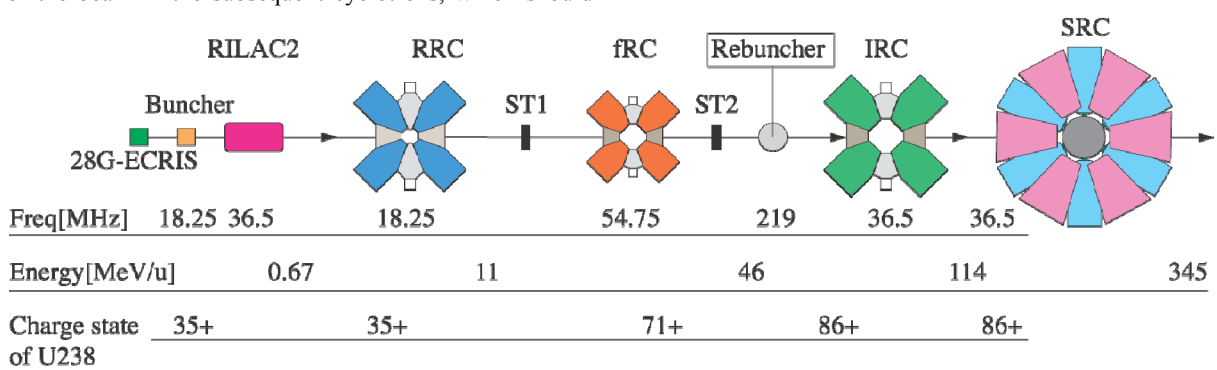


Figure 1: Accelerator chain of RIKEN RIBF for ^{238}U ions.

SIMULATIONS

QWR Structure

The design for a QWR resonator is shown in Fig. 2. The QWR structure is easy to obtain a flat axial E filed distruibution and also is a re-cleanable structure after assembly. In this design, two cavities would be included in a single cryostat in the real rebuncher, bringing the total voltage to 3 MV. The Ep/Eacc value is very high, mainly caused by the field concentration in the bottom region under the drift tube, as shown in Table 1.

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SOME DESIGN ANALYSIS ON THE LOW-BETA MULTI-SPOKE CAVITIES*

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Abstract

The spoke cavities have achieved some promising gradients worldwide, which make them good candidates for accelerating low beta proton and ions. Although, there is still a space to further optimize them, especially for multi-spoke cavities, the design and optimization are re-considered based on the total capital and operational efficiencies over a given beta range. An initial result of the 3D Electromagnetic (EM) design optimization by the CST MWS code for a double-spoke, velocity β ~0.5 cavity is reported. An equivalent circuit for the double-spoke cavity is also developed.

GOAL FOR EM OPTIMIZATION

Accelerating Efficiency of the Low-β Cavities

Currently when a cavity is being designed, people usually focus on the performance at β_0 which refer to the max transient time factor (TTF). When the cavity design is finished, the overall acceleration within a given β range is calculated by integrating the EM field numerically. It will be interesting if we can find some methods to optimize the acceleration efficiency in a given β range into consideration at the EM design phase.

It is well known that, by omitting the β change within a cavity, the TTF can be calculated as [1]:

$$\mathrm{TTF}(\beta)=\frac{\int_{-\infty}^{\infty}E(x)\cos(\omega x/\beta c)dx}{\int_{-\infty}^{\infty}|E(x)|dx} \qquad (1)$$

where cosine is for the even field profile. Then the increment of β for one cavity is found to be:

$$\Delta\beta=\frac{U_0}{m_0c^2}\frac{TTF(\beta)}{\beta\gamma^3} \qquad (2)$$

where $U_0=qV_0\cos\varphi$, $V_0=\int_{-\infty}^{\infty}|E(x)|dx$, and φ is the phase of field when the particle is in the middle of the cavity.

Now assuming one cavity shape is used from β_1 to β_2, if longitudinal stability is not an issue, we can drive all the cavities on crest (i.e. φ=0), then the number of cavities to be used is

$$Nca(\beta_1,\beta_2)=\frac{m_0c^2}{U_0}\int_{\beta_1}^{\beta_2}\frac{\beta\gamma^3}{TTF(\beta)}d\beta \qquad (3)$$

So we can define the accelerating efficiency of this cavity from β_1 to β_2 as:

$$Eff(\beta_1,\beta_2)=\frac{\Delta E_k}{U_0Nca}=\frac{\gamma_2-\gamma_1}{\int_{\beta_1}^{\beta_2}\frac{\beta\gamma^3}{TTF(\beta)}d\beta} \qquad (4)$$

The efficiency can be seen as an averaged TTF in the β range. The result of Eq.4 typically has a less than 1% error comparing with particle tracking results.

Project Specified Goals

General challenges and considerations to low and medium β cavity design have been well described [2]: Ep, Bp, G*R/Q and HOM are usually most concerned for EM design. Here we restrict ourselves to fundamental mode and discuss the goals for more specified cases.

- Pulsed machine:

For pulsed machines, dynamic heat loading may not be important, so gradient and peak surface field that will affect the capital cost, will be set as the design goal. The published test results at 2K of overall 13 spoke cavities show that [[3]-[4]]: Bp achieved 80-130 mT, and Ep achieved 30-80 MV/m, while 5 of them had field emission around Ep=30MV/m and all were processed away expect for one that had a large surface defect. These typical levels of surface field and FE have also been reported for QWR [4].

So, if an accelerator is proposed within the state of art, then a goal of Ep<30MV/m and Bp<80 mT is reasonable; if for some reason, an accelerator is proposed to push the limit of low-beta cavities, then a goal of Ep<60-80MV/m and Bp<120mT could be considered, in other words, lower Bp/Ep ratio is preferred.

Since the number of cavities and their total length are:

$$\begin{cases} Nca(\beta_1,\beta_2)=\dfrac{\Delta E_k}{q\cos\varphi}\dfrac{Ep/\overline{Va}}{Ep} \\ Ltotal(\beta_1,\beta_2)=\dfrac{\Delta E_k}{q\cos\varphi}\dfrac{Ep/\overline{Ea}}{Ep} \end{cases} \qquad (5)$$

where $\overline{Va}=V_0Eff(\beta_1,\beta_2)$, $\overline{Ea}=\overline{Va}/Lend$, and Lend is the length of the cavity from one end to the other end. So, the optimization goal should be: $Ep/\overline{Va}$ or $Ep/\overline{Ea}$ as low as possible, while keeping Bp/Ep ratio less than a chosen value.

- CW machine:

For CW machine cryogenic loss is worth taken into consideration. The number of cavities is possibly determined by the trade-off of between capital and

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THE SC CW-LINAC DEMONSTRATOR – FIRST SECTION OF A SC CW-LINAC

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Abstract

The realisation of the first section of a new superconducting (sc) continuous wave (cw) LINAC is planned in 2013. The project is called "cw LINAC Demonstrator" and is financed by the Helmholtz Institute Mainz (HIM). The aim is a "full performance test" at GSI-HLI of a new 217 MHz sc CH-Cavity which is designed by the Institute of Applied Physics (IAP) of the University Frankfurt [1, 2].

According to an engineering study for the cryostat, a frame has been designed to support the cavity embedded by two sc solenoids. A nuclotron -suspension analog to the SIS-100 Magnets for FAIR is used, which nearly prevents the displacement of the components on the frame while cooling down. Another challenge is to reduce the magnetic field of the solenoid from 9.3 T to 50 mT at the cavity within some centimeters by moveable compensation -coils.

This and other technical solutions in the cryogenic environment of the Demonstrator are presented.

INTRODUCTION

Since 1990 the High Charge Injector (HLI) is in service to provide Super- Heavy- Element (SHE) experiments (SHIP and TASCA) with beam at GSI. It comprises a 14 GHz ECR, an RFQ, and an IH anti-parallel to the UNILAC. In 2005 an upgrade program for the HLI was defined to make the HLI cw-capable [3, 4]. Straight forward to this injection line the Demonstrator should be assembled for a "full performance test" with beam.

In order to use these favourable conditions it is planned to adjust the test environment, with the cryostat, a 3000ltr. Helium reservoir, a radiation protective shield, the beam diagnostics and other supply units in this area (Fig.1). In order to solve the physical, technical, and assembling requirements some solutions are presented to accomplish the components (solenoids, cavity, supporting frame) and keep the needed tolerances. Another challenge is the detection of the displacements of the components while cooling down.

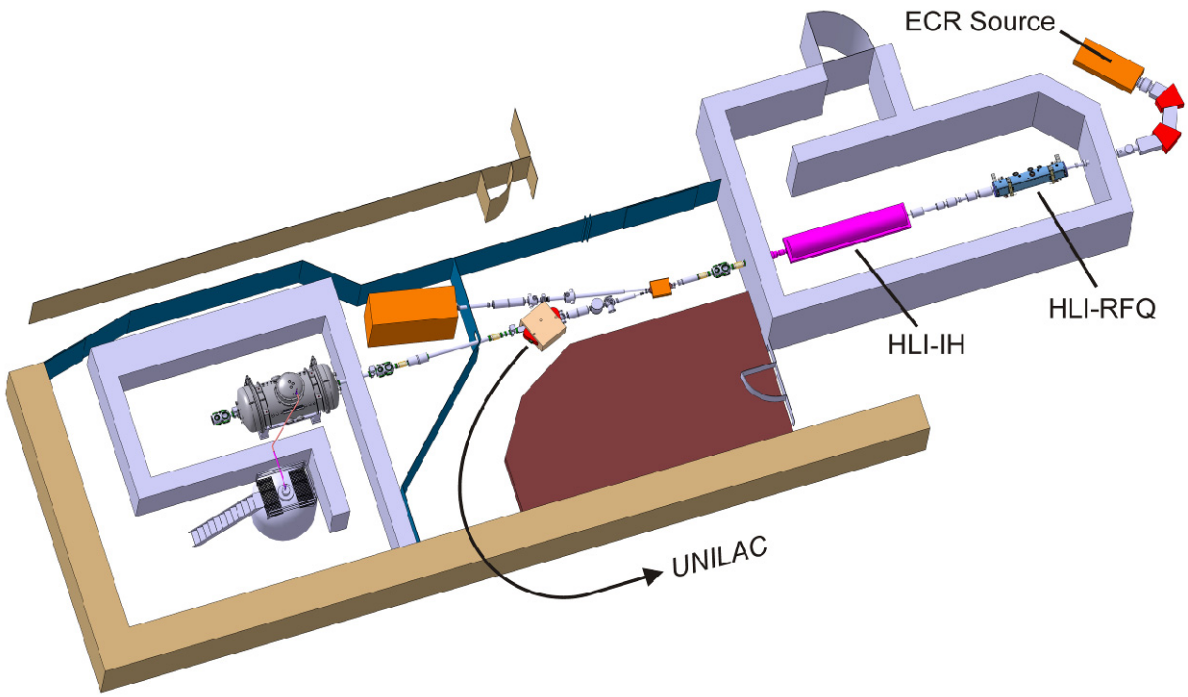


Figure 1: The future layout of the GSI accelerator facility with the cw-LINAC Demonstrator integrated in the existing High Charge Injector (HLI).

ELECTRO-MAGNETIC OPTIMIZATION AND ANALYSES OF ETCHING FOR HIRFL QUARTER-WAVE RESONATOR

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Abstract

A superconducting accelerating section for SSC-linac system (injector into separated sector cyclotron) is under development at the HIRFL (heavy ion research facility of Lanzhou). Two types of superconducting quarter-wave resonators (81.25 MHz, optimum beta = 0.041 and 0.085) will be used for acceleration to energies of up to 10 MeV per nucleon. The beta=0.041 QWR works at the accelerating voltage of 1 MV and beta=0.085 QWR works at 2 MV, in order to reach a record high performance, the EM design was carefully optimized for both cavities. A selected number of cavity geometry parameters were analyzed to see how they affect the electro-magnetic parameters of the cavity, and different influence levels of these geometry parameters are ranked. In this paper, we will also present how the etching thickness changes the frequency during the buffered chemical polishing processing, and the difference of the change for the two type cavities has been compared.

INTRODUCTION

The main objective of high energy accelerators is to impart a large amount of energy to the beam without a substantial loss. Reduction of the losses is directly to the reduction of the surface resistance in the cavity walls, therefore radio frequency (RF) superconductivity has become an important technology for particle accelerator. Superconducting cavities currently used for acceleration of ions with low velocity are based frequently on quarter wave resonators (QWR) due to their simplicity, accessibility and low fabrication cost [1,2]. The Institute of Modern Physics (IMP) has been doing the research of superconducting QWR cavity since 2007.

A SSC-Linac system (injector into separated sector cyclotron) is being designed in the HIRFL (heavy ion research facility of Lanzhou) of IMP. As part of the SSC-Linac, the superconducting segment will use QWR cavities of f=81.25 MHz, βopt=0.041， 0.085 to accelerate beams from β~0.02 to β~0.16.The EM design and optimization of the cavities have been done and the mechanical analysis is being performed. The optimization of the cavity geometric shape and its influence on RF behavior will be presented and discussed.

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ELECTRO-MAGNETIC CAVITY OPTIMIZATION

CST was used for EM simulation of the QWR cavities, in order to reach a high accelerating voltage per cavity, the shape design was carefully optimized. We mostly care about four EM parameters, they are the peak surface electric field--E_{peak}, the peak surface magnetic field--B_{peak}, the geometric shunt impedance--R_a/Q_0 and the geometric factor--G. During the optimization, we will pay attention to all the relevant geometry parameters' influence on the EM behaviors. In Figure 1, we present the most important 6 geometry parameters, they are explained below [3,4]:

1) The cavity top radius (TopR)
2) The cavity radius (CavR)
3) The stem top radius (STTR)
4) The stem bottom radius (STBR)
5) The drift tube gap width (DTGW)
6) The beam tube radius (BTR)

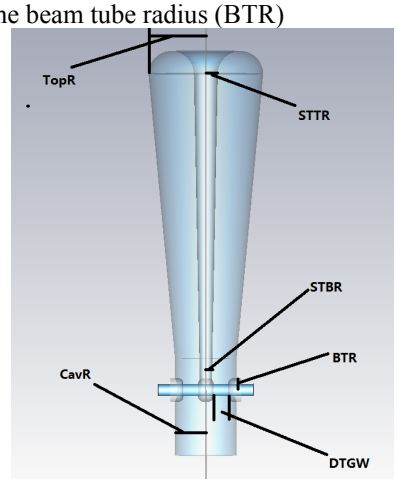


Figure 1: Parameters of the cavity geometry used in the EM optimization.

DEVELOPMENT OF A FREQUENCY MAP FOR THE WIFEL SRF GUN*

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Abstract

SRF cavity design requires the integration of several different software and analytic tools to produce a cavity which, after production and cool down to liquid helium temperatures, has the correct resonant frequency. We describe a 'map' which starts with a cold cavity at the correct frequency and moves back through the series of production steps producing an expected resonant frequency at each step. For example, contributions to cavity deformation from vacuum and tuner loading are modeled in ANSYS and a piecewise linear fit is produced which is re-inserted into the SUPERFISH[1] model to determine the new resonance point. We describe the steps and calculations used to develop the frequency map for the Wisconsin SRF electron gun and the specific initial cavity geometry.

INTRODUCTION

In order to use a superconducting rf cavity in a particle acceleration system, it is necessary to synchronize its resonant frequency to other accelerator systems; e.g. the photocathode drive laser. To do that the cavity itself must have its mechanical dimensions adjusted such that its resonance is an integer harmonic of all other accelerator systems. It must resonate at that exact frequency in order to accelerate particles correctly. Fortunately, modern electromagnetic design codes allow the resonant frequencies of cavities to be calculated very accurately. For superconducting cavities there are additional complications due to the mechanical deformations which occur due to evacuation and cool down to cryogenic operating temperatures. This problem is mitigated somewhat by the inclusion of an active tuner on the cavity with several bandwidths of range, but calculations of the effects on the mechanical dimensions as the cavity is taken through production and processing must be done in order to ensure the cavity has the correct frequency when completed. In addition, multiple resonance and dimensional measurements are made throughout the production process to verify the calculations, particularly on a first article.

The SRF electron gun being produced by the University of Wisconsin (UW) is a single cavity device with a unique geometry and frequency. As such, it is subject to all of the limitations stated above. It does enjoy the benefit of being a single cell, quarter wave resonator, design. This simplifies the problem since only the mechanical dimensions of a single cell need to be considered; the effect of shrinkage or stresses on adjacent cells can be ignored, and its frequency can be adjusted prior to the final cavity weld by trimming its length. However, only a single article will be produced and so the analysis to determine that length and frequency is very important. To better understand how each fabrication step effects the frequency of the cavity and to allow correction in subsequent cavities fabricated, each event in the cavity fabrication process is analyzed separately for dimensional and frequency effects. By starting with the dimensions of the final, finished cavity and applying these corrections a frequency map[2] leading from the desired finished state to the initial, prior to final weld, state can be produced. As the cavity is manufactured, actual measurement data is recorded and can be used to improve the corrections at each step, leading to a cavity with a frequency very close to the design goal.

ELECTROMAGNETIC SOLUTION AND CONVERSION TO MECHANICAL DESIGN

The initial electromagnetic solution for the UW gun was generated using Superfish[1].

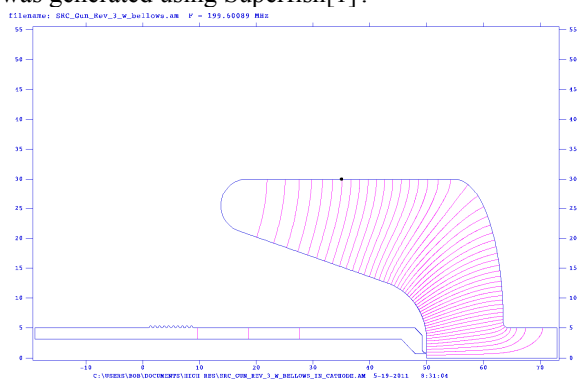


Figure 1: Electromagnetic design showing resonant frequency and final cavity dimensions.

Figure 1 shows the electric field pattern and resonant frequency of the cavity. The cavity shape was optimized to minimize the ratio of Epk / Eacc and the maximum magnetic field[3]. The mesh used was constrained to 50 microns in the cathode region to minimize errors due to the small structures and radii.

To convert the internal dimensions of an idealized cavity into a realistic mechanical structure one has to assume a particular fabrication process. Except for the cathode nose cone region that will be machined from a niobium ingot, most of the cavity will be fabricated from niobium sheet that has been rolled or deep drawn into various shapes that eventually are e-beam welded together. 4 mm thick niobium sheet is generally regarded

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DESIGN OF SUPERCONDUCTING SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS

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Abstract

Superconducting spoke cavities have been designed and tested for particle velocities up to $\beta_0 \sim 0.6$ and are currently being designed for velocities up to $\beta_0 = 1$. We present the electromagnetic design for two-spoke cavities operating at 325 MHz for $\beta_0 = 0.82$ and $\beta_0 = 1$.

INTRODUCTION

Accelerating charged particles from $\beta_0 = 0.6$ to $\beta_0 = 0.8$ has typically been accomplished using elliptical cavities. Single and multiple-gap spoke cavities offer several advantages over their elliptical counterparts. The diameter of a spoke cavity is on the order of the half the rf wavelength, whereas the diameter of an elliptical cavity is twice that. This allows for either smaller physical dimensions at the same operating frequency or close to half the operating frequency for the same physical diameter. Since the BCS surface resistance is proportional to the square of the rf frequency, spoke cavities could allow for 4 K operation as well as a higher voltage gain over a wider range of velocities [1, 2]. We report here on the design of double-spoke 325 MHz cavities for $\beta_0 = 0.82$ and 1.

ELECTROMAGNETIC DESIGN

High surface fields in superconducting cavities can have detrimental effects on performance. If the surface magnetic field is too high, quenching can occur and if the surface electric field is too high, field emissions can be induced. When comparing the performance of cavities, we often refer to the normalized surface fields, E_p/E_{acc} and B_p/E_{acc}, where E_p is the peak surface electric field, B_p is the peak surface magnetic field and E_{acc} is accelerating electric field which is defined here as

$$E_{acc} = \frac{\Delta W(\beta_0)}{\beta_0 \lambda} \quad (1)$$

where $\Delta W(\beta_0)$ is the energy gain at the optimal velocity. Minimizing these fields is often the first step in cavity design, and the results of which are presented here.

Optimization of Peak Surface Fields

The cavity's radius and iris-to-iris length are approximately determined by the operating frequency and desired β_0. The peak surface fields, however, depend greatly on the shape and dimensions of both the spoke base and the spoke aperture region. All of the results presented are at a frequency of 325 MHz and $\beta_0 = 0.82$ and $\beta_0 = 1$.

Figure 1 shows the spoke parameters discussed here. For convenience, we will refer to the elongated dimension of the spoke (base or aperture, elliptical or racetrack) as either being longitudinal or transverse with respect to the beam line. Both the spoke base and aperture region have been investigated with the elliptical, cylindrical, and racetrack geometries.

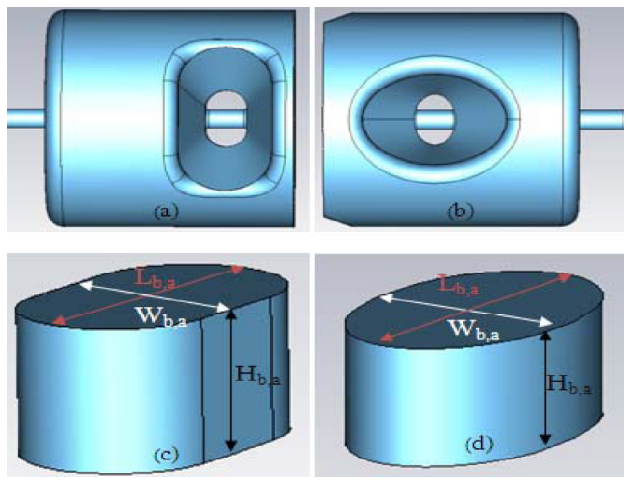


Figure 1: CST MWS view of half the cavity with a transverse racetrack design at the base and aperture (a) and longitudinal ellipse at the base and transverse ellipse at the aperture (b). Racetrack part of spoke (c) and elliptical part of spoke (d). The dimensions of each carry a subscript a or b which refers to either the aperture or base.

Spoke Base

The magnetic field of the fundamental accelerating mode in a spoke cavity is more concentrated near the outer conductor's surface and encircles the spokes. The size and shape of the spoke base region can thus have a strong effect on the peak surface magnetic field. The spokes run radially through the cavity, so changing the size of the base does have an effect in the beam-line region as well since the spoke tapers down to the center. In figure 3, the normalized magnetic field is shown as a function of the spoke base dimensions. The dimension is normalized to the rf wavelength corresponding to a frequency of 325 MHz. More detail on the optimization procedure can be found elsewhere [3].

For a longitudinal spoke base orientation, the length of the spoke base is changed beginning from cylindrical to a value at which the spoke is close enough to the outer wall

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OPTIMIZED RF DESIGN OF 704 MHZ BETA=1 CAVITY FOR PULSED PROTON DRIVERS

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Abstract

The high energy part of the Superconducting Proton Linac at CERN (SPL) is composed of two families of elliptical 704 MHz cavities with respective beta's of 0.65 and 1.0. These cavities are aimed to work in pulsed mode (50Hz, duty cycle 5%), with a beam current of 40 mA and RF peak power up to 1 MW.

At CEA-Saclay, in the frame of the FP7/EUCARD program (European Coordination for Accelerator Research & Development), we designed the beta =1 cavity. Since this cavity should reach a challenging gradient of 25 MV/m in operation, the RF design has been carefully optimized. Precise location of high power coupler has been determined to achieve the optimal external coupling at full beam current, and monopole high order modes have been identified and characterized. In order to keep the extra power required to stabilize the accelerating field in operation, we studied the mechanical behaviour of the cavity and how it influences the RF characteristics.

RF OPTIMIZATION OF THE GEOMETRICAL PARAMETERS

The β=1 SPL cavity is aimed to work in the pulse mode, with the set of machine parameters resulting from the optimization of the SPL accelerator design [1] given in Table 1.

Table 1 : Design parameters for the β=1 part of the SPL accelerator

RF frequency	**704.4 MHz**
Cavity β	**1**
Number of cells	**5**
Accelerating gradient (Eacc)	**25 MV/m**
Average pulse current (Ibeam)	**40 mA**
Synchronous phase (φs)	**-15 °**
Peak RF power	**1 MW**
Repetition frequency	**50 Hz**
Duty cycle	**5%**
Operating Temperature	**2 K**

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As the design gradient of 704.4 MHz - β = 1 cavities is 6 % above the gradient specified for XFEL superconducting cavities (25 MV/m instead of 23.4 MV/m), we used the elliptical TTF cavity [2] as a starting design. Thus the geometry of inner cells is resulting from a scaling from 1300 MHz down to 704.4 MHz

The shape of each outer cell has been adjusted separately to optimize the RF parameters while fitting on beam tubes with different diameters. Though smaller diameters could help to increase the shunt impedance, a 140 mm diameter is fixed on one side due to fundamental power coupler (FPC) geometry and Qext specification. Since the new Saclay V frequency piezo-tuner has to fit the beam tube of opposite side, diameter is fixed to the maximum value (130 mm). Our reference cavity ends with 80 mm diameter flanges, which means tapered tubes at both side of the cavity. From flange to flange, the overall length of the cavity is 1393 mm.

The RF parameters associated with this geometry are summarized in Table 2.

Table 2: RF parameters of the β = 1 SPL cavity

Frequency [MHz]	**704.4**
Bpk/Eacc [mT/(MV/m)]	**4.20**
Epk/Eacc	**1.99**
G [Ohm]	**270**
Cell to cell coupling	**1.92 %**
r/Q [Ohms]	**566**
Lacc = Ngap.β.λ/2 [m]	**1.0647**
Maximum energy gain @ Bpk = 100 mT	**25 MeV**

The accelerating mode (π-mode) in the optimized SPL cavity is shown on Figure 1.

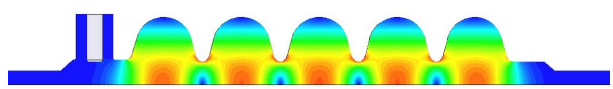


Figure 1: E field of the TM01 fundamental mode in the beta=1 704.4 MHz SPL cavity.

The BCS resistance has been calculated using the formula [3]:

$$R_{BCS} = 2.10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 e^{-17.67/T}$$

STRUCTURAL MECHANICAL ANALYSIS OF SUPERCONDUCTING CH CAVITIES*

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Abstract

The superconducting (sc) Crossbar-H-mode (CH) structure has been developed and tested successfully at the Institute for Applied Physics (IAP) of Frankfurt University. It is a multi-gap drift tube cavity for the acceleration of protons and ions in the low and medium energy range based on the H_{211}-mode. At present two types of superconducting CH structures (f = 325 MHz, β = 0.16, 7 cells and f = 217 MHz, β = 0.059, 15 cells) are under construction.
For the geometrical design of superconducting cavities structural mechanical simulations are essential to predict mechanical eigenmodes and the deformation of the cavity walls due to bath pressure effects and the cavity cool-down. Therefore, several static structural and modal analyses with ANSYS Workbench have been performed. Additionally, a new concept for the dynamic frequency tuning including a novel type of a piezo based bellow tuner has been investigated to control the frequency against microphonics and Lorentz force detuning.

MOTIVATION

The mechanical requirements for superconducting structures are strict to assure a stable operation of the cavity. Due to their thin walls superconducting cavities are very sensitive to external ascendancies, which lead to frequency changes in the range of several hundred kHz. Reasons of frequency variations include Lorentz Force Detuning, microphonics and fast bath pressure fluctuations during operation. To investigate the deformation of the cavity shape and consequential the frequency variations due to external forces the mechanical analysis is an important basic appliance. For all mechanical simulations of the sc CH cavity we use ANSYS Workbench to analyze the cavity deformation [1].
To control the frequency variations of prospective sc CH cavities during operation a novel tuning concept was worked out. Dynamic capacitive bellow tuners welded inside the cavity are provided reaching a tuning range of several hundred kHz to compensate the dynamic frequency shift. To analyze their mechanical behavior, several static structural simulations have been carried out where a bellow tuner model was exposed to a range of static forces.

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STRUCTURAL MECHANICAL ANALYSIS

The investigated cavity is a sc 325 MHz CH cavity which is designed and optimized for high power applications. It consists of 7 accelerating cells and has a design gradient of 5 MV/m [2]. Its frequency is the third harmonic of the UNILAC at GSI. The structural mechanical simulations with ANSYS Workbench have been made to investigate the deformation of the cavity walls and the resulting frequency variations due to external effects.

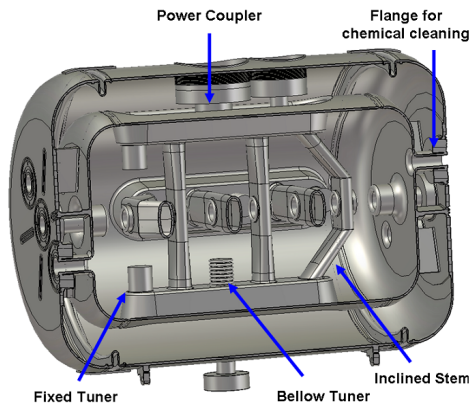


Figure 1: Layout of the sc 325 MHz CH cavity [3].

The complete 325 MHz CH cavity is produced of niobium sheets (thickness 3 mm). The following physical properties of niobium are used for the mechanical simulations:

- Young's modulus $E = 1.05 \times 10^{11}$ Pa
- Density $\rho = 8570$ kg/m^3
- Poisson's ratio $\nu = 0.38$

For all mechanical simulations a yield stress of 470 MPa in the range of the cryo-temperatures was used for niobium.

Cool-Down and Evacuation

The initial step of the mechanical simulation is the structural deformation analysis of the sc 325 MHz CH cavity due to evacuation and cool-down to 4.2 K. For the ANSYS analysis model to calculate the deformation caused by evacuation the attachments at each end of the cavity are chosen to be the fixed support. The end caps are completely fixed against deformations in any direction. For the case of the cavity cool-down only one end cap is fixed. In this case the applied load is the temperature of 4.2 K, while the atmospheric pressure on the surface of the cavity walls is the

DESIGN OPTIMIZATION OF SPOKE CAVITY OF ENERGY-RECOVERY LINAC FOR NON-DESTRUCTIVE ASSAY RESEARCH

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Abstract

We are proposing non-destructive assay system of nuclear materials with laser Compton scattering combined with an energy-recovery linac and a laser. To construct this system for nuclear safeguards and security purpose, it is important to make the accelerating cavity small. The spoke cavity has advantages over the elliptical cavity to adopt for our proposing system. We are designing a spoke cavity favorable to compact cavity. Design optimization calculation of the spoke cavity shape is being carried out using 3D electro-magnetic field simulation code with multi-objective genetic algorithm. The results will be presented.

INTRODUCTION

Energy Recovery-Linac (ERL) can accelerate low emittance and high current beam, which generates high brightness and high quality light source. The high quality beam of ERL combined with lasers can also significantly improve brightness and monochromaticity of X/γ-ray generated by laser Compton scattering (LCS). Nuclear resonance fluorescence (NRF) with the LCS-γ ray can be utilized to nondestructively inspect nuclear materials such as Uranium, Plutonium and minor actinoid elements in spent reactor fuels. This method is significant technology for nuclear safeguards and security. We are proposing non-destructive assay system of nuclear materials by LCS combined with an ERL and a laser. [1]

Practical use of this system requires downsizing the ERL so that it is important to compact the accelerating cavity.

Since the beam instability due to higher-order modes (HOMs) limits the beam current of the ERL, HOM damping is significant for the ERL cavities. Elliptical cavities have tendency to increase the total accelerator length since HOM absorbers, HOM couplers and input couplers are attached to the beam pipes. On the contrary, spoke cavities have an advantage of shortening the total accelerator length [2]. The spoke cavity design suitable for ERL has been being multi-objectively optimized with electro-magnetic simulation code. The present paper describes the results of calculation.

ADVANTAGES OF SPOKE CAVITY

The superconducting spoke cavity used for ERL has following advantages.

1) A superconducting cavity requires HOM absorbers or HOM couplers to damp HOM and input couplers to feed RF power into the cavity. These elements can be installed along the side of the spoke cavity so that the total length of spoke cavity can get shorter than that of elliptical cavity and the distance between the cavities can be decreased. (Fig. 1)

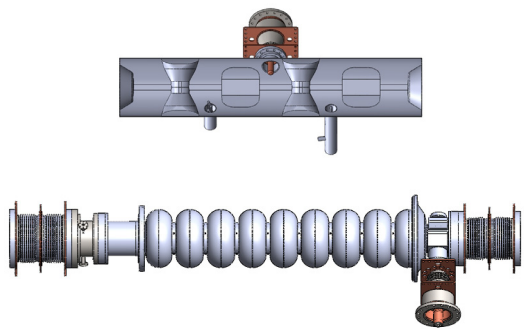


Fig. 1: Schematic views of spoke cavity (upper) and elliptical cavity (lower).

2) The resonant frequency of spoke cavity mainly depends on the spoke length, and high cavity stiffness reduces the fluctuation of cavity resonant frequency due to microphonics. The ERL cavity of small frequency fluctuation can decrease the required RF power and tolerance of the input coupler. This results in making the RF power supply compact.
3) When the outer size of spoke cavity is similar to that of elliptical cavity, the resonant frequency of spoke cavity is nearly half of elliptical cavity. Lower frequency can decrease the energy spread because of the narrow accelerating phase spread for the same bunch length beam. Small energy spread beam can increase the brightness of LSC X/γ-ray.
4) Cell coupling of spoke cavity is stronger than that of elliptical cavity since the outer size of the tank is almost same along the axis. Stronger cell coupling makes the field flatness easier to adjust and less disturbed to increase number of cells. This increases the effective accelerating length.

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DEVELOPMENT OF SUPERCONDUCTING CH CAVITIES*

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Abstract

At present, two superconducting (sc) CH cavities are under development at the Institute for Applied Physics (IAP) of Frankfurt University. The construction of a sc 325 MHz CH cavity with 7 cells and an envisaged design gradient of 5 $\mathrm{MV/m}$ is almost finished. It is planned to test this cavity with beam at GSI Universal Linear Accelerator (UNILAC), Darmstadt to show its performance as a candidate for the UNILAC upgrade. Furthermore, the 217 MHz CH structure with 15 accelerating cells and a real estate gradient of 5.1 $\mathrm{MV/m}$ will be the first cavity of the new sc continuous wave (cw) LINAC at GSI. This proposed cw LINAC is highly requested to fulfil the requirements of nuclear chemistry and especially for a competitive production of new Super Heavy Elements (SHE). To demonstrate the cavity capabilities under a realistic accelerator environment, a full performance test by injecting and accelerating a beam from the GSI High Charge Injector (HLI) is planned in 2013/14. The current status of both sc CH cavities is presented.

MOTIVATION

Since in the future the existing UNILAC at GSI will be used as an injector for FAIR (Facility for Antiproton and Ion Research), beam time availability for nuclear chemistry and especially for SHE production will be very limited. For this reason a new sc cw LINAC at GSI is desired by a broad community of future users [1]. The layout of this heavy ion LINAC (see fig. 1) was worked out at the Institute for Applied Physics (IAP) at Frankfurt University [2]. The main acceleration of approximately 35 MV will be provided by nine sc multi-gap CH cavities operated at 217 MHz. At present, the first cavity of the proposed cw LINAC is under development. As a first step, a full performance test is planned to demonstrate the cavity capabilities by injecting and accelerating a beam from the 1.4 AMeV GSI HLI in 2013/14. Furthermore, for the FAIR project a higher beam intensity as well as an improved beam quality is required, which can not be provided by the existing UNILAC at the moment. Hence, it needs a upgrade of the present UNILAC, especially of the Alvarez-DTL part. The construction of a new sc 325 MHz prototype CH cavity at RI (Research Instruments GmbH, Bergisch Gladbach, Germany) is almost finished. In order to show its performance as a suitable candidate for the UNILAC upgrade, it is planned to test this cavity with a 11.4 AMeV beam at the UNILAC in 2012.

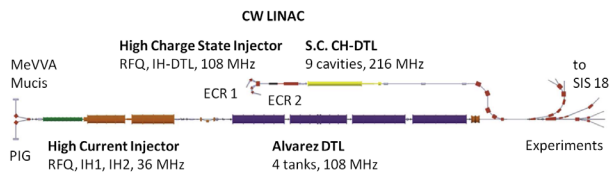


Figure 1: Future layout of the new sc cw LINAC (top) in parallel to the existing GSI UNILAC (bottom).

STATUS OF THE 325 MHZ CH CAVITY

The sc 325 MHz CH cavity (see fig. 2) is designed and optimized for high power applications, consists of 7 accelerating cells and has a design gradient of 5 $\mathrm{MV/m}$ [3]. Its frequency is the third harmonic of the Alvarez-DTL.

Inclined end stems inside of the cavity lead to a homogeneous field distribution due to their increased inductance. This allows a very compact longitudinal design of the cav-

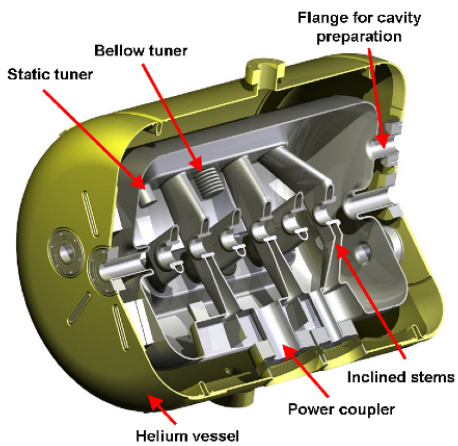


Figure 2: Design of the sc 325 MHz CH cavity.

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DEVELOPMENT OF THE DEMOUNTABLE DAMPED CAVITY

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Abstract

We have designed a new HOM free cavity named Demountable Damped Cavity (DDC) as an ILC R&D. DDC has two design concepts. The first one is an axial symmetry to eliminate kick off effect by HOM coupler itself. DDC is applied coaxial structure along the beam axis to make strong coupling with HOMs. HOMs are damped in RF absorber at the end of coaxial waveguide and the accelerating mode is reflected by the choke filter mounted nearby the end cell. The second concept is demountable structure which can make cleaning the end group easy in order to suppress the Q-slope problem at high field. In this paper, we will report about a RF absorber shape, thermal structure, 9 Cell cavity shape and preliminary vertical test result on the single cell DDC structure.

INTRODUCTION

We are developing the Demountable Damped Cavity (DDC) as R&D of ILC main linac (Fig. 1). There are two features in DDC. One is the axial symmetry structure, which will eliminate the beam kick effect in the TESLA type HOM coupler [1]. The second feature is the demountable structure. It makes cleaning the end group easy in order to suppress the high field Q slope [2].We finished designing the choke cavity structure. We have designed the absorber shape.

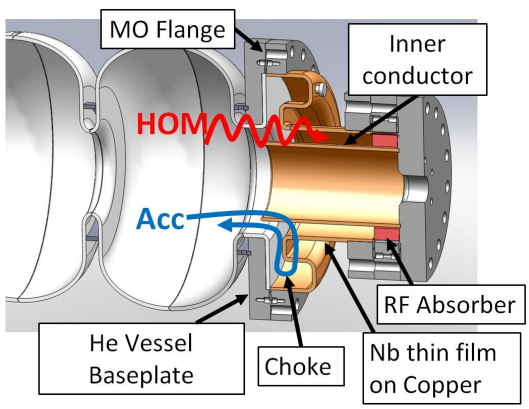


Fig. 1: The design of the DDC.

RF ABSORBER STRUCTURE

In the ILC main linac, the heat flux to 2K liquid helium has to be suppressed strictly. The RF absorber, which is mounted at the end of coaxial waveguide, is kept at 80K in our design. Data of absorber material parameter measured at 80K is very limited. We measured the Ni-Zn ferrite absorber (CMD10; Ceramic Magnetic Inc. [3]) at 80K. In the ILC 1.3GHz cavity, harmful HOMs are excited around 2~3 GHz. We designed DDC HOM damper shape mainly for those HOMs to be damped based on the measured data.

Absorber Measurement System

We measured the complex permeability $\mu = \mu' + i\mu''$ and the complex permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ of the ferrite at same time by the Nicolson-Ross-Weir method [4]. This is an easy method because reflection Γ and attenuation P can be measured by just inserting the sample in a transmission line.

$$\Gamma = \frac{\sqrt{\mu/\varepsilon} - 1}{\sqrt{\mu/\varepsilon} + 1} \quad (1)$$

$$P = \exp\left(-\frac{j\omega d}{c}\sqrt{\mu\varepsilon}\right) \quad (2)$$

, where ω is the angular frequency, d is the sample length, c is the speed of light.

We made a 50Ω coaxial waveguide sample holder (Fig. 2). It can keep the sample under vacuum to measure the RF property without any gas environment. The sample length is fixed 20mm, because the ferrite characteristic parameters dominate around 1MHz~1GHz. The measurement system was calibrated by measuring a copper sample with the same ferrite's shape and measuring empty sample holder. We confirmed our measurement system by measuring polyethylene's RF characteristics well known. Our result with polyethylene permittivity is $\varepsilon = 2.2 \pm 0.1$, which is the same value with one reported already [5].

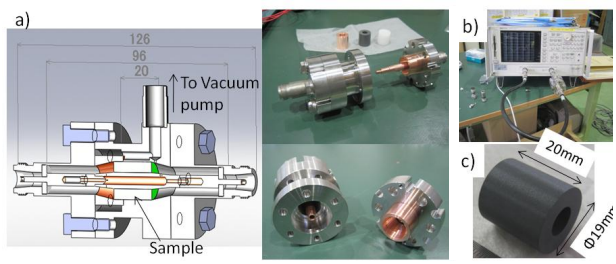


Fig. 2: Permeability and permittivity measurement system a) 50Ω coaxial sample holder b) Measurement view with Network Analyzer c) Ferrite sample.

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MECHANICAL DESIGN OF TRIPLE SPOKE CAVITY FOR EURISOL

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Abstract

Within the framework of the EURISOL (European Isotope-Separation-On-Line facility) programme, supported by European Union, IPN Orsay has proposed a 352MHz triple-Spoke superconducting cavity: for the intermediate energy section ($\beta = 0.3$) of high power proton linear accelerators.

In terms of structure design, a triple-spoke superconducting cavity has a complicate geometry, 3D modelling is necessary. More, the design require simulations which couple electromagnetic with mechanics.

To perform these tasks, the mechanics simulation code CAST3M (Calcul et Analyse de Structure et Thermique par la mthode des Elments Finis) [1] has been linked to the electromagnetics code Opera3D [2] via a dedicated plateform, which has been developed for this purpose. This work allows the instantaneous passage from CAD (CATIA) design to mechanical calculations using Cast3m and electromagnetical simulations with Opera3D. As a consequence, the deday of design studies has been considerably reduced.

The electromagnetics and mechanics behaviours of the triple are presented and discussed in this paper.

INTRODUCTION

Superconducting (SC) RF cavities have a high efficiency accelerating gradient and bore aperture. This technology is also expected to be advantageous in a linear accelerator in terms of power consumption, construction cost and beam loss. Although this conclusion is well accepted for the high energy part of the accelerator, it is still challenging at low energy. A 352 MHz triple Spoke cavity (triple Spoke cavity) has been proposed by IPN Orsay for the low beta ($\beta = 0.3$) sections of the proton linac in the Eurisol project [3]. Meanwhile, the study of a 352 MHz ($\beta = 0.48$) triple Spoke cavity for the HIPPI project [4] has been achieved and also referenced for Eurisol triple Spoke cavity design. The classical mechanical design uses CAD computer design (Catia at IPN Orsay). The original platform [5] which links Catia to the electromagnetic optimization code Opera-3d and the mechanical code Cast3m has been used to couple 3D simulations.

FROM RF TO MECHANICS

The RF design of the 352 MHz $\beta = 0.3$ multi-Spoke superconducting cavity takes into account physics requirements (beam energy and acceptance) in order to reach the highest accelerating efficiency (minimum ratio E_{pic}/E_{acc}, B_{pic}/E_{acc}). The inner shape of the cavity has been optimized in order to get a best ratio between maximal electromagnetic field and accelerating field [6] on the cavity surface. As the same times, the electromagnetical field distribution has been simulated with Opera3D/Soprano in order to perform coupled electro-mechanical simulations. The figures 1 and 2 show the electromagnetics fields.

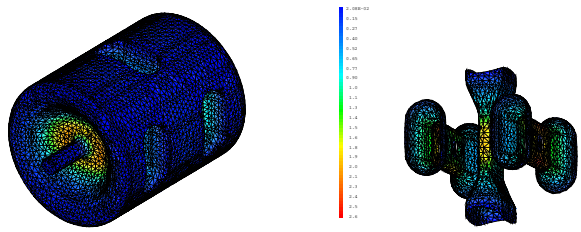


Figure 1: Electric field

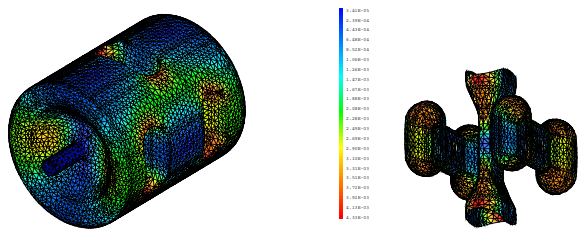


Figure 2: Magnetic field

Coupled with electromagnetical simulations, the mechanical simulations have been performed to evaluate freqency shift due to Lorentz forces, figue 3. The coupled electromechanical simulations allow also to design power coupler port and pick up ports. Many mechanical simulations have been carried out to optimize the cavity wall thickness choose the adapted stiffeners and all the supports of the cavity, especially to guarantee the cavity integration with its cold tuner into the helium vessel.

Since another important criterion of the mechanical design is the high cost of niobium: minimization of the thickness is required. Starting from a 3 mm wall, mechanical simulations using Cast3m showed that the maximum Von Mises stress level under 1 Bar pressure exceed 50 MPa which is the elastic limit of niobium at room temperature.

In order to reduce the stress level at the front part of the cavity, the solution consists, on one hand, in increasing the

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CONCEPTUAL DESIGN OF THE BETA = 0.86 CAVITIES FOR THE SUPERCONDUCTING LINAC OF ESS

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Abstract

CEA-Saclay is in charge of the design, the fabrication and the tests of the superconducting high beta cavities for the high energy part of the European Spallation Source (ESS) linac. This paper reports the actual status of the RF and mechanical design of these cavities. According to ESS specifications, these cavities will be 5-cells elliptical, with frequency 704 MHz and β = 0.86. They will work in pulsed mode, with a beam current initially equal to 50 mA. The target accelerating gradient is 18 MV/m on the linac, and 20 MV/m in vertical tests. For the RF design, the cavity efficiency and the peak fields were optimized, while the feasibility of the external coupling with RF power was taken into account. Attention was also paid to the HOM frequencies and impedances and to their future extraction. Coupled RF/mechanical FEM calculations have been carried out and the Lorentz detuning, critical for a pulsed mode cavity, is lowered by the insertion of stiffening rings.

INTRODUCTION

The superconducting part of the ESS proton linac consists in a 352.21 MHz spoke resonator section followed by two different sections of 704.42 MHz 5-cell elliptical bulk niobium cavities. The medium beta and the high beta cavities are grouped in cryomodules of 4 and 8 cavities respectively. The high beta section accelerates protons from 500 MeV up to the linac output energy of 2.5 GeV corresponding to a reduced velocity range β=v/c from 0.76 to 0.96. The specifications for the β = 0.86 cavities are shown in table 1:

Table 1: Relevant specifications for the design of the high beta elliptical cavities

Frequency (MHz)	704.42
Number of cells	5
Operating temperature (K)	2
Maximum surface field in operation (MV/m)	40
Nominal Accelerating gradient (MV/m)	< 18
Q_0 at nominal gradient	> 6e9
Repetition rate (Hz)	14
Beam pulse length (ms)	2.86
Beam current (mA)	50
Nominal peak power transmitted by power couplers (kW)	< 900

The cavity design must take into account all the aspects related to high power pulsed beam operation, in particular the feasibility of RF coupling, the control of high order mode excitation, damping and propagation, and the mechanical stability of the cavity itself.

RF DESIGN

One of the main parameters in the design of a multi-cell cavity is the cell-to-cell coupling κ. Choosing a low κ value emphasizes the cavity efficiency only. With increasing κ, the efficiency is reduced but major gains numerous: it is easier to achieve an even field distribution in the cavity, and therefore to control the homogeneity of the peak surface fields among the cells. The frequency separation between the accelerating mode and its neighbor is also increased. Even more important for a high current application the high κ translates into higher iris diameters, and better high order mode (HOM) propagation. We have investigated designs with different κ values from 1.1 to 2.5 for the β = 0.86 cavity. The conclusion was that the loss in cavity efficiency was excessive above κ = 2.

One important geometrical parameter for designing a multi-cell elliptical cavity is the wall angle, related to mechanical stability, sensitivity to Lorentz force detuning (LFD) and the ease of cavity preparation (chemical etching, high pressure water rinsing and drying) which is a key point for achieving cavity performances. Based on experience with β = 0.5 and β = 0.65 with which we have explored wall angles between 5.5 and 8.5 degrees [1,2], we have chosen a minimum wall angle of 8 degrees. This of course restricts the range of geometrical cell parameters accessible for cavity optimization for peak fields in particular.

The main cavity parameters of the design are shown in table 2:

Table 2: High beta cavity RF properties

Geometrical beta	0.86
Iris diameter (mm)	120
Cell to cell coupling κ (%)	1.8
π and 4π/5 mode separation (MHz)	1.2
Epk/Eacc	2.2
Bpk/Eacc (mT/(MV/m))	4.3
Maximum. r/Q (Ω)	477
Optimum beta	0.92
G (Ω)	241

Taking into account the cryogenic duty cycle, the average power dissipated in one cavity at 18 MV/m is less than 5.3 W at the Q_0 specification.

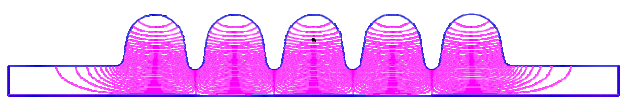


Figure 1: β = 0.86 cavity geometry.

COUPLER DESIGN FOR A SAMPLE HOST TE CAVITY*

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Abstract

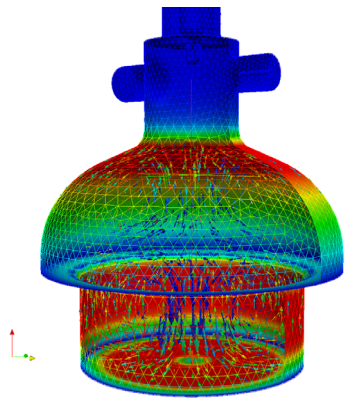
A sample host niobium superconducting cavity operating at both TE_{012} and TE_{013} modes has been developed. The cavity features a flat 3.75 inch diameter demountable bottom plate allowing RF testing of new materials such as Nb_3Sn and MgB_2. Since the surface resistance of the sample plates may vary a lot, an adjustable input coupler has been developed for this cavity. A hook shape coupler tip is designed and optimized to couple to the magnetic field of both transverse electric modes. The coupler optimization, external Q calculations and 3D multipacting simulations using ACE3P will be discussed.

INTRODUCTION

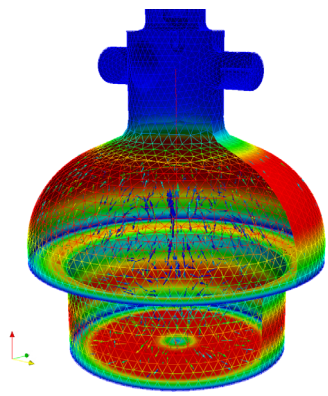
The rf surface resistance of superconducting niobium is typically studied by testing single cell or multi-cell superconducting cavities. Due to the time consuming and complex process of preparing those entire cavities, getting statistically significant data sets on various phenomena impacting surface resistance is challenging. To systematically characterize rf surface resistance of niobium and other new materials such as MgB_2 and Nb_3Sn, a sample plate demountable superconducting niobium cavity was designed and fabricated [1],[2]. The mushroom shape cavity operates at both TE_{012} and TE_{013} modes as shown in Fig.1.

The rf design parameter are shown in Tab.1. The maximum magnetic field which can be achieved at the sample plate is estimated based on niobium breakdown field 2000 Oe. The design enables that the sample plate is exposed to the maximum field in the entire cavity. The main design goal is to maximize the ratio R of maximum sample plate surface magnetic field to maximum host cavity surface magnetic field. Three optimized shape had been obtained and only the shape which enables dual modes operation and operates at monopole transverse electric field TE_{0mn} was chosen to be fabricated. The maximum of the surface magnetic field on the sample plate is at the same location for both modes as seen in Fig.2.

The input coupler port is located at the center top of the mushroom type cavity and the pickup probe and pumping probe are distributed symmetrically at the input coupler port. In the following sections, the rf design of the input coupler, coupler heating considerations and 3-dimensional multipacting simulations using SLAC A3P codes will be described.



(a) Spacial magnetic field distribution of TE_{012} mode,red indicates high magnetic field, the maximum magnetic field on the sample plate is 1.24 times higher than on host cavity wall



(b) Spacial magnetic field distribution of TE_{013} mode, red indicates high magnetic field, the maximum magnetic field on the sample plate is 1.57 times higher than on host cavity wall

Figure 1: Magnetic field distribution of TE mushroom cavity.

Table 1: The design parameters of the TE mushroom cavity (H_{max} on sample assumes 2000 Oe maximum field on host cavity wall)

	TE_{012}	TE_{013}
f(GHz)	4.78	6.16
H_{max} @ sample (Oe)	2480	3480
Sample diameter (cm)	10.0	10.0

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MECHANICAL STUDY OF SUPERCONDUCTING PARALLEL-BAR DEFLECTING/CRABBING CAVITIES*

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Abstract

The superconducting parallel-bar deflecting/crabbing cavity [1] has improved properties compared to conventional cavity structures. It is currently being considered for a number of applications. The mechanical design analysis is performed on two designs (Figure 1) of the 499 MHz parallel-bar deflecting cavity for the Jefferson Lab 12 GeV upgrade. The main purpose of the mechanical study is to examine the structural stability of the cavities under the operating conditions in the accelerators. The study results may suggest the need for additional structural strengthening. Also the study results will help to develop a concept of the tuning method. If the cavity is to be installed in the accelerator it should satisfy certain design parameters due to the safety requirements (for example, pressure system requirements) which are much more severe than the actual operating condition.

INTRODUCTION

The current 6 GeV Jefferson Lab electron accelerator has a capability to simultaneously separate the beam to the three experimental halls. The current separator cavities are operated at room temperature. In order to preserve this capability after the 12 GeV upgrade, a new separator design is needed which presents the opportunity for a new idea to be considered for implementation. The 499 MHz superconducting parallel bar deflecting cavity is a perfect candidate. To prove the design concept a prototype will be built and tested. The test results will determine the new separator cavity type either the superconducting or the room temperature cavity.

The superconducting cylindrical parallel bar cavity is approximately 50cm long and 25cm in diameter.

CAVITY DESIGN

The shape of the cavity has been optimized in an RF study [2,3]. Over the RF cavity design (vacuum volume) shells of various thicknesses were created. The shell represents a cavity fabricated by a stamping process. Machined components were also considered to see if it offers better mechanical stability. The best value fabrication method should be determined later. This study will present mainly the cylindrical outer conductor with trapezoidal shaped bars. Table 1 shows the parameters of the cavity.

*Work supported by U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
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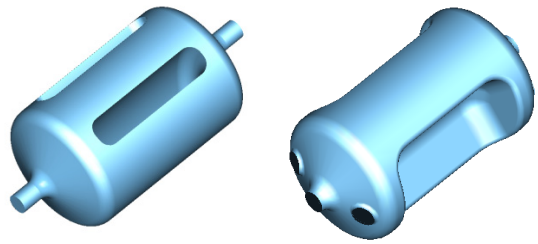


Figure 1: Cylindrical parallel bar cavity designs [2].

Table 1: Parameters-Cavity with trapezoidal bars [3]

Frequency of π mode	499.0	MHz
Cavity length	440.0	mm
Cavity diameter	241.9	mm
Aperture diameter	40.0	mm
V_T per cavity	3	MV
E_P/E_T	2.96	
B_P/E_T	4.49	mT/(MV/m)
$[R/Q]_T$	982.2	Ω
Geometrical factor	105.6	Ω
Power with beam	~0.5	kW
Power without beam	<10	W

The internal surfaces of the cavity directly affect the electromagnetic behaviour. The field sensitive areas were identified in the RF study [3] as shown in Figure 2 and 3.

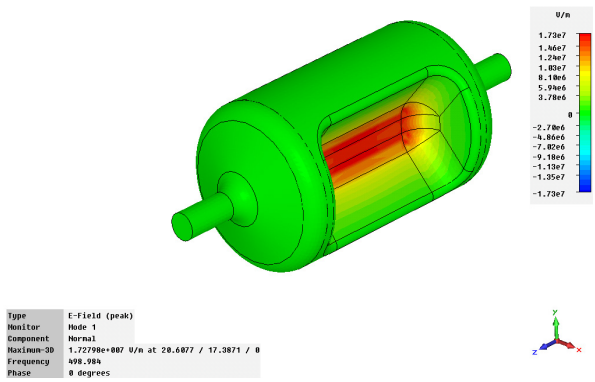


Figure 2: Surface electric field.

ELECTRO-MAGNETIC OPTIMIZATION OF A HALF-WAVE RESONATOR*

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Abstract

The optimization procedure developed for the electromagnetic (EM) design of a quarter-wave resonator (QWR) optimized for β = 0.077 for an ATLAS upgrade has now been successfully tested. This prototype QWR achieved record peak surface fields for low-beta cavities of 70 MV/m and 105 mT and is capable of providing a voltage gain of 4.4 MV, far exceeding the design voltage of 2.5 MV. We have developed and applied a similar procedure for the EM design of a 322 MHz, β ~ 0.29 half-wave resonator (HWR) for the medium energy section of the FRIB driver linac. The optimization approach and the final results will be described. The choice of aperture and its effect on the EM design parameters will be discussed. A comparison between equivalent half-wave and single-spoke resonators will also be presented. The transition from the electromagnetic model in Microwave Studio to the engineering model in the CAD program Inventor was carefully studied as it may affect both the EM design parameters and the cavity fabrication.

INTRODUCTION

The FRIB driver linac design [1] is based on quarter–wave resonators (QWR) in the low-energy section and half-wave resonators (HWR) in the medium and high-energy sections. The recent SRF developments at Argonne [2] showed that the design and production of these structures could be very well optimized to achieve record high accelerating voltage. A procedure, similar to the one used for the design optimization of the QWR for the ATLAS intensity upgrade [3], was developed for the electromagnetic design optimization of a 322 MHz HWR for the medium-energy section of the FRIB driver linac. In this section, a uranium beam is accelerated from 16 to 55 MeV/u, with a β_{opt} ~ 0.29 for the HWR. The mechanical and engineering design is reported in a separate contribution [4].

HWR GEOMETRY: CHOICES, CONSTRAINTS AND PARAMETERS

Following the success of the conical QWR developed for the ATLAS upgrade [3], we chose a (double) conical shape for this HWR. A conical HWR has been proposed and studied before [5,6] but never built. Both the outer and inner conductors are conical giving the cavity the "hour-glass" shape shown in figure 1. The cavity outer shell (CV) middle section is cylindrical while the inner conductor (IC) has a race-track central section. The inner conductor and outer shell are joined with two toroidal sections on the top and bottom. The drift tube (DT) re-entrant nose is also of conical shape. These choices are based on preliminary shape optimization. Figure 1 shows the most important geometry parameters used in the optimization and Table 1 gives their description. It is worth noting that other dimensions like the drift tube penetration depth (DTPN) and the inner conductor race-track width (ICRTZ) are fully determined from the cavity middle radius (CVMR), the mid-gap distance (MGD) and the gap width (GapW) and they are not directly used in the optimization.

In addition to the choices made above, we have to consider a several constraints. Some of these constraints are purely geometric; others are based on the manufacturing experience of the ATLAS intensity upgrade QWR. The main constraints are:

1) The inner conductor top radius (ICTR) was varied to study its effect then set to the QWR value of 8 cm due to manufacturing considerations.
2) The inner and outer conductor cones are required to end with short flat cylindrical sections for frequency adjustment cuts.
3) The distance between gap centres (MGD) is fixed to approximately half the wave length at the design β_G, MGD ~ $\beta_G\lambda/2$ to have β_{opt} ~ 0.29.
4) The difference between the cavity top (CVTR) and middle (CVMR) radii should not exceed 5 cm to take advantage of cavities interconnections without additional real-estate to fit the larger top.

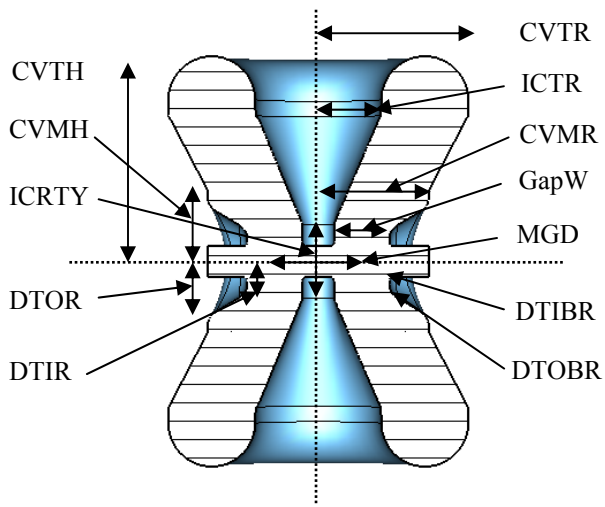


Figure 1: HWR cavity geometry and parameters used in the electro-magnetic optimization.

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and WFO85Y64 Supported by Michigan State University.
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COUPLED ELECTROMAGNETIC AND MECHANICAL SIMULATIONS FOR HALF-WAVE RESONATOR DESIGN*

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Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) will produce primary beams of ions at 200 MeV per nucleon for nuclear physics research. The driver linac will require 344 superconducting cavities, consisting of two types of Quarter-Wave Resonators (QWRs, β = 0.041 and 0.085) and two types of Half-Wave Resonators (HWRs, β = 0.29 and 0.53). A first-generation β = 0.29 HWR has been designed, prototyped, and tested. Second-generation versions of the other cavities are being developed, with multiple resonators of each type having been tested. Second-generation β = 0.29 and 0.53 HWR designs are nearing completion, making use of the experience with the first-generation HWRs. In the second-generation design, the inner conductor is tapered to reduce the peak surface magnetic field. The outer conductor is a straight cylinder to increase the mechanical stiffness. Mechanical simulations of the β = 0.53 HWR at 322 MHz have been performed, this work will be repeated for the β = 0.29 HWR design by the end of the year. Part of this work has been the optimization of the mechanical properties to minimize Lorentz Force Detuning and Helium bath pressure sensitivity while providing adequate tuning range. The simulation techniques used for this work and the resulting proposed cavity stiffening will be presented.

INTRODUCTION

The FRIB driver linac will deliver stable beams to a production target at 200 MeV/u or greater energy. For heavier ions, as many as five charge states will be accelerated to the target to deliver beam power of up to 400 kW [1]. To efficiently provide the flexibility required, a CW superconducting linac [2, 3] was chosen. Half-Wave Resonators (HWRs) were chosen for the high energy section because they are among the most effective geometry at the frequency and velocities (322 MHz, β = 0.29 and 0.53) required. Although several groups have designed and prototyped HWRs or spoke cavities [4], the only HWR operational experience so far is at the SARAF linac, which uses β = 0.09 HWRs [5]. A significant problem discovered in the SARAF HWR design was mechanical instability and pressure sensitivity. This instability made the low-level RF control of these cavities far more complex than expected. Learning from their experience and avoiding similar problems is a significant focus of our mechanical simulation work.

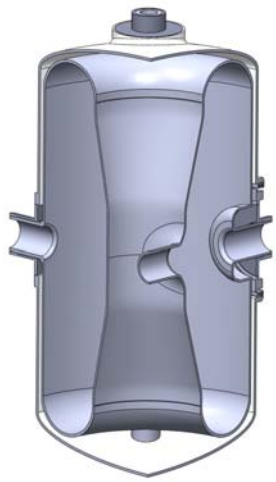


Figure 1: A sectional view of the cavities with helium vessel. Note the beam port on the right, RF port on the left, and rinse port at the top.

Design Overview

The 322 MHz β = 0.29 and 0.53 half wave resonators (HWRs) have a 40 [mm] aperture in the drift tube, and a 42 [mm] beam port inner diameter. All FRIB cavities will operate at 2 K with the HWRs having dynamic heat load goals of 2.9 and 6.3 [Watts], respectively. Frequency control will be provided by means of a mechanical tuner attached to the helium vessel. This tuner will move the beam ports by means of a stepper motor and piezoelectric actuator in series. Both the stepper motor and piezo actuator will be outside the cryomodule. Ports perpendicular to the beam axis on the mid-plane will be used for RF coupling (see Figure 1). Four ports have been added to the top shorting plate to facilitate etching and provide better access during the high-pressure rinsing step which precedes clean room assembly.

Cavity Features

The cavity figures of merit are shown in Table 1. During development of these half wave geometries, special attention was paid to the need for the design to be compatible with established techniques for cavity fabrication and surface preparation, maximizing the probability of reliable performance. The most notable examples of this were the

* This material is based upon work supported by MSU and by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661
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ELECTROMAGNETIC OPTIMIZATION OF THE FRIB 322 MHz ß=0.29 HALF WAVE RESONATOR*

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Abstract

A third generation medium velocity Half Wave Resonator (HWR) is in the final stages of design at Michigan State University (MSU) for use in the Facility for Rare Isotope Beams (FRIB) driver linac. The cavity is being designed to deliver 1.9 MV accelerating voltage reliably, with on optimum β=0.29. The aim is to reduce significantly the peak magnetic field from the first and second generation designs without changing the cryostat design and the linac layout. The design effort optimizes the surface fields for reliable operation but also considers frequency stability and tunability altogether with straightforward fabrication and surface preparation procedures. The electromagnetic and mechanical design started from an existing design and incorporated lessons learned from the MSU developed 322 MHz HWRs for β=0.53. The third generation cavity has a similar shape but a different design of the beam port flanges which maximizes the available space for the outer conductor.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) located at Michigan State University (MSU) is funded by a joint agreement between the US Department of Energy (DOE) and MSU for the advanced study of rare isotope beams [1]. The driver linac for FRIB is a 200 MeV/u superconducting linac with a final beam power of 400 KW [2]. The superconducting linac will be constructed using four types of resonators [3]. This paper will discuss the β=0.29 half wave resonator shown in Figure 1. Two problems were present in the previous generation cavities design: first, the B_{pk}/E_{acc} value of 10.8 $mT/(MV/m)$ was rather high due to the space available in the cryostat; second, the beam aperture of 30 mm was just the minimum acceptable in that linac section. So the third generation design had the aim of increasing the beam aperture to 40 mm and of reducing B_{pk}/E_{acc} by increasing as much as possible the cavity diameter without changing the available flange-to-flange length in the cryostat.

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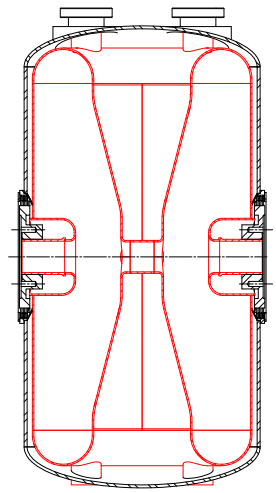


Figure 1: 322 MHz β=0.29 Half Wave Resonator.

OPTIMIZATION

Current development of half wave RF structures have been extensively described by Conway [4]. Superconducting RF optimizations have been largely limited by trial and error studies where experience plays an extensive part. The optimization process is similar for the β=0.29 and β=0.53 half wave resonators with evaluation of each shape with the same purpose of the satisfaction of electromagnetic performance and then on manufacturing and cost [5], and the same optimization parameters are adopted for both half wave resonators. The sketch with notations of optimization parameters is shown in Figure 2. The optimized β=0.29 and β=0.53 half wave resonators are shown in Figure 3.

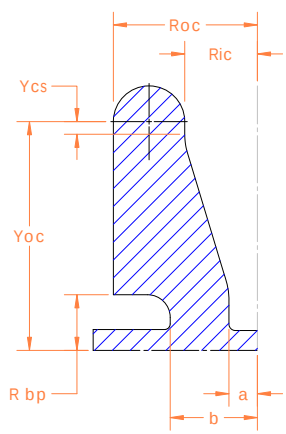


Figure 2: Sketch of optimization parameters.

HOM CAVITY DESIGN FOR THE TRIUMF eLINAC

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Abstract

The TRIUMF eLINAC, currently in its design phase, is a 50 MeV electron linear accelerator and will be used for photo-fission to produce rare isotopes for experiments. Future upgrade plans include an option to go to a recirculating LINAC to provide higher energies. This brings up the need to calculate the shunt impedances of higher order modes (HOM) to avoid beam instabilities and beam break up (BBU). The cavity design for a 9 cell cavity has to account for the limitations given by the desired beam current of 10mA and the layout of the recirculating path to create a high enough BBU limit.

Work on the cavity design to accommodate for those requirements will be presented as well as a way to reduce the shunt impedance by the use of ring dampers will be discussed.

INTRODUCTION

The TRIUMF e-Linac consists of five nine-cell cavities. Each cavity is supposed to provide 10MV of accelerating voltage at 1.3 GHz and a $Q_0 \geq 10^{10}$. The linac is divided into one injector cryomodule (ICM) with one cavity and two accelerating cyromodules (ACM) with each two cavities. The ACM section of the linac is under consideration to be extended to an energy recovery Linac (ERL) or recirculating linac. This future upgrade requires attention to the HOMs of the cavity. Modes with a high shunt impedance will cause beam breakup and too much dissipated power in the cavity, especially if one of the modes is on a beam repetition rate harmonic. One of the goals is to come up with a cavity design that does not rely on active HOM couplers to work within the given limit.

The baseline for the cavity design is the TESLA 9 cell cavity as described in [1]. TESLA cavity HOMs have been measured in [2] and [3].

To accelerate 10 mA electrons by 10 MV per cavity two power couplers provide each 50 kW rf power to combine to the needed 100kW. Modifications to the cavity shape have to be made due to those high power couplers and the BBU considerations. Simulations are done with the codes CST MWS for the coupler positioning and damping calcuations and SLANS for the fabrication error study. For SLANS a custom input file generator script was written as well as a post processing application that allows for calculations of damping with resistive materials.

DEFINITIONS

The dipole shunt impedance of mode *n* is defined [4] as:

$$(\frac{R_d}{Q})_n = \frac{V_z^2(\rho)}{\rho^2(\frac{\omega_n}{c})^2\omega_n U} \quad (1)$$

with ρ being the distance off axis.
For the proposed recirculating beam dynamics a $R_d/Q \cdot Q_L \leq 10M\Omega$ for each mode should give a threshold current for BBU of 20 mA. A value of 1 MΩ should give enough safety margin on the threshold current compared to the design current of 10 mA. The beam pipe with the power couplers attached to it will be called the 'coupler side' of the cavity, the opposing side is the 'tuner side'.

COUPLERS

To provide the beam with 100 kW cw power two 50 kW couplers are specified and are placed at the coupler of the cavity symmetrically opposed. Two coaxial couplers, opposing each other, are each delivering 50 kW cw. Because of the attached helium vessel the 62 mm inner diameter coupler ports have to be at a distance of 72 mm away from the last iris. Since a Q_{ext} of 10^6 is required to provide the required bandwidth for the 10mA beam, the couplers have to penetrate the beam pipe by 3.5 mm. The couplers are orientated in the horizontal plane.

DAMPING RINGS

To decrease the Q_L of a mode damping rings of normal conducting material are introduced at the beam pipes on both ends of the cavity. Those dampers introduce an additional loading to the mode and dissipate rf power. They will be located outside the helium reservoir and are temperature wise staged at 77K, so there is no additional heat load on the 2K helium. The generated heat will be transported out of the cryogenic system over the LN2 circuit. The distance of 117mm between damper rings and iris of the closest halfcell also guarantees no additional damping of the accelerating mode as the Q_{ext} of those rings for the accelerating mode is designed to be greater than 10^{11}. We are exploring different materials but for the purpose of this paper to be used as dampers: stainless steel and Sigradur [5] are considered, a glassy carbon with a electric conductivity of around $2 \cdot 10^4 S/m$. For more details on the design of the damper rings and Sigradur, see [6].

CAVITY SHAPE

Three different variants for a nine cell cavity have been studied. The main difference in each model is the size

ELECTRO-MAGNETIC OPTIMIZATION OF A QUARTER-WAVE RESONATOR

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Abstract

The Institute of Modern Physics (IMP) has been trying to design a highly effective accelerating quarter-wave resonator (QWR) cavity which can work at a record high voltage of 2.5 MV with as low as possible peak surface electromagnetic (EM) fields. In the cavity design, we set the goal of the optimization to minimize the peak magnetic and electric fields while still keeping good values for the R over Q and the geometric factor. Take the design of the QWR cavity with frequency of 81.25 MHz and beta of 0.085 for example, from a regular cylindrical shaped inner and outer conductors, the optimization has led them to a conic inner conductor and an elliptical cylinder outer conductor. In this paper, we will present how the cavity geometry parameters evolve in order to approach optimal EM design.

INTRODUCTION

The most appealing aspect of superconducting radio frequency (SRF) accelerating cavities is that they can operate in continuous wave (CW) mode or long pulse mode while providing a high accelerating gradient due to low heat loss. The quality factor Q of SRF cavities is very high since the surface resistance of SRF cavities is 5 orders lower than that of copper cavities. The SRF cavities are refrigerated with liquid helium in order to achieve the surface resistance in nΩs. The cavities' operating temperatures are generally either above 4K or below 2K. The cryogenic load of the superconducting cavities is an important factor when we design a SRF accelerating facility.

The dynamic heat load calculation was done by calculating the cavity's RF power dissipation from fundamental cavity parameter , and the power dissipation is inversely proportional to $(Ra/Q_0)G$. Therefore, the SRF cavity optimization should include the minimization of the peak surface magnetic and electric fields while keeping favorable values for the shunt impedance and the geometry factor [1].

The large number of QWR cavities needed for the superconducting linac in IMP may exert great pressure on the cryogenic plant in the future, so it is necessary to design the superconducting QWR cavities with high geometric shunt impedance and geometry factor in order to minimize the cryogenic load.

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A NEW-SHAPED QWR CAVITY WITH AN ELLIPTICAL CYLINDER OUTER CONDUCTOR

To maximize the geometric shunt impedance and geometry factor, we tried an elliptical cylinder outer conductor of the cavity and noticed that this new shape will improve the parameters of interest significantly, including the shortening of the cavity height, approximately a ~68% increase of the $(Ra/Q_0)*G$ and a ~15mm reduction of the cavity height, compared to the QWR with a conventional cylindrical outer conductor, whose outer conductor radius is of the short axis radius of the elliptic cylinder in order to keep the same optimum β(Figure 1). The EM parameters in Table 1 show the comparison of a not optimized QWR with an elliptical cylinder outer conductor and QWR with a conventional cylinder outer conductor.

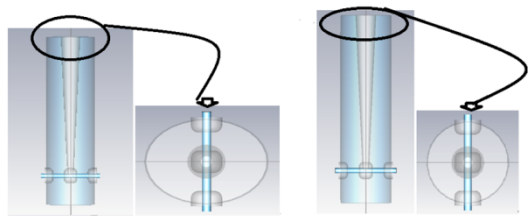


Figure 1: The comparison between QWR with an elliptical cylinder outer conductor and QWR with a conventional cylinder outer conductor.

Table 1: The EM parameters of a not optimized QWR with elliptical OC and a QWR with conventional OC

Parameter	Elliptical OC	Conventional OC
R_a/Q_0 *G (Ω^2)	~15249	~11842
B_{peak}/V_{acc}(mT/MV)	~34.4	~36
E_{peak}/V_{acc} (m^{-1})	~20	~22
Height (mm)	~895	~910

Not only can this design achieve better value of (R_a/Q_0) times G, it can also lower the cavity height which is an important factor for consideration of reasonable cryomodule size and mechanical stability; in the meantime, we use the short axis to accelerate the beam which is helpful to maintain relatively high real-estate gradient.

DESIGN OF A 1500 MHZ BUNCH LENGTHENING CAVITY FOR NSLS-II

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Abstract

NSLS-II is a new ultra-bright 3 GeV 3rd generation synchrotron radiation light source. The performance goals require operation with a beam current of 500mA and a bunch current of at least 0.5mA. Ion clearing gaps are required to suppress ion effects on the beam. The natural bunch length of 3mm is planned to be lengthened by means of a third harmonic cavity in order to increase the Touschek limited lifetime. A niobium cavity and full cryomodule including LN2 shield, magnetic shield and insulating vacuum vessel have been fabricated and cold tested. The cavity design and initial cold test results are presented.

INTRODUCTION

NSLS-II storage ring RF system will have four 500MHz superconducting single-cell cavities providing 4.9 MV total ring voltage. Without the harmonic cavity the bunch length is ~3mm rms and the resulting lifetime is ~2 hours which would require frequent top-off injections that will interfere with user operations. An established method [1, 2] of increasing the lifetime is to use a harmonic cavity to flatten the potential well and lengthen bunches which decreases the charge density and increases the lifetime for Touschek lifetime limited machines. The design and test of a 2 cell 1500 MHz cavity for bunch lengthening is presented.

Table 1: NSLS-II parameters.

Beam energy	3 GeV
RF frequency	500 MHz
Average Current	500 mA
Circumference	792 m
Harmonic number	1320
# cavities(500MHz single-cell)	4
# cavities(1500MHz two-cell)	2
Cryogenic temperature	4.5 K

1500 MHZ CAVITY RF DESIGN

The decision to use SRF passive cavities is based on the lower R/Q that can be achieved with their design which limits the transient induced by the ion clearing gap in electron storage rings [3]. An innovative approach with two coupled cells in a common cryostat was taken that allows very strong damping of HOM's and a room temperature external tuner in a relatively compact space. However, having the two coupled cells results in two fundamental modes, 0 and π. The unwanted 0-mode cannot be damped since the frequency separation between the zero and the pi mode is only 21 MHz, too close to easily filter. Since the mode spacing is fixed by the coupling we realized that careful control of the 0-mode in design and in operation would keep the 0-mode fields to acceptable levels. The excitation of the 0-mode is much less sensitive than the π-mode due to a couple of large factors that work in our favor. First is the careful design of the cavity geometry for minimum impedance of the 0-mode by adjusting the length of the two cells to get a near perfect cancelation of the 0-mode fields due to the transit time factor of the cavity. Second, the intensity of of the revolution lines in the vicinity of the zero mode are a factor of 30 less than near the 3rd harmonic RF line.

The design goal of the 1500 MHz harmonic cavity was to achieve an R/Q of the π-mode of < 90 ohms [3], an R/Q of the 0-mode of << 1 ohm and a large beam pipe diameter to reduce the wake field heating of the ferrite mode dampers to acceptable levels. These goals were achieved (Table 2) by taking the conceptual cavity design [4] and increasing the beam pipe diameter to 120 mm, increasing the iris between the cavities to 38 mm and iterating the cell lengths to reduce the 0-mode impedance. The cavity geometry is shown in Figure 1.

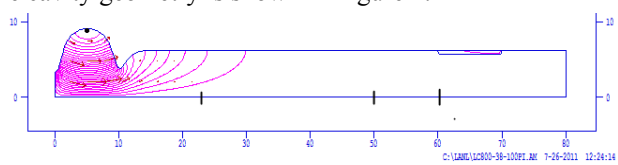


Figure 1: 1500 MHz cavity geometry with Nb-Cu interface (4K), 77K shield and 300K interface marked on axis.

Table 2: NSLS-II harmonic cavity parameters.

Freq(π-mode)	MHz	1499.25
R/Q (Pi)	Ω	88
Q_0	@4.5K	$2.6*10^8$
Accelerating Voltage	MV	1.0
Freq (0-mode)	MHz	1478.03
R/Q (zero)	Ω	0.15
Q_0	@4.5K	$2.7*10^8$

The cavity thermal design trade off was made by keeping the thermal heat leak to 4.5 K and the dynamic RF losses to the Cu plated stainless steel thermal transition to less than 10% of the superconducting RF dynamic losses. A thermal heat shield was incorporated at 50cm from the cavity center point. Figure 2 shows the power dissipated per segment as calculated by Superfish. Segments 1cm long starting at the Nb-Cu interface in the straight beampipe shows the power losses of the fundamental evanescent mode as it decays. The boundary between Nb and Cu is clearly seen at the end of segment

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DESIGN FOR MANUFACTURE OF SUPERCONDUCTING HALF WAVE CAVITIES*

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Abstract

322 MHz medium velocity half wave resonators (HWR) with β = *0.29* and *0.53* have been designed at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) for use in a heavy ion linac. The β = *0.29* and β = *0.53* are to provide $1.9MV$ and $3.7MV$ of accelerating voltage with a peak magnetic field of $54mT$ and $77mT$, respectively. The cavities are designed for a peak surface electric field of $30MV/m$. The cavities were optimized for manufacturing recommendations based on previous design as well as for stiffness, tunability, assembly, and cleaning. Finite element analysis simulations were performed for mechanical modal frequency analysis, liquid helium bath pressure sensitivity, Lorentz force detuning factor and mechanical force to complete the tuning range. The helium vessel, fundamental power coupler (FPC), and frequency tuner systems which interface to the cavity have been designed and prototypes fabricated.

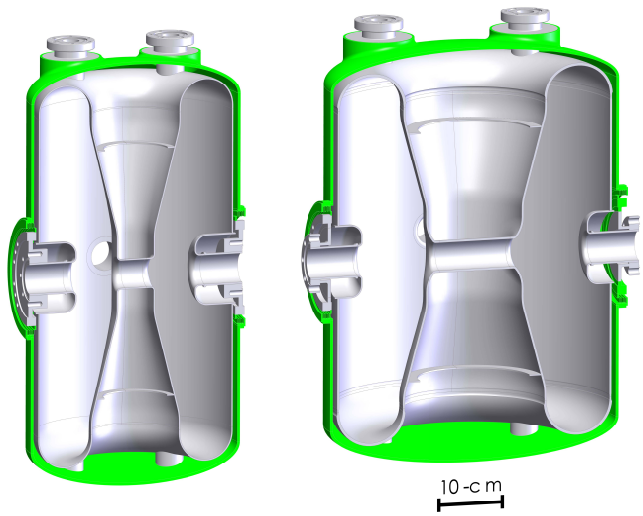


Figure 1: Optimized for production β = *0.29* and β = *0.53* resonators.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) located at Michigan State University (MSU) is funded by a joint agreement between the US Department of Energy (DOE) and MSU for the advanced study of rare isotope beams[1]. The driver linac for FRIB is a $200MeV/u$ superconducting linac with a final beam power of $400kW$[2]. The superconducting linac will be constructed using four types of resonators[3]. Two quarter wave resonators operating at *80.5 MHz* with optimized β = *0.041* and β = *0.085*, and two half wave resonators operating at *322 MHz* optimized for β = *0.29* and β = *0.53*, shown in Figure 1. This paper will discuss the latter cavity type. A total of five β = *0.53* prototypes have been fabricated, one by FRIB and four by two different sources in industry[4]. Results from vertical dewar tests are presented at this conference[5].

Input from industry after manufacturing prototypes suggested revisions to geometry that simplify mass manufacture. These suggested adjustments can affect rf and mechanical performance. Since FRIB will use approximately 225 half wave resonators, small changes can greatly reduce cost for the project; however, sacrificing rf and mechanical performance is not desired so optimization is needed.

OPTIMIZATION

The cavity mechanical design is strongly influenced by the design of the helium vessel, FPC, and frequency tuner systems shown in Figure 2. The design is similar for the β = *0.29* and β = *0.53* resonators. The optimization focused first on the satisfaction of electromagnetic performance and then on manufacturing and cost. A cylindrical section between the short plate and inner conductor was added to solve machining mismatch and welding difficulties encountered in the prototype. A conical inner conductor, with an elliptical cross-section, is implemented for manufacturing convenience where previously a three dimensional profile was used. Moreover, the design of the beam port cup includes a flat surface that allows frequency tuning by means of beam port deformation without exceeding plastic limits.

SRF Optimization

The performance of a SRF cavity is determined by the electric and magnetic fields on the cavity. Optimization of the cavity involves changing its geometry to lower the peak electric and magnetic fields while maintaining the required accelerating voltage. The geometry had several constraints to optimize manufacture. For both resonators it was determined that a cylindrical interface between the short plate and inner conductor would need approximately *9.5 mm* to

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STUDIES ON A PLUNGER TUNER SYSTEM FOR A DOUBLE SPOKE CAVITY MODEL

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Abstract

ESS-Bilbao proton linac warm section will end at 50 MeV. A cryomodule with two double spoke cavities, currently in R&D stage, will be tested at that energy. The two spoke cavity prototypes to be built will be fully compatible with the ESS project spoke cavities (β 0.57). Different tuning systems will be studied for ESS spoke resonators, and one alternative is the use of plunger tuners. In this paper, a study of this kind of tuners on DSR cavities is presented, including electromagnetic and thermal simulations. These results will be tested experimentally on the β 0.39 DSR aluminium model built at ESS-Bilbao within this year.

INTRODUCTION

ESS-Bilbao light ion linear accelerator [1,2] is conceived as a multipurpose machine that will be the core of a standalone accelerator facility in southern Europe and that fulfils the specifications for a driven injector for ESS.

In the present ESS-Bilbao linac design the normal conducting section ends at an energy of 50 MeV. A superconducting section will follow, and the first step is to build two prototypes of SC double spoke resonator cavities (DSR) and a cryomodule to test them with beam at 50 MeV.

The DSR cavity prototypes will be equivalent to the ESS project ones and will have the same RF design, increasing in this way the cavities statistics for this European project [3]. Apart from the RF design, other aspects of the cavity will be different in order to test diverse approaches to, for example, mechanical stiffening or tuner system.

During the last years spoke cavities have received an increasing interest for their application in high power proton linacs ([4,5]). About the frequency tuning system for these cavities, the usual approach has been to use cavity deformation. In addition to this conventional method, a niobium plunger tuning system will be considered for ESS and ESS-Bilbao prototypes. This method has been successfully designed and tested for Spiral-2 QWR cavities [6]. The plunger tuners must be built in niobium and kept at 4.2 K during operation.

In this report electromagnetic and thermal simulations results for a plunger tuning system in a DSR cavity are presented.

SIMULATION DETAILS

The electromagnetic design and simulations of the tuner have been done using the β=0.39 DSR cavity model made in aluminium in ESS-Bilbao [7]. The plunger tuning system will be tested at room temperature also in this cavity model.

Codes Accuracy

Numerical simulations have been done using COMSOL Multiphysics software [8]. As the accurate calculation of surface fields and frequencies is critical for the design process of the Nb plunger tuner, a benchmark of the simulation code has been performed, using the same procedure than K. Tian in [9], where simulation results obtained using different codes are compared with models with known analytical solution (a sphere of radius 10 cm). Our results are shown in Fig. 1. The obtained accuracy for frequency and for surface magnetic field is of the same order of the best results shown in [9].

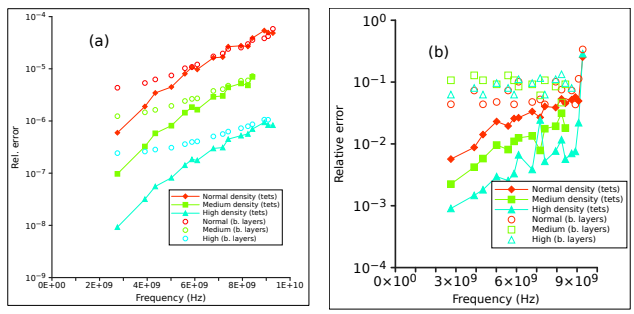


Figure 1: Accuracy of the numerical values of resonant frequencies and magnetic surface fields for a 10 cm radius sphere compared to analytical values. Accuracies are of the same order than the best reported in reference [10].

Simulations of Cavity with Tuners

General details on the model cavity modes and field profiles (numerical and measurements) have been described elsewhere [7]. All simulations have been done using COMSOL and MATLAB as scripting language. Plunger tuners are simulated as cylindrical volumes subtracted from the main vacuum of the cavity. The location of the plunger in the cavity is described for each of the cases studied.

DESIGN OF SUPERCONDUCTING PARALLEL-BAR CAVITIES FOR DEFLECTING/CRABBING APPLICATIONS*

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Abstract

The superconducting parallel-bar cavity is a deflecting/ crabbing cavity with attractive properties, compared to other conventional designs, that is currently being considered for a number of applications. The new parallel-bar design with curved loading elements and circular or elliptical outer conductors have improved properties compared to the designs with rectangular outer conductors. We present the designs proposed as the deflecting cavities for the Jefferson Lab 12 GeV upgrade and for Project-X and crabbing cavities for the proposed LHC luminosity upgrade and electron-ion collider at Jefferson Lab.

INTRODUCTION

A variety of superconducting parallel-bar cavity [1] geometries with rectangular, cylindrical and elliptical outer conductors and straight, curved bars have been analyzed [2, 3]. The geometry with a cylindrical outer conductor and trapezoidal shaped bars is proven to have better properties compared to other geometries in terms of lower and balanced surface fields and higher shunt impedance. The fundamental deflecting mode in the parallel-bar cavity which is used to deflect and crab the beam has a transverse electric field between the bars with magnetic field at top and bottom of the cavity as shown in Fig. 1.

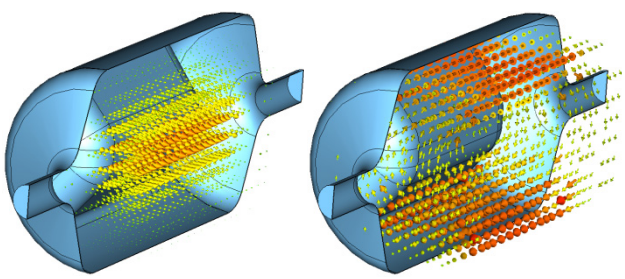


Figure 1: Electric field profile (left) and magnetic field profile (right) of the parallel-bar cavity.

This field orientation gives rise to surface electric fields on the bar surfaces and surface magnetic fields at top and bottom surfaces of the cylindrical outer conductor as shown in Fig 2. The trapezoidal shaped geometry of the bars allows reducing both surface electric field and magnetic field independently by varying the inner bar height and the slope of the bars connecting to the outer conductor.

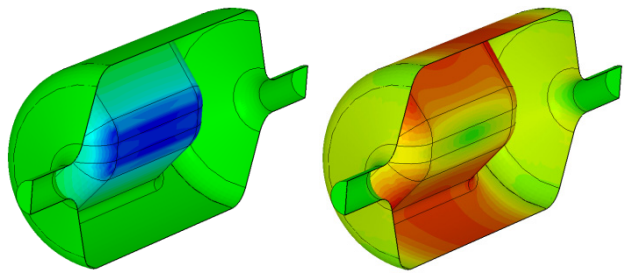


Figure 2: Surface electric field (left) and surface magnetic field (right) of the parallel-bar cavity.

Also this geometry has the fundamental deflecting mode as the lowest frequency mode. The parallel-bar cavity with trapezoidal shaped bars has wider mode separation in the higher order modes (HOMs) spectrum [3] making this geometry very attractive in HOM damping, especially in high current applications.

Currently the parallel-bar cavity is considered for two deflecting cavity and another two crabbing cavity applications. The major applications of the superconducting parallel-bar cavity are the 499 MHz deflecting cavity for the Jefferson Lab 12 GeV upgrade and the crabbing cavity for the proposed LHC luminosity upgrade operating at 400 MHz. These two designs are being optimized to meet the requirements and are in the initial phase of prototype fabrication. The parallel-bar cavity is also being considered for the 750 MHz crabbing cavity for medium energy electron ion collider (MEIC) at Jefferson Lab and the 365.625 MHz deflecting cavity for Project-X.

The parallel-bar designs for all the above mentioned applications are presented in this paper with detailed optimization and cavity properties.

PARALLEL-BAR CAVITY DESIGNS

499 MHz Deflecting Cavity

The 499 MHz deflecting cavity for the Jefferson Lab 12 GeV upgrade is required to separate the 5th pass beam of 11.025 GeV in to 3 beams, in order to deliver the maximum energy beam to the 3 experimental halls simultaneously. The required net deflection of a peak transverse voltage of 5.6 MV is applied to the bunches in the beam with a phase offset of $\pm 120^0$ to separate the beam to halls A and C, where the beam for hall B passes without any deflection. The dimensional constraints for

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SUPERCONDUCTING 112 MHZ QWR ELECTRON GUN*

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Abstract

Brookhaven National Laboratory and Niowave, Inc. have designed and fabricated a superconducting 112 MHz quarter-wave resonator (QWR) electron gun. The first cold test of the QWR cryomodule has been completed at Niowave. The paper describes the cryomodule design, presents the cold test results, and outline plans to upgrade the cryomodule. Future experiments include studies of different photocathodes and use for the coherent electron cooling proof-of-principle experiment. Two cathode stalk options, one for multi-alkali photocathodes and the other one for a diamond-amplified photocathode, are discussed.

INTRODUCTION

A quarter-wave resonator concept of superconducting RF (SRF) electron gun was proposed at BNL for electron cooling hadron beams in RHIC [1, 2]. QWRs can be made sufficiently compact even at low RF frequencies (long wavelengths). The long wavelength allows to produce long electron bunches, thus minimizing space charge effects and enabling high bunch charge. Also, such guns should be suitable for experiments requiring high average current electron beams.

A 112 MHz QWR gun was designed, fabricated, and cold-tested in collaboration between BNL and Niowave [3]. This is the lowest frequency SRF gun ever tested successfully. In this paper we describe the gun design and fabrication, present the cold test results, and outline our plans. This gun will also serve as a prototype for a future SRF gun to be used for coherent electron cooling of hadrons in eRHIC.

112 MHZ GUN DESIGN AND FABRICATION

The cavity geometry was designed using Superfish [4]. Figure 1 shows the model used to calculate the cavity RF parameters, summarized in Table 1. Since the fields will appear nearly electrostatic, a Pierce-type geometry (recessed cathode, as shown in the figure) can be used to focus the beam and compensate for the space charge of the high intensity electron beam. The Pierce electrode shape has higher electric fields away from the cathode, but these field levels are controlled in the design.

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE. Work at Stony Brook University is supported under grant DE-SC0005713 with the U.S. DOE. Work at Niowave is supported by the U.S. DOE under SBIR contract No. DE-FG02-07ER84861
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Table 1: RF parameters of the 112 MHz SRF gun cavity

Parameter	Value
Frequency	112 MHz
R/Q (linac definition)	126 Ohm
Geometry factor G	38.2 Ohm
Quality factor Q_0 w/o cathode insert	$> 3.5\times10^9$
Operating temperature	4.5 K
E_{pk}/V_{acc}	19.1 m^{-1}
E_{pk}/E_{cath}	2.63
B_{pk}/V_{acc}	36.4 mT/MV
Length	1.1 m
Aperture	0.1 m
Maximum diameter	0.42 m

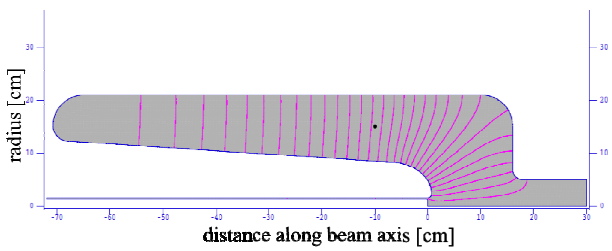


Figure 1: Cavity geometry used in Superfish calculations.

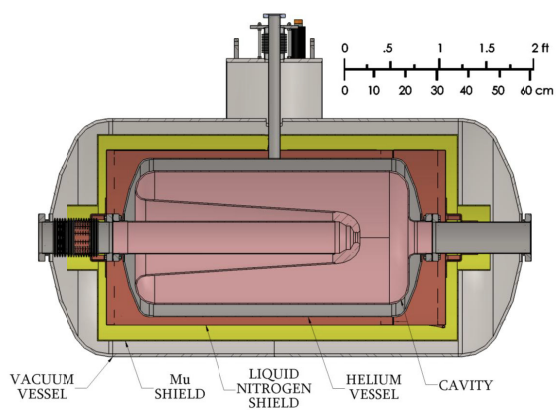


Figure 2: 112 MHz electron gun cryomodule.

SUPERCONDUCTONG RESONATORS PRODUCTION FOR ION LINACS AT MICHIGAN STATE UNIVERSITY

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Abstract

Superconducting quarter-wave resonators and half-wave resonators are being prototyped and fabricated at Michigan State University (MSU) in effort to support the Facility for Rare Isotope Beams (FRIB) project. FRIB requires a 200 MeV per nucleon driver linac, operating 341 resonators at two frequencies (80.5 and 322 MHz) and four betas (0.041, 0.085, 0.29, and 0.53). FRIB cavity development work is underway, with the prototyping of all four resonators, including helium vessel design, stiffening strategy, and tuner interface. In addition, the acquisition strategy for FRIB resonators is being finalized, and the technology transfer program is being initiated. The status of the resonator production effort will be presented in this paper, including an overview of the acquisition strategy for FRIB.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is an approved ~550M$ project funded by a cooperative agreement between Michigan State University (MSU) and The US Department of Energy (DOE) for advancement in the study of rare isotopes. The driver linac for the FRIB project is a 200 MeV/u superconducting linac with final beam power reaching 400 kW. There are four types of resonators used; two quarter-wave resonators (80.5 MHz, β = 0.041 & 0.085) and two half-wave resonators (322 MHZ, β = 0.29 and 0.53) [1]. The resonators are housed in rectangular, bottom loaded cryomodules with internally built focusing solenoids. In total, the FRIB linac will require 341 superconducting cavities, housed in 51 cryomodules.

FRIB continues to advance the design of the four cavities to be used in the FRIB driver linac. The cavity acquisition plan is in place with requests for proposals submitted to cavity vendors. FRIB will select vendors early in the project and work with the awarded vendors through development to production.

CAVITY ACQUISITION PLAN

A Request For Proposal (RFP) will be submitted for each of the four FRIB cavities. The RFP will lay out a path to production in three stages: fabrication of two complete cavities, a production run of 10 cavities, and final production of required number of cavities. Early vendor selection allows the FRIB project time to work with vendors and develop cavity fabrication procedures to ensure cavity quality and production rates. The first stage will require vendors to fabricate two cavities. The vendors will be supplied a cavity design based on the prototyping efforts prior to the RFP; as discussed further in the CAVITY STATUS section. Vendors will fabricate two complete cavities, working with FRIB technical staff to work through final frequency measurements and positioning. Stage one cavities will be fabricated with out helium vessels.

Stage two will require the fabrication of a small production run of 10 cavities. Cavities will be built to completion including helium vessels. It is also FRIB's desire to have cavity vendors perform the bulk chemical treatment to completed cavities. This will be handled as part of a separate RFP. Stage two also allows an opportunity to implement any necessary design changes realized in Stage one fabrication, as agreed upon by FRIB and vendor.

Stage three signifies the start of FRIB cavity production. Cavity fabricated during this stage will be shipped to FRIB and sequenced for cavity certification. Vertical test certification of FRIB cavities is required for all cavities prior to cold-mass assembly. Cavities will be inspected and tested real time with vendor delivery to ensure no deviations from production drawings and cavity performance.

Vendors will be required to fabricate all required dies and tooling to produce the awarded cavities at the agreed upon production rate. All high RRR niobium (>250) and helium vessel transition materials will be supplied by FRIB. FRIB scheduling will require vendors to supply cavities at a rate of 12 per month. This rate will support a cryomodule production schedule of two units per month. Cavity production will span 36 months with a 6 month ramp up. Production of Stage one cavities (two units) is scheduled to begin Q4 2011 with Stage three production to start in Q4 2013.

CAVITY STATUS

Prior to the RFP release, cavity development research initiated with the fabrication of 11 quarter-wave, beta=0.085 and 5 half-wave, beta=0.53 cavities. These cavities were fabricated using a step by step approach where commercial vendors were contracted to supply only cavity subassemblies. After receipt of the subassemblies, stack-up frequency measurements were completed by FRIB personnel. The subassemblies were

BEAM BREAK-UP STUDIES FOR CORNELL'S ENERGY RECOVERY LINAC*

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Abstract

New results are presented of beam break-up (BBU) studies for the Cornell ERL main linac. Previously, a 1.3 GHz main linac 7-cell cavity was optimized to maximize the BBU current through the accelerator. This work realistically models the ERL main linac cavity shapes by taking into account small machining variations in ellipse dimensions. Cavity shapes were simulated with random errors from a uniform distribution, and their higher-order mode spectrum computed. The strongest higher-order modes can cause resonant excitations in the beam which can lead to beam loss. The threshold current through the accelerator is determined resulting from a linac comprised of cavities with machining variations using particle tracking and demonstrates that the threshold current is well above the 100 mA design goal for the Cornell's Energy Recovery Linac.

INTRODUCTION

Beam break-up (BBU) current is the maximal current that can travel through an accelerator before the beam becomes unstable and is lost. Primary contributors to this effect are dipole higher-order modes (HOM) in the superconducting cavities that give transverse kicks to off-axis particles. For the first time we present a detailed simulation of realistic cavities in the latest lattice for the Cornell ERL and compute the threshold current that is attainable as a function of expected fabrication tolerances. This is important to ensure that the linac can support the design current of 100 mA [1].

Previous work optimized a superconducting 1.3 GHz 7-cell main linac cavity with respect to the BBU current through the accelerator. We demonstrated that BBU current is related to the worst higher-order mode's (HOM) figure of merit

$$\xi_\lambda = (R/Q)_\lambda \frac{\sqrt{(Q_L)_\lambda}}{f_\lambda}, \qquad (1)$$

where λ is an index across HOMs [2].

In reality, cavities can not be made to conform ideally to the optimized geometry, nor should they be. Slight shape variations that arise from small machining errors cause a spread in HOM frequencies that can have the desired effect of reducing coherent kicks given to the beam by multiple cavities. Reducing coherent HOM excitation in multiple cavities increases the BBU current. However, cell shape errors can have the highly undesired effect of increasing the R/Q and/or Q_L of some of the HOMs. In extreme cases, modes can even become trapped with very high Qs. Thus, it is necessary to ensure that shape variation introduced by machining tolerances are large enough to introduce frequency spread that yields high BBU current, but not so large that they cause strong adverse effects on the HOM R/Q, Q_L or lead to trapped modes.

Previous investigations into shape variations showed even very small machining perturbations can lead to very poor HOM properties, but this was overcome by introducing a more robust center cell shape and increasing the cell-to-cell coupling in the structure [3]. In another example, the ERL at Jefferson lab was limited to low BBU current due to a single cavity with a large shape error [4], demonstrating why it is essential to understand and carefully control machining errors.

METHODS

Shape variations in the optimized 7-cell cavity geometry were simulated by adding random errors to each ellipse parameter from a uniform distribution for the error cases of $\pm 1/8$, $\pm 1/4$, $\pm 1/2$ and ± 1 mm. These resulting cavity shapes were tuned cell by cell to 1.3 GHz to ensure field flatness. Subsequently the dipole mode spectrum was calculated up to 10 GHz, using 4 boundary conditions at the at the center plane of the HOM beamline absorbers at the ends of the cavity beamtubes (electric-electric, magnetic-magnetic, electric-magnetic and magnetic-electric) to simulate the superposition of HOMs that are possible for a cavity in a long cavity string.

In this way, 400 unique cavities were generated per error size, and 384 cavities were randomly placed into the Cornell ERL lattice (version 8.4). The HOMs for each cavity were chosen as the 5 modes with the largest BBU parameter, ξ. These HOMs were included in two polarizations. Finally 100 different ERLs were simulated by placing these cavities at random locations.

Particle tracking was done with a subroutine based on BMAD that calculates the maximum current that can be supported through the ERL [5]. Since each cavity is unique, no artificial frequency spread is introduced into the simulation. The only source of frequency spread in our simulations is in the differences in HOM mode variations arising from machining errors.

RESULTS

The results of the 400 BBU calculations (100 simulated ERL runs/error size) are presented in Figs. 1–4. In the optimized cavity geometry, the strongest mode limiting thresh-

* Work Supported by NSF award DMR-0807731 and Cornell University.

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COUPLER KICK STUDIES IN CORNELL'S 7-CELL SUPERCONDUCTING CAVITIES*

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Abstract

Cornell is developing a 5 GeV Energy Recovery Linac operating at 100 mA with very small emittances (∼30 pm at 77 pC bunch charge) in the horizontal and vertical directions. We investigate the effect of the fundamental RF power couplers of the main linac SRF cavities on the beam using the ACE3P software package. The cavities in the ERL main linac will be operated at very high loaded quality factors of up to 6.5×10^7, corresponding to a full bandwidth of only 20 Hz. Cavity microphonics will detune the cavities by more than one bandwidth during operation, thereby causing a time dependent change of the coupler kick in addition to its fast oscillation at the RF frequency. We show that a compensation stub geometry located opposite to the input coupler port can be optimized to reduce the overall kick given to the beam and the emittance growth, but for the Cornell input coupler geometry is satisfactory without a compensation stub. Finally, our calculation of the coupler kick as a function of detuning shows the necessity of operating within the designed microphonic limits.

INTRODUCTION

This paper presents work that for the first time calculates the time dependent coupler kick on a bunch in a beam as a function of RF cavity detuning. Understanding this effect is very important to ensure that the beam emittance in Cornell's Energy Recovery Linac (ERL) remains small (∼30 pm-rad at 77 pC bunch charge)[1].

The fact that these simulations are done as a function of detuning is of central importance because ERLs operating detuning is large ($\Delta f/f_{1/2} \geq 1$).

Previous work optimized a superconducting 1.3 GHz 7-cell main linac cavity with respect to the beam break-up current through the accelerator[2]. To this design, a fundamental power coupler was added with $Q_{ext} = 6.5 \times 10^7$. The effect of the coupler on the beam has previously been explored with Microwave Studio for the case of on resonance excitation.[3] However, due to the required sensitivity, and the need to compute the kick as a function of detuning, we used SLAC's ACE3P software suite for these simulations.[4]

It has also been shown that the coupler kick effects can be mitigated by introducing a compensation stub directly opposite the coupler to reduce asymmetry in the coupler region.[3] Cavity geometries with and without a compensation stub are shown in Figs. 1–2.

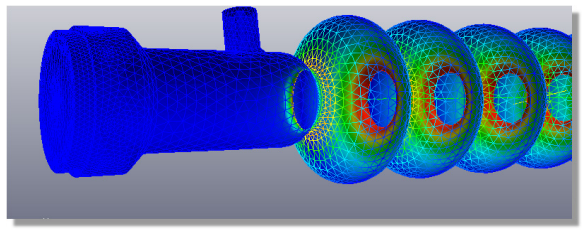


Figure 1: View of 7-cell cavity coupler region of a model without a compensation stub. The mesh coloring corresponds to electric surface field intensity.

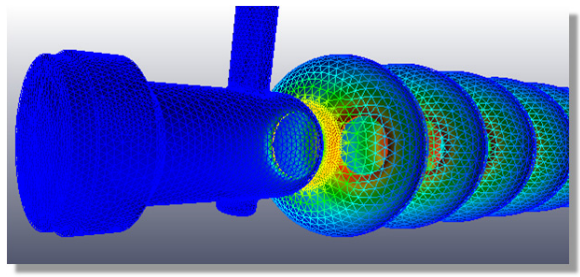


Figure 2: Model of 7-cell coupler region with a short compensation stub diametrically opposing fundamental power port. Mesh coloring corresponds to electric surface field intensity.

To investigate the minimization of bunch kicks due to the fundamental power coupler, we investigate the maximum normalized coupler kick as a function of stub height by either increasing or decreasing the height of the compensation stub, as illustrated in Fig. 3.

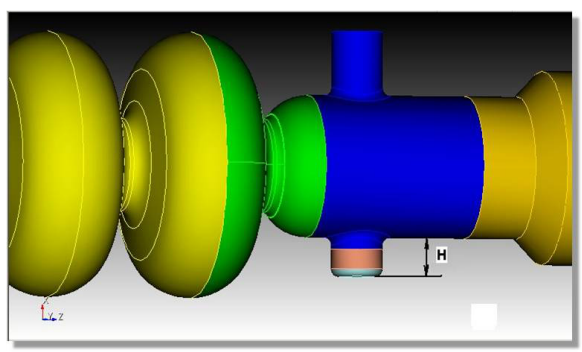


Figure 3: Coupler region of 7-cell cavity geometry. Orange cylinder illustrates method used to tune the compensation stub height, by an additional amount H.

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ANALYSIS OF BEAM DAMAGE TO FRIB DRIVER LINAC*

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Abstract

Damage caused by the particle beam is an important issue in a superconducting linac. The FRIB driver linac will deliver a beam on target about 1 mm in diameter, increasing beam power density significantly compared to other SRF linacs. Because the stopping power of a heavy ion beam is a few ten times larger than proton or electron beam, the situation is more severe: at full power, 400 kW, a uranium beam may cause component damage in less than 40 μs. A fast response machine protection system is necessary, in addition to special protection design, very careful linac beam tuning and operation. In this paper, the temperature rise of niobium and stainless steel at different beam incident angles are compared, and thermal stress analyzed for nominal FRIB beam at different energies. Some protection designs are also briefly discussed.

INTRODUCTION

The Facility for Rare Isotope Beam (FRIB) is currently under construction at Michigan State University (MSU), which also hosts the largest campus-based nuclear science facility in the U.S.A – The National Superconducting Cyclotron Laboratory. As a national user facility, FRIB is funded by Department of Energy (DOE). It will provide intense beams of rare isotopes for ions up to uranium for nuclear physics and nuclear astrophysics research. FRIB is based on a heavy ion superconducting driver linac which will deliver a minimum energy of 200 MeV/u for uranium at a beam power of 400 kW. The facility includes the driver linac, a production target, an in-flight fragment separator, gas-stopping stations, and a re-accelerator for fast, stopped and reaccelerated rare isotope beams [1].

As high beam power and SRF techniques are involved, component damage caused by particle beams is a concern. The issues not only include normal operations with excessive beam halo and loss in a limiting beam aperture, but also include any accelerator subsystem failure which redirects high power beams to a component other than the target. Both occasions are not expected to be rare in routine operations. In this paper, we analyze beam heating and thermal stress in stainless steel and niobium when hit directly by a nominal FRIB beam, and compare different machine protection system requirements.

BEAM HEATING

Beam heating is calculated by Monte-Carlo simulation of stopping power dE/dx in niobium and in stainless steel with the SRIM code [2] first, then we use a nominal beam size, rms radius 1 mm, and a nominal current to compute beam deposited power density in the materials. Finally, the data is entered into a finite-element code ANSYS [3] to compute temperature rise versus the beam heating time.

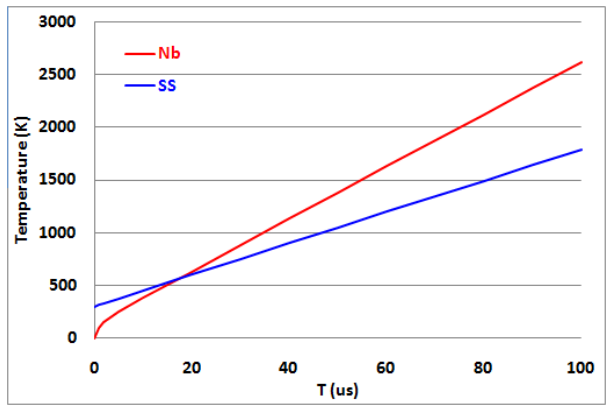


Fig. 1: Temperature vs. time of stainless steel (SS) from 300K, and niobium (Nb) from 2K, after hit by a uranium beam, 100 MeV/u, 200 kW, and beam rms radius 1 mm.

Figure 1 shows the temperature rise of stainless steel (SS, from 300K) and niobium (Nb, from 2K) after being hit by a uranium beam, 100 MeV/u and 200 kW, at 90° incident angle. In about 100 μs, both materials reach their melting points, which means component damage could happen in a shorter time. An argument is that it could be rare for a beam hit a surface at 90°, unless intentionally on a target, or accidently on a valve. However, if we ignore scattering and reflecting of particles when beam hits a surface at a large grazing angle, which is very close to the case for a heavy projectile at low energy, the relationship between incident angle and damage time is weak.

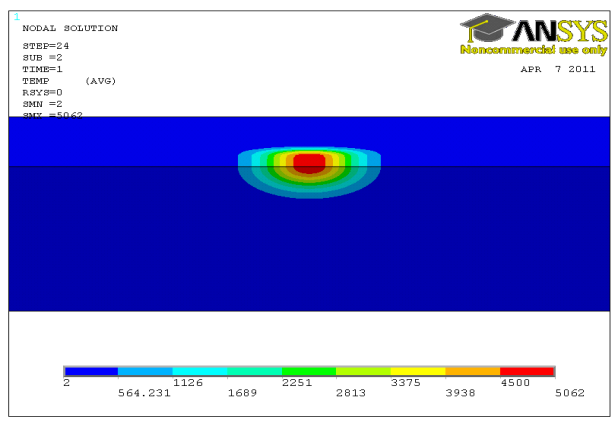


Fig. 2: Temperature of niobium, hit with a uranium beam at a 90° incident angle, after irradiation of 200 μs.

Figure 2 shows a temperature distribution of niobium after 200 μs irradiation with 100 MeV/u, 200 kW uranium beam at a 90° incident angle. Figure 3 shows that of a 15° incident angle. In reality, we could not heat niobium above its melting or boiling point, 2750 and 5017 K. Simulations are shown here only to demonstrate the

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HIGHER ORDER MODES FOR BEAM DIAGNOSTICS IN THIRD HARMONIC 3.9 GHZ ACCELERATING MODULES*

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Abstract

An international team is currently investigating the best way to use Higher Order Modes (HOM) for beam diagnostics in 3.9 GHz cavities. HOMs are excited by charged particles when passing through an accelerating structure. Third harmonic cavities working at 3.9 GHz have been installed in FLASH to linearize the bunch energy profile. A proof-of-principle of using HOMs for beam monitoring has been made at FLASH in the TESLA 1.3 GHz cavities. Since the wakefields generated in the 3.9 GHz cavities are significantly larger, their impact on the beam should be carefully minimized. Therefore our target is to monitor HOMs and minimize them by aligning the beam on the cavity axis. The difficulty is that, in comparison to the 1.3 GHz cavities, the HOM-spectrum is dense, making it difficult to identify individual modes. Also, most modes propagate through the whole cryo-module containing several cavities, making it difficult to measure local beam properties. In this paper the options for the HOM-based beam position monitors are discussed.

INTRODUCTION

Higher Order Modes (HOM) are electromagnetic eigenmodes excited by charged particle bunches passing through accelerating structures. They can damage the beam quality, but can also be used to measure beam properties, for example its transverse position.

This paper presents the concept and options of HOM-based beam position monitors (HOM-BPMs) for the superconducting 3.9 GHz cavities at the Free-electron LASer in Hamburg (FLASH).

FLASH

FLASH is a self-amplified spontaneous emission free electron laser delivering ultra-short laser-like pulses with a wavelength between about 4.5 and 47 nm [1,2]. It is a user and a test facility. Fig. 1 shows the main components of the linac. A photoelectric gun generates trains of electron bunches. The charge of each bunch is between 100 pC and 1 nC. The pulses are up to 800 µs long and have a repetition frequency of 10 Hz. The bunch repetition frequency within the pulses is up to 1 MHz.

The electrons are accelerated to up to 1200 MeV by 7 accelerating structures (cryo-modules), each containing eight super-conducting 1.3 GHz TESLA cavities. Two bunch compressors reduce the length of each bunch to the order of hundreds of femtoseconds. Four 3rd harmonic cavities working at 3.9 GHz are used to linearize the longitudinal phase space. The beam passes through transverse and energy collimators and then produces laser pulses in special undulators. The photons continue to the FEL experimental hall, while the electron beam is sent to the dump. A bypass is used to protect the undulators during special experiments. sFLASH is a seeded experiment.

3rd Harmonic Cavities

Just behind the first accelerating module, cryo-module ACC39 containing the four 3rd harmonic superconducting cavities is located. These are shown schematically in Fig. 2. Each 9-cell cavity has at one side a power coupler and at each side a HOM coupler, extracting power from the beam-excited fields, other than the fundamental mode at 3.9 GHz.

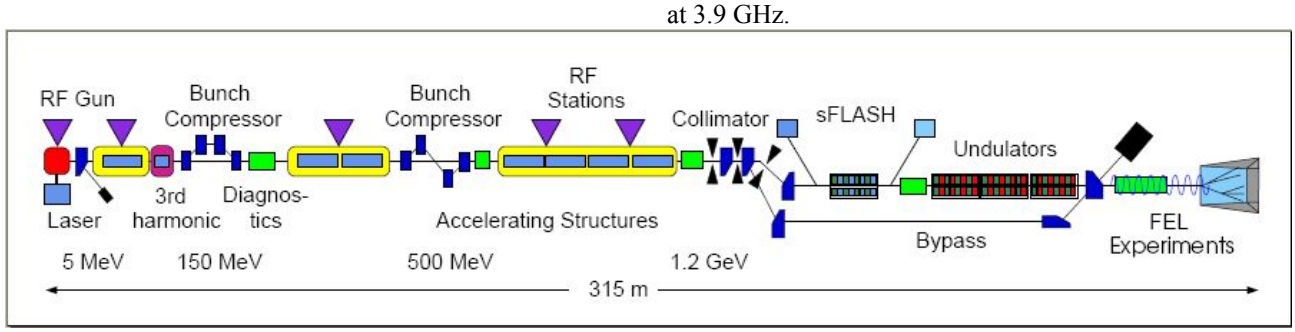


Figure 1: Layout of the FLASH linac [2].

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EFFECTS OF ELLIPTICALLY DEFORMED CELL SHAPE IN THE CORNELL ERL CAVITY

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Matthias Liepe, Nicholas Valles, Cornell University, Ithaca, NY, U.S.A.

Abstract

The Cornell ERL cavity is optimized to minimize the dipole mode beam breakup (BBU) parameters to achieve the required high beam current (100mA). Deformations due to errors in fabrication and tuning of the accelerating mode can result in a cavity shape different from the ideal. Elliptically deformed cells can cause dipole mode frequency spread and splitting of the mode polarizations leading to an x-y mode coupling. To investigate these effects, we use a mesh distortion technique to generate an elliptically deformed cell cavity model as a base for studying random imperfections. Simulation results of 50 randomly elliptically deformed cell cavities from the eigensolver Omega3P covering the first three dipole bands will be presented. The results will be used as input to the beam tracking code BMAD to calculate the impact of such imperfections on the dipole mode BBU parameters.

INTRODUCTION

Cornell has proposed a 5 GeV superconducting (SC) energy recovery linac (ERL) light source design, which can provide a high average current of 100mA with low emittance of 30pm-rad at 77pC bunch charge [1]. Because the achieved high current is limited by the dipole modes excited by the beam in the linac cavities, the Cornell 7-cell SC cavity, working at 1.3GHz, is carefully optimized to minimize the dipole mode BBU parameters measured by $\xi \equiv (R/Q)\,\mathrm{sqrt}(Q)/f$ to suppress beam instabilities [2].

However, due to errors in cavity fabrication and tuning of the accelerating mode, the actual dipole mode properties differ from those of cavities with the nominal dimensions. Figure 1 shows an example of actual dipole mode measurements for the first two dipole bands in the eight cavities of the TTF Module 5. In general, the dipole mode frequencies spread and are shifted to lower values, the mode splitting is larger than expected, and the Qext's have a larger scatter. Therefore, it is essential to determine the threshold current including the effects of varying dipole mode parameters in the Cornell ERL SC cavities.

All SC cavities are fabricated and prepared following the same procedures, and thus the nature of the imperfections is similar. Cavity imperfection models can be generated for five types of deformations (Figure 2) using a mesh distortion method [3]. The first three types of deformations had been investigated using 2D finite element codes CLANS/CLANS2 [2]. Cavity shapes with tiny bumps/dents can only cause field enhancement which affect the fundamental mode performance without much impact on the dipole mode properties [4].

Elliptically deformed cell imperfections can cause the dipole mode frequencies spread and splitting of the dipole mode polarizations. The mode frequencies spread can help suppress the wakefield accumulation in the linac, but the mode polarizations varying will lead to an x-y mode coupling. In this paper, we will investigate the effects of elliptically deformed cell shapes on the dipole modes in the Cornell ERL cavity.

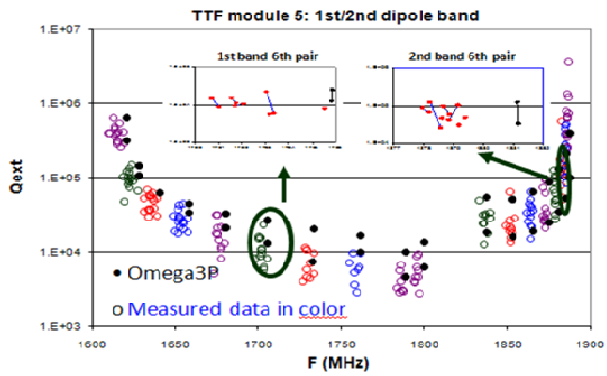
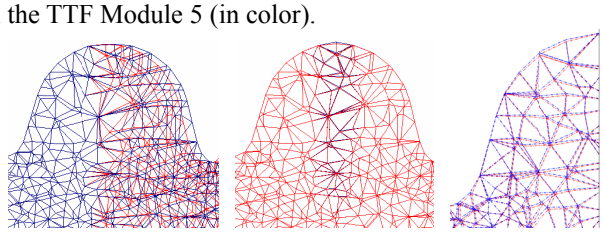
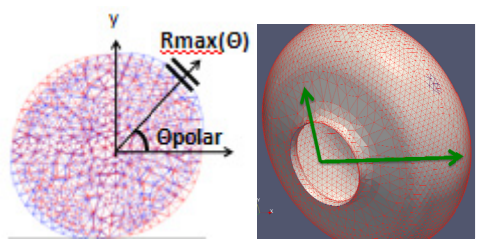


Figure 1: Comparison between ideal cavity results from Omega3P (black dots) and measurements from 8 cavities in the TTF Module 5 (in color).



(1) cell length error (2) Cell radius error (3) Deformed cell surface



(4) Elliptically deformed cell (5) Cell with bump

Figure 2: Meshes for imperfect models with ideal cell in red and deformed cell in blue.

BEPCII SRF SYSTEM OPERATION STATUS

Y. Sun, G.W. Wang, W.M. Pan, J.P. Dai, Z.Q. Li, H.Y. Lin, Q. Ma, P. Sha, S.P. Li, Z. Zhang, Y.P. Liu, Q.Y. Wang, B. Xu, T.M. Huang, H.M. Qu, G. Li, L.P. Yang, M.C. Zhan, Y.L. Yu, F. Qiu,
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Abstract

Two cavities of 499.8MHz have been operated for BEPCII since 2006. The maximum beam power is over 120kW for both cavities. In collision mode, Helium gas pressure only increases with beam current in one cavity. Beam tests have been taken to search for the reason, such as measuring HOM power, optimizing orbit. A brief introduction of the research is given below.

INTRODUCTION[1]

BEPCII[2] is a double ring e+/e- collider and also a SR light source. Typical parameters achieved of SRF system is listed in table 1. Two Superconducting Cavities, East and West cavity are installed at the outer Rings of electron Ring (BER) and positron ring (BPR), and respectively symmetric beside the beam crossing point. In SR mode, e- beam runs along the outer Rings. In collision mode, e+ and e- beam are separated in vertical crossing, as shown in Fig. 1 and Fig. 2. Both beams are injected with full energy.

Table 1: Typical operation parameters achieved

Parameters	Collision mode BER & BPR	SR mode BSR
Beam energy (GeV)	2×(1.89~2.0)	2.5
Beam current (mA)	2×750	250
Bunch number	2×(80~88)	160
RF voltage (MV)	1.65 /Ring	1.90
Beam power (kW)	2×120	92
U_0 (KeV)	121~152 / Ring	334
f_{rf} (MHz)	499.8	499.8
Circumference (m)	237.53 /Ring	241.13
Harmonic number	396 /Ring	402
α_p	0.0237	0.0142
Cavity numbers	2×1 /Ring	1
Cavity detune angle	-12^0 /cavity	0^0
Coupler DC bias (kV)	+1.5	+1.5

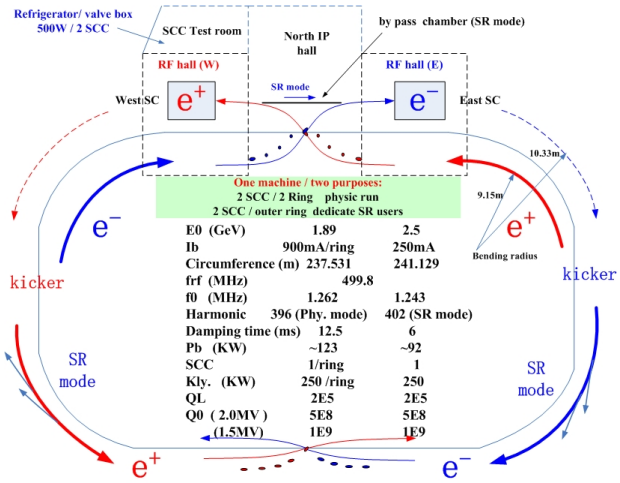


Fig. 1: Two SRF stations of BEPCII.

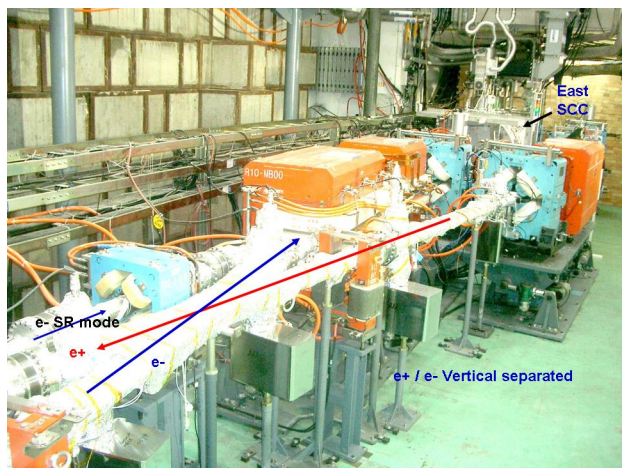


Fig. 2: Beam crossing nearby cavities.

RECENT OPERATION

From Sep. 2010 to Jul. 2011, the operation of SRF system of BEPCII is shown in table 2.

Table 2: Operation status of SRF of BEPCII

E_0 (GeV)	1.89/Ring	2.0/Ring	2.5
Run days	180	29	102
Beam curr.(mA)	2*750	2*750	250
Beam power(kW)	2*100	2*120	92
RF voltage (MV)	2*1.60	2*1.65	1.90

Beam Current and RF Power

HOM MEASUREMENTS WITH BEAM AT THE CORNELL INJECTOR CRYOMODULE*

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Abstract

The Cornell ERL injector prototype [1] is undergoing commissioning and testing for running unprecedented currents in an electron cw injector. This paper discusses preliminary measurements of HOMs in the injector prototype's superconducting RF cryomodule. These include HOM spectra up to 30 GHz measured via small antennae located at the HOM beam line absorbers between the SRF cavities. The spectra are compared at different beam currents and repetition rates. The shape of the spectra are compared to ABCI simulations of the loss factor spectrum of the cryomodule beam line. The total HOM power dissipated in the HOM loads was also measured with beam on, which allowed for an estimate of the loss factor. This measurement was accomplished via temperature sensors on the loads, calibrated to input power by heaters on the loads.

INTRODUCTION

At Cornell University, an accelerator designed to sustain a 100 mA electron beam cw is being commissioned as an injector to an Energy Recovery Linac (ERL). The beam is generated by a DC photogun, compressed with a buncher cavity, and then accelerated to 5.5-15.5 MeV by five two-cell 1.3 GHz superconducting cavities contained in the injector cryomodule (ICM). The short bunch length ($<$1 mm) and high current generate significant power in undesirable higher order modes (HOMs) up to tens of GHz, which is intercepted in HOM beam line absorbers located between SRF cavities [2]. The layout of the ICM beam line can be seen in Fig. 1 (next page). The strong HOM power generated in the ICM provides a unique opportunity to perform experimental HOM studies. This paper presents observations of the effect of varying beam parameters on HOM excitation in the cryomodule. The results are preliminary, meant to show the feasibility of the measurement methods at beam parameters not yet at the design specification.

MEASUREMENT

The HOM absorbing system of the ICM consists of six HOM loads placed between between subsequent cavities and at either end of the cavity string. The HOM loads, depicted in Fig. 2, absorb power in RF-lossy absorber tiles which are cooled with 80 K high pressure helium gas. The loads each have 8 pickups installed near the tiles, as well as thermometers and resistive heaters outside the beam line.

* Work supported by NSF Grant No. PHY-0131508 and NSF/NIH-NIGMS Grant No. DMR-0937466.

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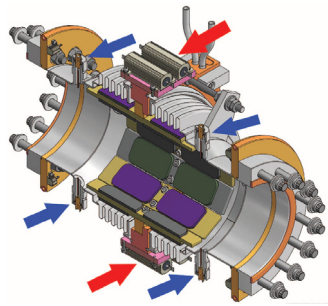


Figure 2: Cut-away view of HOM absorber section with RF probes (blue) and calibration heaters (red) indicated.

HOM spectra were obtained by connecting a spectrum analyzer to one of these pickups and measuring incident power over frequencies from 0-50 GHz. A typical scan requires several minutes of uniform beam and has a resolution of approximately 50 kHz. The coupling stregth of the pickup used and the losses in the RF cables inside the cryomodule could not be measured directly, so they were estimated by measuring transmission loss between pickups on opposite sides of an HOM load and then dividing by two. As an example, a spectrum measured at 2.0$\pm$0.1 mA and 50 MHz bunch repetition rate is shown in Fig. 3. The integrated spectrum is plotted on the same graph, illustrating the contribution to total HOM power at different frequencies.

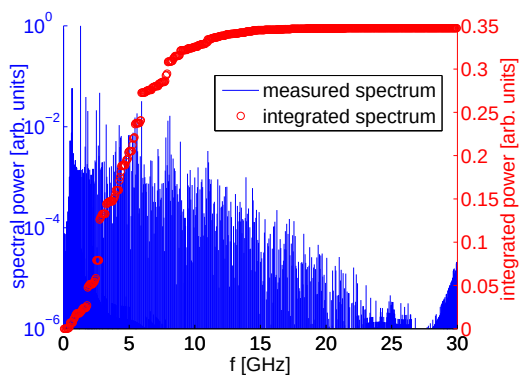


Figure 3: HOM spectrum measured at one of the HOM loads. The integrated spectrum is plotted on the secondary axis. Above 30 GHz only noise is measurable.

Observe that HOMs with frequency $>$15 GHz contribute negligibly to the total power and that certain stronger modes cause large jumps in the integrated spectrum. However, there are no very strong lines present in the spectrum, which one would expect to see in the case of a resonant excitation of an HOM with higher Q. This shows excellent

ADAPTIVE LORENTZ FORCE DETUNING COMPENSATION IN THE ILC S1-G CRYOMODULE AT KEK

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Abstract

The recent tests of the S1-Global [1] cryomodule at KEK provided a unique opportunity to compare the performance of four different styles of 1.3 GHz SRF cavities and tuners under similar operating conditions. An adaptive Lorentz Force Detuning (LFD) compensation system deployed at KEK successfully reduced LFD from between 100 to 700 Hz at the maximum gradient to better than 20 Hz for all four of the cavity types tested.

INTRODUCTION

As a part of ILC Global Design Effort, the S1-Global Cryomodule was built and installed at KEK by groups from KEK, in Japan, DESY and INFN in Europe and FNAL and SLAC in the USA.

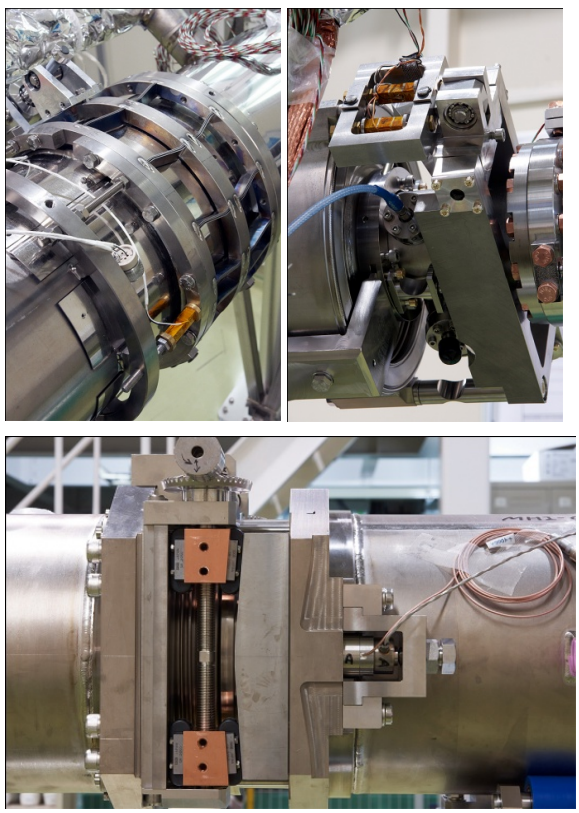


Figure 1: S1-G Cavity Tuners; a) INFN Blade Tuner/FNAL Cavity, b) Saclay Tuner/DESY cavity, and c) KEK Slide Jack Tuner/KEK cavity.

*This manuscript has been authorized by Fermi Research Alliance, LLC under Contract N. DE-AC02-07CH11359 with U.S. Department of Energy.
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One aim of the S-1G project was to compare the static and dynamic detuning performance of different candidate designs for the 1.3GHz 9-cells SRF elliptical cavities ILC cavities. S1-G contained a total of eight cavities, two each of four distinct designs as outlined in Table 1. The four cavity designs differ significantly in the mechanical response to the Lorentz force and to the piezo actuator and each of the four different tuners was designed to provide appropriate static and dynamic tuning ranges for their respective cavities.

Two independent methods were successfully employed to compensate for Lorentz force detuning in the S1-G cavities.

The first method employed the standard approach of exciting the piezo actuator with a half cycle of sine wave prior to the arrival of the RF pulse. The duration, delay and amplitude of the half sine wave are optimized manually by trial and error. The results of those tests are described in detail elsewhere [2,3].

The second method used an adaptive feed-forward algorithm based on least-squares to automatically determine an optimal waveform for each individual cavity. The results of these measurements are described below.

ADAPTIVE LFD COMPENSATION

A LFD control system built at FNAL was delivered and commissioned at KEK during the S1-G LFD studies. The system implemented an adaptive feed-forward algorithm that has been described in detail elsewhere [4].

The 10 MHz IF signals from S1-G the cavities were recorded using 100 MHz ADC and digitally converted to baseband. The baseband signals were then corrected for contamination and used to estimate the cavity detuning during the course of each RF pulse.

Prior to compensation, the mechanical response of each individual cavity was characterized by driving the piezo with a sequence of impulses from 10 ms prior to the arrival of the RF pulse to 10 ms after while recording the resulting detuning. The results of this procedure effectively measure the piezo to detuning impulse response over a 20 ms window centred on the RF pulse.

SCREAMm – MODIFIED CODE SCREAM TO SIMULATE THE ACCELERATION OF A PULSED BEAM THROUGH THE SUPERCONDUCTING LINAC*

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Abstract

The code SCREAM [1,2] – **S**uper**C**onducting **RE**lativistic particle **A**ccelerator si**M**ulation was significantly modified and improved. Some misprints in the formulae used have been fixed and a more realistic expression for the vector-sum introduced. The realistic model of Lorentz-force detuning (LFD) is developed and will be implemented to the code. A friendly GUI allows various parameters of the simulated problem to be changed easily and quickly. Effective control of various output data is provided. A change of various parameters during the simulation process is controlled by plotting the corresponding graphs "on the fly". A large collection of various graphs can be used to illustrate the results.

KEY FEATURES OF THE CODE

Code SCREAMm is used for the simulation of the longitudinal beam dynamics in a superconducting linac. To optimize the acceleration of a beam passing through a string of superconducting cavities the control of the phases and amplitudes of the RF fields in the cavities is required. This is particularly true in a section of the linac, where the beam velocity changes continuously, while the cavity-β changes (only in a few discrete steps in a case of low beta sections). The RF control system becomes more complicated in the typical case in which multiple cavities are driven by one klystron. The changing beam velocity also results in increasing beam loading along the cavity string. It demands additional adjustment of the cavity fields. In addition, superconducting cavities are very susceptible to deformations of their shape caused by electromagnetic pressure (Lorentz-force detuning) and microphonics. Other effects which have to been taken into account include incoming beam energy/phase jitter, particle distributions in the bunch over energies and phases. All these and some other effects were taken into account in the code to design the realistic RF control system.

The SREAMm program is a tool to calculate the optimal phase and amplitude settings for the superconducting cavities in a linac. It implements fast RF control techniques such as vector-sum regulation feedback. The earlier version contained a possibility to simulate fast ferrite vector-modulators [3] as part of the control system for Fermilab proton driver [4]. Each run in SCREAMm calculates the acceleration of the beam in one beam RF pulse. Several runs can be collected in one "file". The beam pulse (or run) contains many bunches. The beam pulse consists of two parts: cavity filling and flat-top interval. Obviously, the beam is launched only once filling is completed. To limit computing time, the particles in the bunch are regrouped into macro-particles, which have the mass and charge proportional to the sum of the particles in them but are regarded as single particles during the simulation of the acceleration process in the linac. The exact number of single particles contained in each macro-particle is taken into account when the beam loading is calculated. The macro-particles are distributed in longitudinal phase-space so as to simulate the distribution of the particles in a real bunch. Although more granular, bunches in the SCREAMm occupy more or less the same footprint in phase-space as the real bunches. The bunch-charge, bunch-centroid and arrival time at injection are randomly varied bunch-to bunch ("incoherent") and pulse-to-pulse ("coherent") to explore the longitudinal acceptance of the linac. The program also provides an option of simulating different particle species.

HOW PROGRAM SIMULATES THE LINAC

A code starts with reading of the structure of the linac from the input file. Once that is done, program sequentially calculates the energy/time profile of each macro-particle along the linac. This requires the simulation of the effective accelerating voltage provided by each cavity to each macro-particle. This voltage is not only determined by the particular cavity design field, by also by the phase difference of the each particle with respect to the cavity RF phase. Furthermore, voltage attenuation and phase error ensue in the case of detuning of the cavity, i.e. a shift of the cavity resonance frequency from the (fixed) klystron frequency as a result of mechanical deformations related LFD and microphonics. Important effect of the mismatch between cavity-β design and current particle velocity is described by the transit time factor. This effect is especially important in long multi-cell cavities. It also includes the effect of the sinusoidal variation of the accelerating field in the cavity in time and space on the effective acceleration of the beam.

Then typically the beam phase in proton linac is offset by $\approx$-10° to obtain gradient (or phase-) focusing of the bunch. Gradient focusing consists of accelerating the beam ahead of the RF crest so that slower particles are accelerated more than faster particles. Due to injection jitter, the particle phase difference smears the particle around the particle phase advance setting. The phase-factor is also strongly affected by detuning and beam

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CW MEASUREMENTS OF CORNELL LLRF SYSTEM AT HOBICAT*

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Abstract

In Energy Recovery Linacs, such as the Cornell ERL or BERLinPro, the main linac cavities are operated CW at low beam-loading. The choice of the external Q is given by two competing factors: The achievable field stability and the maximum provided RF power. To determine the optimum external Q, LLRF measurements with the Cornell system were performed at HoBiCaT to study the field stability at given microphonics detuning of a TESLA cavity for different gain settings and external Q values. Stable operation at external Q up to $2{\cdot}10^8$ was demonstrated at a field phase stability of 0.02 degrees.

INTRODUCTION

The Cornell Laboratory for Accelerator-based ScienceS and Education (CLASSE) plans for an X-ray light source based on Energy-Recovery-Linac (ERL) [1]. The Helmholtz-Zentrum Berlin is going to build the ERL demonstrator facility B*ERL*inPro [2]. ERLs, suitable for light sources, need to accelerate high beam currents up to 100 mA. However, the high beam power is recovered in the cavities by the decelerated beam so, that the CW operated superconducting (SC) cavities of the main linac experience zero net beam loading.

In the case of no beam loading the needed RF power to establish a given accelerating voltage in a cavity is given by

$$P_\mathrm{f} = \frac{V_\mathrm{acc}^2}{4\left(\frac{r}{Q}\right)Q_\mathrm{L}}\left(1+\left(\frac{\Delta f}{f_{1/2}}\right)^2\right) \qquad (1)$$

with $\left(\frac{r}{Q}\right)$ the normalized shunt impedance in linac definition, Q_L the loaded quality factor, Δf the cavity detuning offset and $f_{1/2} = f_0/2Q_\mathrm{L}$ the cavity half-bandwidth (as given in Figure 1). The optimal Q_L for minimized power requirements is therefore a function of the peak cavity detuning Δf_peak occurring during operation:

$$Q_\mathrm{L,opt} = \frac{1}{2}\frac{f_0}{\Delta f_\mathrm{peak}}. \qquad (2)$$

This loaded Q will reduce the RF power requirements to save capital cost. Figure 1 displays the required forward RF power for a seven cell SC cavity operated at 20 MV/m versus the loaded quality factor for different detuning levels. The three black lines denote the Q_L values analyzed in this work.

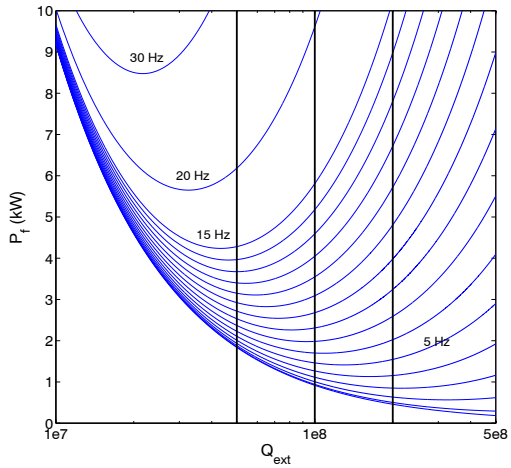


Figure 1: Required forward power for a seven cell superconducting cavity with E_acc=20 MV/m versus external quality factor Q_ext for different detuning (without beam-loading). The black lines denote the Q_ext analyzed in this work.

Choice of Q_L

Obviously the choice of the optimal Q_L has to fulfill two competing requirements. On the one hand for a given detuning Q_L has to be chosen such to minimize the required power level to maintain the desired accelerating voltage. On the other hand the required field stability limits the maximum Q_L as the cavity bandwidth decreases with higher Q_L. Narrow bandwidth operated cavities are even more susceptible to microphonics detuning and ponderomotive instabilities. ERLs typically require a field stability of better than 0.1 degrees RMS in phase and some 10^{-4} for the relative field amplitude [3]. Thus, before fixing on the design value for the loaded quality factor a measurement program has to demonstrate the following key questions and tasks:

- What is the microphonics detuning level at various cavity bandwidths? To what extend does a smaller cavity bandwidth filter out higher frequency detuning components? What are the noise sources triggering the microphonics detuning, especially peak events?

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RELIABILITY IMPROVEMENTS OF THE DIAMOND SUPERCONDUCTING CAVITIES

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Abstract

For successful operation of superconducting cavities in light sources, high reliability and minimal beam losses are essential. Diamond started operation with users in January 2007 and since then, the Diamond storage ring superconducting cavities have been the largest single contributor to unplanned beam trips. We have dedicated extensive effort to improve our data acquisition, numerical modelling and fault analysis to improve our understanding of the main causes of the trips and how to prevent trips or reduce their frequency. In the past seven months, the performance of the cavities has improved significantly. We present here our analysis of some of the trips and their underlying causes and discuss improvements carried out.

INTRODUCTION

The Diamond storage ring (SR) RF system [1] consists of two high power, 300 kW IOT based amplifiers each connected to a 500 MHz Cornell-type superconducting single cell cavity. A third system is available for testing and as a future upgrade. Since the start of operation with users in Jan 2007, the operation of the RF systems is becoming more and more demanding as the beam current is increased and more insertion devices are installed. In all the beam trips at Diamond, around half of trips have been due to the RF systems of which 75% have been cavity trips. Analysis of cavity trips is of vital importance to improve the performance of RF system and Diamond as a whole. A systematic data acquisition system was set up to capture important signals including RF signals, vacuum signals, radiation signals etc [1]. To understand the mechanism behind the trips, extensive particle-in-Cell (PIC) numerical simulations were performed [2]. After various experiments, a set of measures, including pulse conditioning, cavity partial warm up, regular TSP pump firing, is found to be effective to be operation of SRF cavities. The performance of cavities has improved significantly.

CAVITY DIAGNOSTICS SYSTEM

The cavity diagnostics system include a Libera beam position processor configured to record RF amplitude and phase signals, a fast vacuum recorder and a National Instrument PXI data acquisition system. A detailed description can be found in [1]. Recently, radiation monitors have been installed to observe radiation from the SRF modules during RF conditioning and beam operation. The data acquired from the variety of the different signals combined with the results of the beam position monitors, can serve to identify the cause of the beam trip. When it is an RF trip, it provides information regarding the signals immediately before and after the trip and accurate time stamping allows the sequence of events to be investigated.

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CLASSIFICATION OF CAVITY TRIPS

The cavity trips can be classified according to their signatures. They may be classified into fast cavity vacuum trips, trips on the RF window, cavity quench, cavity arc and other trips. The most common and important cavity trips in Diamond are fast vacuum trips. During such a trip, the cavity field collapses within a few microseconds and there are vacuum spikes on all the gauges around the cavity. 80% of the cavity trips are due to this kind of trip. The second type is a trip on the RF window. Vacuum spikes are only seen on the pump-out box and the cavity field decays normally. The Diamond SR cavities also suffer from probe problems. High amplitude spurious signals were observed on many probes. These spurious signals can confuse the LLRF leading to subsequent reaction which may cause a beam trip. We have also experienced trips caused by peripheral devices such as water flow meters, insulation vacuum and the N2 heater.

FAST CAVITY VACUUM TRIPS

Fast vacuum trips were observed as early as the commissioning of CESR SRF cavities at Cornell. It has also been observed in many other labs. The trip rate is found to be increasing with time and eventually they limited maximum cavity voltage and RF power through the coupler. This is the most dangerous trip to the long term stable operation. Sometimes cavity voltage and input RF power have to be lowered to keep the system working.

The vacuum post-mortem is shown in Figure 1. From the vacuum post-mortem, it can be observed that there are vacuum spikes on every gauge around the cavity which tripped. Gas can travel to and beyond the other cavity. Gas can't travel through the cold waveguide bend into the waveguide of the other cavity.

The RF signals captured by NI PXI data acquisition system is shown in Figure 2. The cavity field collapsed within 4.8μs.

There is always a spike on the e- pickup before the trip. During conditioning, probe blips together with X-ray spikes were observed.

PRELIMINARY TEST RESULTS FROM 650 MHz SINGLE CELL MEDIUM BETA CAVITIES FOR PROJECT X*

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Abstract

We have fabricated two single cell 650 MHz β = 0.61 cavities of a JLab design [1], which possibly can be used for the proposed Project X proton linac application. Both cavities were manufactured at JLab from RRR>250 niobium sheet of 4 mm thickness using standard techniques such as deep drawing, electron beam welding, buffered chemical polishing, hydrogen degassing heat treatment, high pressure ultrapure water rinsing and clean room assembly. A detailed description of the design and fabrication procedures is forthcoming [2].

Initially cavity #1 was – after final surface treatment by buffered chemical polishing (BCP) – measured without any provisions for stiffening. As expected, the pressure sensitivity and the Lorentz Force detuning coefficients were relatively high; however, the RF performance was very encouraging: the cavity exhibited a Q-value > 10^{11} at 1.6K, corresponding to a residual resistance of < 1.5 nΩ. The initial gradient was limited to E_{acc} ~ 18 MV/m, limited by field emission.

In a subsequent test, the cavity was re-rinsed and stiffened up, resulting in a somewhat improved mechanical behavior, but no improvement in rf performance. The second cavity was also tested twice-before and after low temperature baking. The results from all tests are reported in this contribution.

INTRODUCTION

Project X is a multi-MW proton accelerator - complex proposed to be built at Fermi National Accelerator Laboratory based on a CW H^- linac utilizing superconducting cavity technology. In the present early design stage many national laboratories as well as international partners from Indian, European and Asian institutions are supporting this effort.

The presently proposed layout as outlined in the P5 report of the High Energy Physics Advisory Panel envisages three low beta, 325 MHz spoke cavity sections, two families of medium beta (0.61 and 0.9), 650 MHz elliptical–type 5-cell cavities and a final beta=1 section of 1300 MHz 9-cell ILC-type cavities. J Lab has proposed a 5-cell cavity design for the beta=0.61 section as an alternative to an existing FNAL design. One of the major differences of the JLab design to the FNAL designs an increased beam aperture, which has some advantages with respect to cell-to-cell coupling, mechanical stability, less field flatness distortions, chemical surface treatment, reduced possibility for HOM trapping and HOM field tilts to name a few. However, this larger iris diameter does not come without the expense of sacrificing some the rf properties of the structure. In table 1 the major properties of both designs are listed:

Table1: Comparison between a JLab and FNAL 5-cell, β=0.61 cavity design for Project X

Parameter	Unit	JLab	FNAL
# of cells		5	5
Frequency	MHz	650	650
Iris aperture	mm	100	83
Equator diameter	mm	380.4	389.9
Active length	mm	694	705
c-to-c coupling	%	1.4	0.75
G	Ω	190	191
R/Q	Ω	296.6	378
E_{peak}/ E_{acc}		2.71	2.26
B_{peak}/ E_{acc}	mT/(MV/m)	4.78	4.21

CAVITY FABRICATION

Both cavities – "A" and "B" – were fabricated from 4 mm thick high purity niobium sheet of RRR>300 by standard fabrication techniques:

After the deep drawing of the half cells from round discs, the half cells were trimmed for iris and equator butt welds. Beam pipes were rolled from reactor grade niobium and welded along the seams. After trimming and attachment of the flanges made from NbTi flanges by EWB they were welded to the half cells with an interpenetrating inside/outside electron beam weld. Prior to the final equator weld the half cell subassemblies were inspected for surface imperfections, which were removed by mechanical grinding with a fibrous wheel with embedded Al_2O_3.

During the fabrication sequence the mechanical dimensions were carefully monitored and the frequencies of the half cells were recorded. This information is of importance for the fabrication of multi-cell cavities, if one wants to minimize the amount of "after fabrication" tuning to achieve the appropriate frequency and a "flat" field.

In preparation for the cryogenic testing the cavities received a bulk removal of the damage layer by BCP (app. 250 μm) and a 600C, 10 hr hydrogen degassing heat treatment. Wall thickness measurements at 12 points on the cavity surface were carried out before and after the bulk chemistry to determine the actual material removal.

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ATMOSPHERIC SURFACE TREATMENTS FOR IMPROVING THE Q-VALUE OF 6 GHz NIOBIUM CAVITIES

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Abstract
A new technique for nitriding niobium cavities has been discovered and tested on 6 GHz resonators. The reduced size of the resonator at such a frequency allows to fabricate, surface treat, process and RF test at low temperature a high number of resonators at low cost and in a reduced time. The nitridation process is performed at temperature close to the Niobium melting point, for a few minutes, in Nitrogen stream and without the use of vacuum technology. Results are encouraging since the low field Q-factor is increased up to five times. The field gradient is instead reduced by the presence of a non-stoichiometric nitride under-layer that acts as a thermal barrier. Current research is developed in order to increase the superconducting properties of the superconducting top nitride layer and to decrease the thickness of the insulating under-layer.

INTRODUCTION

The Q-value of superconducting resonators is inversely proportional to Surface Resistance. The BCS contribution to the Surface Resistance will decrease exponentially with the Superconducting Critical Temperature T_c, while it will increase with the square root of the dc resistivity in normal state.

Superconductors with T_c higher than that of Niobium are then interesting for achieving at 4,2K the Q-values that Niobium reaches at 1,8K [1]. Worldwide efforts have been spent in order to find superconductors different than Niobium with higher T_c . The requirement is that the candidate material will be as much as possible metallic in normal state and will have as high as possible critical fields. Materials that have been applied up to now to fabricate cavity prototypes are the following: Mo-Re alloy, B1 compounds (NbN, NbTiN) and A15 compounds (Nb3Sn). Q-values even higher than those of Niobium have been applied. However none of the above mentioned materials gave an accelerating field comparable with the values achieved with Niobium. The used experimental techniques were mainly based on Sputtering and/or on Thermal Diffusion. In any case both technologies require ultrahigh vacuum.

What we propose in the following is a new technique, that does not require vacuum technology, and it is suitable for preparing superconducting thick films for RF applications. The achieved results on 6 GHz cavities show the possibility to increase even of a factor 5 the Niobium Q-value at low field. Unfortunately first attempts gave low accelerating field values, but results are under continuous improvement.

There is one severe limitation to the research historically done on B1 and A15 compounds for SRF: the fact that the investigation performed on samples is not always meaningful and scalable to a resonator. On the other side samples are useful because working with a real accelerating cavity prototype is time and resource consuming, due to the big dimensions of the cavity itself.

Working with 6 GHz cavities is a particularly convenient choice, since it is well known that the BCS component of surface resistance scales with the square power of frequency. Therefore 6 GHz cavities are an extremely powerful tool for the full comprehension of physics under RF superconductivity [2]. Moreover 6 GHz cavities, in the way they are produced at Legnaro National Laboratories of INFN, are intrinsically inexpensive because they: i) are fully seamless; ii) require a little amount of Niobium; iii) need short fabrication times. In addition to that, other advantages consist in: i) fast and low cost BCP and EP treatments; ii) inexpensive Cryogenics; iii) quick RF measurements.

The SRF scientific community includes three different classes of experimentalists: i) those mainly involved in sample production and characterization; ii) the ones focused on methods for the measurement of Surface Resistance; iii) those mainly busy with real size cavity production and testing.

Certainly, the final goal of acceleratorists is the production of a nine cell resonator, and the sample production phase (surface morphology and microstructure analysis, Resistive and Inductive Measurement of T_C, Measurement of H_{C1}) is of course a mandatory step, but it is also the farthest from the world of production.

In terms of scalability the surface resistance measurement methods (Pillbox cavities, etc: Calorimetric Methods; Differential methods for Surface Resistance Measurements; microstrip resonators) are already closer than samples to the final goal, but still far from it.

From the final goal, 6 GHz monocell prototypes are the lowest step among all cavity choice (6 GHz cavities; 1,5 and 1,3 GHz monocells. 1,3 GHz 3-cell cavities, 1,3 GHz 9-cell cavities), but they interface the simplicity of samples with the technologies used for treating and testing a cavity.

With the same amount of Niobium required for a ninecell 1,3GHz cavity, we have instead produced 200 monocell 6 GHz resonator prototypes. Moreover due to the tiny sizes of such small resonators we can treat and measure up to 4 cavities per day. Obviously if our purpose was the optimization of the engineering of a ninecell cavity inside a cryomodule, the 6 GHz research

MULTILAYER COATINGS: OPPORTUNITIES AND CHALLENGES.

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Abstract

The use of multilayer coatings may enable significant increase of the breakdown fields or operating temperatures of SRF cavities by utilizing materials with the thermodynamic critical field Hc higher than Hc = 200 mT for Nb. However, such coating materials have shorter coherence length so the significant effects of impurities or grain boundaries on the surface resistance should be understood. In this talk I'll analyze the dynamics of penetration of vortices along grain boundaries and dissipation in a thin film coating in strong rf fields. I'll also discuss the role of impurities, in particular their contribution to the nonlinear Meissner effect which affects the surface resistance in the dirty limit. And finally I'll discuss the nonlinear response in two-band superconductors like MgB2 in which strong rf fields can cause decoupling of bands at fields H < Hc, which can contribute to the high-field Q slope.

CONTRIBUTION NOT RECEIVED

MAGNETIC SCREENING OF NbN MULTILAYERS SAMPLES

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Abstract

In 2006 Gurevich proposed to use nanoscale layers of superconducting materials with high values of $H_c > H_c^{Nb}$ for magnetic shielding of bulk niobium to increase the breakdown magnetic field inside SC RF cavities [1].

We have deposited high quality "model" samples by magnetron sputtering on monocrystalline sapphire substrates. A 250 nm layer of niobium figures the bulk Nb. It was coated with a single and multi-stacks of NbN layers (25 or12 nm) separated by 15 nm MgO barriers, and characterized by X-Ray reflectivity and DC transport measurements.

DC or AC measurement of H_{C1} is an important goal for multilayer evaluation during the sample evaluation phase. A clear increase of H_{C1} at low frequency is promising indication since H_{C1} is expected to increase with frequency (see e.g. [2] and references therein). We have measured the first penetration field (H_P~H_{C1}) on DC magnetization curves in a SQUID system. H_P of NbN covered sample is increased compared to Nb alone. We have also developed a set-up that allows measuring a large range of field and temperature with a local probe method based on 3rd harmonic analysis. We have confirmed the screening behavior of a single 25 nm NbN layer placed on the top of a Nb Layer.

INTRODUCTION

The use of a superconductor allows building RF cavities with very high quality factors (Q_0 about 10^5 higher than for copper). This technology is the only one allowing having appreciable accelerating gradients (up to 40-45 MV/m) in continuous wave. Up today, Niobium is the only superconductor extensively used for this technology. Attempts to use other superconductors seem to have failed.

In principles, the limitation in accelerating field occurs when the magnetic component of the RF field reaches the RF critical field of the superconductor.

Nevertheless, the exact definition of the ultimate achievable field in a superconducting RF cavity is still in dispute.

Indeed superconducting state has been observed at fields higher than the DC measured value of H_{C1} , and one define a so-called "superheating field" applicable in RF [3]. In the 1960s, the field H_{SH} has been estimated on the basis of thermodynamic considerations related to the surface energy. Several experimental results seem to confirm this model of behavior.

According to the values of the Ginsburg-Landau (K) parameter, the « superheating » field can be approximated by the following expressions [3] :

$$H_{SH} \approx 1.2 H_c \quad \textbf{if } \kappa \sim 1 \qquad (1)$$

$$H_{SH} \approx 0.75 H_c \quad \textbf{if } \kappa >> 1 \qquad (2)$$

where H_C is the critical thermodynamic field.

For several decennia the commonly accepted explanation was that the field reverses every 10^{-9} seconds, whereas it takes 10^{-6} seconds to reach the nucleation of a normal zone. Therefore there is not enough time to trigger the nucleation.

If one follows this model, superconductors like NbN or Nb_3Sn should exhibit improved performances compare to Niobium. Only a few cavities of Nb_3Sn have been tested at various frequencies. They all exhibit a very high low field Q_0 as expected for a higher T_C material, but very soon the Q_0 degrades, and only poor performances where reached [4].

Recently the correctness of this model has been questioned [5-7]. We should consider the penetration of individual vortices, which is considerably faster (~10^{-13} s).

Moreover, at high fields and low temperature some approximations of the general theory (BCS) are no longer valid [8]. Some of the temperature corrections have been evaluated for type II superconductors in the clean limit and at low frequency. As H^{RF} approaches H_C, the normal electrons density and R_{BCS} increase due to the effect of current pair-breaking on thermal activation which in turn increases heating, making R_{BCS} nonlinear at high field. It shows that at high field the nonlinear correction increases exponentially with field and temperature, and can give rise to thermal runaway [6, 9]. This model can in particular explain the hot spots observed on cavities where bundles of trapped vortices can produce localized dissipative regions from which heat spreads over several tens of mm. The magnetic/vortex origin of the hot spots have been recently demonstrated [10].

If one consider the superheating model no vortices penetrates the superconductor until close to H_{SH}. But if on the other hand one assumes the high field dissipation are related to vortices penetration, then high field nonlinear dissipation could explain the monopoly of niobium in SRF applications since Nb has the highest H_{C1} value

MgB_2 THIN FILM STUDIES*

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Abstract

In order to overcome the limitation of Nb associated with its theoretical RF critical magnetic field of ~200 mT, which corresponds to an accelerating gradient of 50-60 MV/m for electron accelerators, studies of coating thin film MgB_2 have been carried out. The B_{pen}, a magnetic field at which a large number of magnetic fluxons start to penetrate into the superconductor has been measured with a DC SQUID magnetometer. An increase in B_{pen} from 500 nm to 300 nm films was observed. Also, 300 nm films showed B_{pen} significantly higher than bulk Nb at 4.5 K. In parallel, RF measurements using 11.4 GHz pulsed powers with TE_{013} mode copper cavity have been carried out at SLAC. Despite the high B_{pen} measured in the magnetization measurements, the MgB_2(100 nm)/Al2O3(20 nm)/Nb system showed significantly lower quench fields, i.e., ~43 mT at 4 K and ~33 mT at 10 K. It was found, however, that these quenches are thermal, not magnetic. Auger depth profile showed inter-diffusion of coating components at the interfaces, which indicates the degradation of RF resistance at these interfaces. A technique to solve this problem is being developed.

BACKGROUND AND MOTIVATION

The technology to produce high-quality SRF cavities made of bulk Nb has advanced so well that more than half of 1.3 GHz 9-cell cavities have shown >35 MV/m, the current goal of the International Linear Collider (ILC). Also, a 9-cell cavity made from large grain Nb showed 45 MV/m recently at DESY [1]. These results are considered to be very close to the fundamental limit of Nb due to its critical magnetic field of ~200 mT. The purpose of this study is to evaluate MgB_2 if it can exceed this limit and can be the material for the next generation SRF cavities with >50 MV/m operating field.

Multilayer Concept

For SRF cavities, having high H_{c1} is very important since otherwise Q_0 degrades due to the flux penetration and subsequent RF losses at fields at $>H_{c1}$. Although most alternative materials such as Nb_3Sn, NbN and MgB_2 have lower H_{c1} than Nb, it has been observed that thin film superconductors possess H_{c1} that is much higher than that of bulk. Based on this, Gurevich proposed multilayer coating concept to enhance the achievable gradient [2]. Figure 1 illustrates the concept of using 3 layers of 77 nm MgB_2 films. The H_{c1} of 77 nm MgB_2 is predicted to be ~550 mT using the formula in the Fig. 1 assuming the coherence length (ξ) of 6 nm and the penetration depth (λ) of 110 nm. With this coating, the surface magnetic field of 500 mT decays to 100 mT when it reaches Nb. In other words, if Nb does not breakdown up to 100 mT, this system sustains the cavity surface field of 500 mT corresponding to an E_{acc} of 125 MV/m!

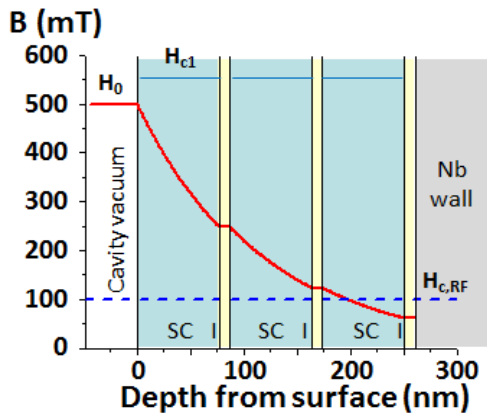


Figure 1: Concept of field enhancement with 3 layers of 77 nm MgB_2 separated by 10 nm insulator layers.

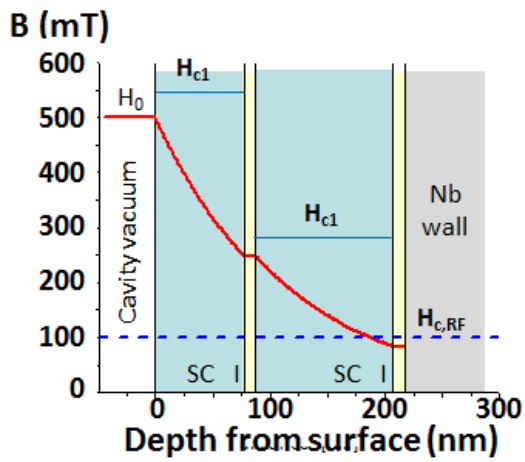


Figure 2: Tuning the thickness of superconducting (SC) layers will allow the reduction in the number of layers to achieve the same gradient.

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THE SUPERHEATING FIELD OF NIOBIUM: THEORY AND EXPERIMENT

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Abstract

This study discusses the superheating field of Niobium, a metastable state, which sets the upper limit of sustainable magnetic fields on the surface of a superconductors before flux starts to penetrate into the material. Current models for the superheating field are discussed, and experimental results are presented for niobium obtained through pulsed, high power measurements performed at Cornell. Material preparation is also shown to be an important parameter in exploring other regions of the superheating field, and fundamental limits are presented based upon these experimental and theoretical results.

INTRODUCTION

An important property of superconductors that has posed both theoretical and experimental challenges is the magnetic superheating field, a metastable state wherein the material remains fully superconducting above the respective critical fields in steady state. Obtaining accurate measurements of this metastable state is essential to expand the theoretical understanding of this phenomena and determine the ultimate limit of radio-frequency superconductors. In this study, niobium is used to probe this limiting field.

Studying the superheating field is important on several counts. First, current theoretical models can immediately be tested against measurements. Second, the regions in which empirical methods accurately describe the field tend to be in limiting cases, such as the low- or high-κ limit,[1, 2] or in small temperature ranges around the critical temperature.[3] Measuring the superheating field in the intermediate range, where $\kappa \sim 1$, provides an important result that can guide development of new models covering the entire range of κ. Third, most models are based upon a phenomenological model of the superheating field, only valid near T_c, and so say nothing about the behaviour as a function of temperature. Newer, non-phenomenological calculations taking temperature dependence into account need accurate data to test against. Finally, the accurate determination of the superheating field also is of particular interest in application. While theory and experiment agree near T_c, niobium microwave cavities for particle accelerators operate at temperatures $< T_c/4$, where theory and experiment are disparate, so measurements can set stringent upper limits for what is possible with these cavities.

This paper begins with a brief review of the the critical fields of superconductors, discusses the current state of knowledge on the superheating field and then presents new research being done at Cornell to probe this phenomena. Finally, the implications of the work presented here are discussed and regions for further study are explored.

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Critical Fields of Superconductors

When a superconductor in a constant magnetic field is cooled below its critical temperature, it expels the magnetic field from the bulk of the superconductor. This is accomplished by superconducting electrons establishing a magnetization cancelling the applied field in the bulk of the material. The magnetic is field limited to a small region close to the surface, characterized by a penetration depth λ, which is the region in which supercurrents flow. Another important length scale in superconductors is the coherence length, ξ_0 which is related to the spatial variation of the superconducting electron density. The ratio of these characteristic length scales yields the Ginsburg-Landau (GL) parameter, $\kappa \equiv \lambda/\xi$.

Pippard improved upon the superconductor model that only assumed local electron interaction to take into account non-local effects. He argued that superconducting wavefunctions should have a characteristic dimension ξ_0. If only electrons around $k_B T_c$ of the Fermi energy can be involved in the dynamics around the critical temperature, and they have a momentum range $\Delta p \approx k_B T_c/v_F$, where v_F is the Fermi velocity, then the approximate coherence length should, by the uncertainty principle be

$$\Delta x \sim \frac{\hbar}{\Delta p} \quad \rightarrow \quad \xi_0 \sim \frac{\hbar v_F}{k_B T_c}. \tag{1}$$

Assuming a pure material has a coherence length ξ_0, Pippard showed that if impurities introduce scattering centers giving an electron mean free path of ℓ, then the coherence length of the impure material, ξ, is modified to be

$$\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{\ell}, \tag{2}$$

and the penetration depth becomes

$$\lambda = \lambda_L \sqrt{1 + \frac{\xi_0}{\ell}}, \tag{3}$$

where λ_L is the mean free-path of the material with no scattering sites.[4]

These expressions can be used to give κ as a function of mean free path:

$$\kappa(\ell) = \frac{\lambda_L}{\xi_0} \left(\frac{\xi_0 + \ell}{\ell} \right)^{3/2}. \tag{4}$$

DEPOSITION OF NIOBIUM AND OTHER SUPERCONDUCTING MATERIALS WITH HIGH POWER IMPULSE MAGNETRON SPUTTERING: CONCEPT AND FIRST RESULTS*

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Abstract

Niobium coatings on copper cavities have been considered as a cost-efficient replacement of bulk niobium RF cavities, however, coatings made by magnetron sputtering have not quite lived up to high expectations due to *Q*-slope and other issues. High power impulse magnetron sputtering (HIPIMS) is a promising emerging coatings technology which combines magnetron sputtering with a pulsed power approach. The magnetron is turned into a metal plasma source by using very high peak power density of ~ 1 kW/cm^2. In this contribution, the cavity coatings concept with HIPIMS is explained. A system with two cylindrical, movable magnetrons was set up with custom magnetrons small enough to be inserted into 1.3 GHz cavities. Preliminary data on niobium HIPIMS plasma and the resulting coatings are presented. The HIPIMS approach has the potential to be extended to film systems beyond niobium, including other superconducting materials and/or multilayer systems.

INTRODUCTION

The common approach to superconducting radio frequency (SRF) cavities is using bulk niobium, a proven technology [1, 2]. Niobium, a type II superconductor, is the material of choice for its high critical temperature (T_c = 9.2 K) and its high superheating critical magnetic field, which is of the order of the thermodynamic critical field (H_c = 2000 Oe). Well prepared niobium SRF cavities can have electric fields exceeding 20 MV/m with a quality factor *Q* of the order 10^{10}. Cavities capable of higher field strength and with higher quality factor have been made, although *Q* generally decreases as the field is pushed to the limits of breakdown and quenching.

The cost of niobium is high, especially high purity material qualified to have a high residual resistivity ratio (RRR, of order 300). Making the cavities of bulk niobium may be prohibitively expensive for high energy linacs that make use of 650 MHz or lower, implying large cavities. A possible approach is to move to niobium coatings, reducing the need for niobium to a tiny fraction [3]. The idea is not new [4, 5]: the LEP-II accelerator at CERN used 288 4-cell cavities at 352.2 MHz, 256 of which were Nb-coated copper cavities. The niobium was deposited using sputtering from a cylindrical magnetron inserted into the cleaned, electropolished, and outgassed copper cavities [6]. Although the accelerator was a success, the performance of the cavities was limited by a significant *Q*-slope: the quality factor drops significantly at high fields. High fields are highly desirable (a) to make a linear accelerator as short and cost-effective as possible, or (b) to obtain the highest energy from a circular machine. Although the details of the *Q*-slope and film structure are still subject to investigations [7], it is clear that an improved film deposition method is needed to achieve higher quality coatings.

A possible approach using energetic deposition from the plasma phase has been investigated for some years using (filtered) cathodic vacuum arcs [8-10]. Very encouraging are recent results where niobium films of RRR = 77 [10] and even 300 [11] were produced, though those record values were obtained for hot sapphire substrates, not cavities. A new energetic deposition technology is high power impulse magnetron sputtering (HIPIMS) [12], also known as high power pulsed sputtering (HPPMS). In this contribution, the concept of using HIPIMS for SRF cavities is explored and some very preliminary results are reported.

HIGH POWER IMPULSE MAGNETRON SPUTTERING

HIPIMS is an emerging technology that combines conventional magnetron sputtering with a pulsed power approach [13-15]. The process is pulsed with a power density at the target surface during the pulse exceeding the typical dc power density by about two orders of magnitude. This implies that the off-time between pulses is long, and the duty cycle is only of order 1%. It is becomes increasingly common to use the term “impulse” to distinguish the process from lower power pulsed sputtering. The most important result of the very significant increase of power is the ionization of the sputtered atoms. The newly formed target ions participate in the sputtering process, i.e. self-sputtering is important. Ionization of the sputtered material delivers energy and momentum to the growing film on a substrate, which greatly affects density and texture of the film. For example, this has been studied for tantalum films, where it was shown that the HIPIMS process leads to smooth films of well aligned grains with their c-axes normal to the surface [16]. A low resistivity bcc phase could be

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ENERGETIC CONDENSATION GROWTH OF Nb THIN-FILMS

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Abstract

This paper describes Energetic Condensation Growth of Nb films using a cathodic arc plasma, whose 60-120eV ions penetrate a few monolayers into the substrate and enable sufficient surface mobility to ensure that the lowest energy state (crystalline structure with minimal defects) is accessible to the film. Hetero-epitaxial films of Nb were grown on a-plane sapphire and MgO crystals with good superconducting properties and crystal size (10mm × 20mm) limited only by substrate size. The substrates were heated to 700°C and coated at 300, 500 and 700°C. Film thickness varied from ~0.25µm to >3µm. Residual resistivity ratio (RRR) values (up to a record RRR 585 on MgO and RRR 328 on a-sapphire) vary with substrate annealing and deposition temperatures. XRD spectra and pole figures reveal that RRR increases as the crystal structure of the Nb film becomes more ordered, consistent with fewer defects and hence longer electron mean free path. A transition from Nb(110) to Nb(100) orientation on the MgO(100) lattice occurs at higher temperatures. SIMS depth profiles, EBSD and SEM images complement the XRD data. Crystalline structure in Nb on amorphous borosilicate substrates has potential implications for future, lower-cost SRF cavities.

ENERGETIC CONDENSATION

This paper describes Energetic Condensation Growth of Nb films using a cathodic arc plasma. Such a plasma uses a low voltage (~30V) arc discharge to generate a highly ionized plasma [1-3] the ions of which consist exclusively of the cathode material. The plasma is created in a vacuum arc discharge, so can be sustained in otherwise ultra-high vacuum (~10^{-8} Torr) conditions. For Nb plasmas, the ion energy spectrum has been measured [4] to lie in the range of 60-120eV, with most of the ions being triply charged. When such energetic ions impinge upon a substrate, they penetrate and deposit their energy within a few monolayers from the surface. The net energy deposited is in the range of 100-170 eV, as the ≈46 eV of ionization potential energy carried by Nb^{3+} is added to the kinetic energy. This energy range greatly exceeds typical binding energies in the lattice, so substrate atoms are displaced and the excess energy goes into electronic and phonon excitations. These ion deposition processes occur on a rapid time scale of ~1 ps. When such deposition is accompanied by substrate heating, the slower time-scale thermal diffusion allows defects to migrate to the surface where they are annihilated. Lifshitz et al [5] and Brice et al [6] have described the details of the interaction between energetic ions (~100eV) and various substrates. They have coined the term 'subplantation' to distinguish this regime of ion-surface interactions from deep implantation (>1keV ions) and surface interactions (<1eV). In subplantation, the incident ions deposit more than enough energy into just a few sub-surface atomic layers to displace atoms from the lattice and create interstitials. The key to effective subplantation is to maximize the number of displacements within this sub-surface layer, while minimizing deeper defects. This is because the ion energy deposition (that occurs on ~1-10ps time scales) must be accompanied by substrate heating. This heating allows sub-surface defects (lattice dislocations, voids and impurities) to migrate to the surface where they are annihilated. Such a synergistic interplay between the non-thermal ion deceleration physics and thermal diffusion physics promotes growth of the film in a low energy state this is likely to be epitaxial growth, evolving as the film thickens, to homo-epitaxial growth. Our pulsed discharge is fired once every few seconds, so the synergistic effects of fast ion deposition and thermal annealing are completed on each pulse.

AASC and Jefferson Lab conduct research into SRF thin-film coatings that are grown using energetic condensation (EC) a term used to represent two complementary approaches: a UHV cathodic arc process and an ECR source process. Both of these sources deliver ions to the coated surface that have ~100-200eV energy. In the case of the cathodic arc the Nb ions are triply charged and have kinetic energy spread over 60-120eV. In the case of the ECR source, the typical singly charged Nb ion energy is ~60eV. A bias of ~100-120V increases the energy to ~160-180eV at the substrate. In the case of either the vacuum arc or the ECR, the energy is easily varied by varying the substrate bias voltage.

Thornton [7] presented a Structure Zone Diagram (SZD) to describe the interplay between thermal and kinetic energy driven film growth in thin films. This SZD is applicable to processes in which the source plasma is created in a partial pressure of noble gas such as Argon. Anders [8] (see Fig. 1) has offered a variation on the SZD that is more appropriate for vacuum deposition. In this case, Thornton's pressure axis is replaced by an energy axis. Zone 2 of Fig. 1 (reproduced from Ref. 8) shows that high energy ions effectively permit low-temperature ion-

SUMMARY OF THE SYMPOSIUM ON INGOT Nb AND NEW RESULTS ON FUNDAMENTAL STUDIES OF LARGE GRAIN Nb*

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Abstract

The First International Symposium on the Superconducting Science and Technology of Ingot Niobium was held at Jefferson Lab in September 2010. Significant activities are taking place at laboratories and universities throughout the world to address several aspects related to the science and technology of Ingot Nb: from ingot production to mechanical, thermal and superconducting properties. The ingot Nb technology has been fully proven in the linear accelerator FLASH at DESY. A summary of the results presented at the Symposium is given in this contribution. New results on the superconducting properties and interstitial impurities content measured in large-grain Nb samples and cavities are briefly highlighted.

INTRODUCTION

R&D activities on large-grain/single-crystal ingot Nb technology have been pursued worldwide, since initial developments at Jefferson Lab in 2005. Following the International Workshop on Single Crystal-Large Grain Niobium Technology held in Araxá, Brazil, in 2006 [1], a two days International Symposium on this subject was organized at Jefferson Lab in September 2010. Fifty-seven participants from fifteen research laboratories and universities and from nine industrial companies attended the Symposium. The latest global developments on both technological and scientific aspects of ingot Nb related to SRF cavities were brought into focus at the Symposium. Proceedings of the Symposium have been published by the American Institute of Physics in 2011 [2].

This contribution provides a concise summary of the developments on ingot manufacturing technology, cavity fabrication and test results and fundamental studies on samples. In addition, highlights from recent work on large-grain cavities and samples at Jefferson Lab will be given in the last section of this article, prior to some final conclusions.

INGOT FABRICATION

CBMM in Brazil, W. C. Heraeus in Germany and Tokyo Denkai in Japan are pursuing R&D on different topics related to Nb ingot production for SRF cavities. CBMM focused on the development of an improved process to produce high-purity ingots by investigating the effects of several parameters such as Ta content, feeding rate, atmosphere, getter and number of melts. As a result, high purity ingots with oxygen, nitrogen, hydrogen and carbon contents lower than 10 wt-ppm were obtained [3]. W. C. Heraeus is pursuing the development of suitable parameters to produce approximately 2 m long ingots with a single-crystal with diameter larger than 150 mm in diameter in the center of the ingot. This would allow avoiding necking and tearing at the iris during deep drawing of a disc. In addition, a multi-wire slicing process was developed to cut multiple Nb discs from an ingot for mass production purposes in a cost effective way [4]. The same process was pursued by Tokyo Denkai where a multi-wire saw was installed which allowed slicing of 150 2.8 mm thick Nb discs from an ingot in 48 h. The accuracy in the discs' thickness was better than achieved with standard rolled sheets by about a factor of five. In addition, they used an ultrasonic tomography method to identify different grain orientations being formed during the electron beam melting of ingots [5]. Additional activities in collaboration with KEK include attempting to grow single-crystal ingots from a single-crystal Nb seed inside the electron beam melting furnace.

CAVITY FABRICATION AND TEST RESULTS

Europe

DESY in Germany has been pursuing the large-grain Nb technology in collaboration with W. C. Heraeus and Research Instruments (RI), formerly ACCEL [4]. Eleven 9-cell 1.3 GHz cavities of the TESLA shape were fabricated by ACCEL out of large-grain Nb of different purity. After fabrication it was found that, although the accuracy of the half-cells' shape was within tolerances, larger deviations resulted from discs with (100) orientation in the central crystal than from discs with (211) or (221) orientations. After fabrication the cavities surface treatments consisted of 100 μm material removal by Buffered Chemical Polishing (BCP), heat-treatment at 800 °C for 2 h under vacuum, 20 μm etching by BCP, high-pressure water rinsing (HPR) and baking in ultra-high vacuum (UHV) at 125 °C for 48 h (LTB). The RF tests at 2 K (Fig. 1) showed accelerating gradients (E_{acc}) up to 25 – 30 MV/m, corresponding to peak surface magnetic field (B_p) values of 110 – 130 mT, with Q_0-values above 1×10^{10}, exceeding the specification for the XFEL project. Further results from the high-power RF tests at cryogenic temperatures showed that:

- No significant dependence of the maximum E_{acc}-value on the Nb residual resistivity ratio (*RRR*) in the range 150 – 500, as shown in Fig. 2.
- The Q_0-values at 1.8 K is almost a factor of two higher than for standard fine-grain Nb cavities,

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TESTING THE RF PROPERTIES OF NOVEL SUPERCONDUCTING MATERIALS *

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Abstract

An X-band RF cryogenic material testing system has been developed at SLAC in the past few years. The system is capable to measure the RF surface resistance of superconducting and normal-conducting materials at the temperature of 3K to 300K, and to characterize the RF quenching magnetic field of superconducting materials. This system employs a high-Q hemispheric cavity with an interchangeable flat bottom hosting a 2-3 inch diameter sample disk. Using a klystron with 50MW 2μs output pulse, the system can measure the quenching H field of about 300mT, and is possible to achieve 700mT by changing the RF distribution configuration.

INTRODUCTION

Niobium superconducting RF technology provides much lower surface resistance and losses, and is becoming more and more attractive for accelerator applications. For many accelerator systems, especially in the accelerators with an RF system under constant wave or high duty cycle operation, the total wall plug power required to achieve the same gradient in a niobium cavity can be significantly less than normal conducting cavities.

To make niobium SRF cavities suitable for high energy accelerators, lot of research progress has been made over the past decades, increasing the accelerating gradient by overcoming the problems caused by high electric and magnetic fields, raising the maximum acceleration gradient from 3MV/m to about 50MV/m, reaching a theoretical limit set by the *lower critical field* H_{c1} of 170-180mT or the *thermodynamic critical field* H_c of about 200mT.

Extensive research efforts are being made in the superconducting materials study, in hope to find new materials with higher quenching RF magnetic field for higher accelerating gradient, at the same time with higher T_c and/or lower surface resistance. Such new materials may enable a lot of new particle accelerator applications. Several BCS superconductors like MgB_2 and Nb_3Sn have larger energy gap and transition temperature compared to Nb, resulted in lower surface resistance and higher H_c, but H_{c1} is much lower than Nb due to the shorter coherence length. A possibility to enhance H_{c1} was suggested by using multi-layers of superconductor films thinner than the London penetration depth with insulator in between [1]. A lot of material samples have been developed [2] trying to demonstrate this theory.

To facilitate the SRF material research, we started to develop an SRF testing system in 2005, which is capable to characterize the quenching field and surface resistance of a flat sample disk with 2-3 inches diameter by measuring the quality factor of a RF cavity. The system operates at 11.4GHz, making it compact in size and needs less energy to build up the RF field in the cavity. Although the system uses a 2μs 50MW SLAC klystron, the current setup only feeds the maximum power of about 2-3MW into the cavity in order to minimize the power reflected back into the klystron and make it easier to produce a flat input pulse. This setup can achieve a maximum H-field of almost 300mT on the sample, and can be enhanced further to 700mT or more by changing the RF distribution.

Our earliest system uses a "mushroom" shape copper cavity with a detachable flat plate to host the samples [3, 4, 5]. The cavity operates under a TE_{013} like mode, which has no radial E-field and current on the wall, and allows a simple demountable sample plate with a small gap. The H-field is concentrated in the sample area. In the recent years, the cavity shape was changed to hemispheric, which can provide higher H in the bottom. However, a more optimized mushroom cavity is under consideration. The copper cavity has many advantages for high power testing, but will have lower accuracy in low power surface resistance characterization, estimated at 0.1-0.2mΩ. A thinfilm niobium cavity with similar shape is under development with the collaboration of CERN.

EXPERIMENT DESIGN

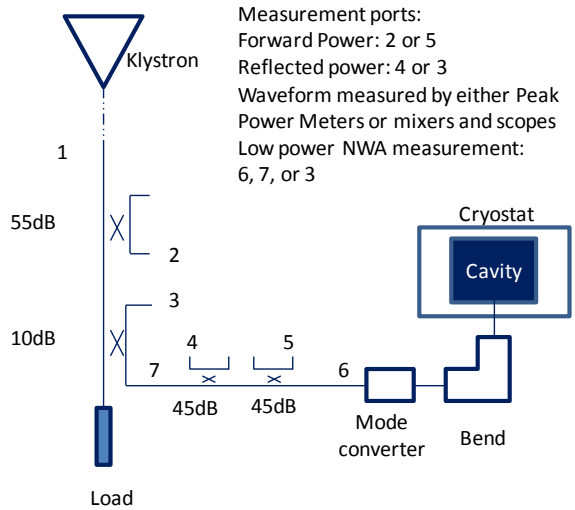


Figure 1: System diagram

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MUON SPIN ROTATION/RELAXATION STUDIES OF NIOBIUM FOR SRF APPLICATIONS

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Abstract

One of the outstanding scientific issues related to superconducting radio frequency cavities made of high-purity bulk niobium is the occurrence of field dependent losses in the walls of the niobium cavity. These losses occur at different RF field levels and pose severe limitations to the niobium technology for both CW or pulsed applications. In this presentation I will explain the results of an experiment which focused on understanding the mechanisms behind losses in the high field regime (above 80-100mT peak magnetic fields). The problem was studied utilizing the unique TRIUMF muon spin rotation (muSR) facility to investigate superconducting properties of niobium samples. In particular, the muon spin rotation experiments aimed at studying the field of first flux entry in high field Q-slope cutouts from small and large grain BCP (buffered chemical polished) 1.5GHz cavities, before and after undergoing 120C UHV-bake. The results obtained will be presented, and it will be discussed in which future direction those results lead.

CONTRIBUTION NOT RECEIVED

NEW APPROACHES TO NB THIN FILM COATING

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Abstract

Niobium films are widely used at CERN and several other Laboratories for the coating of superconducting cavities. The performances of these cavities are highly influenced by the thin film properties, and in particular its microstructure. Energetic condensation, and in particular High Power Impulse Magnetron Sputtering (HIPIMS) gives new opportunities for conventional magnetron sputtering equipment. In this talk we will review the background on thin film performance, the motivations of the study, illustrate the experience that has been gained at CERN during the first months of operation and present the results obtained so far.

CONTRIBUTION NOT RECEIVED

NB FILMS: SUBSTRATES, NUCLEATION & CRYSTAL GROWTH*

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Abstract

Over the years, Nb/Cu technology, despite its shortcomings due to the commonly used magnetron sputtering limitations, has positioned itself as an alternative route for the future of superconducting structures used in accelerators. Recently, significant progress has been made in the development of energetic vacuum deposition techniques, showing promise for the production of thin films tailored for SRF applications. The purpose of using energetic condensation is to improve film structure on low temperature substrates by adding energy to the film during condensation to compensate for the lack of thermally induced growth processes. Energetic condensation is characterized by a number of surface and sub-surface processes enabled by the energy of the incoming ions such as desorption of adsorbed molecules, enhanced mobility of surface atoms, and implantation of impinging ions under the surface. All these with the nature of the substrate and its crystallographic mismatch with Nb have an important influence on the nucleation and subsequent growth of the Nb film.

This contribution shows how the structure and defect density thus electron mean free path (represented by residual resistance ratio values) of Nb films can be tailored on various substrates, crystalline and amorphous, by varying the ion energy and thermal energy provided to the substrate.

INTRODUCTION

Due to the very shallow penetration depth of RF fields (only ~40nm for niobium [Nb]), SRF properties are inherently a surface phenomenon, involving a material thickness of less than 1 micron. One can then foresee the merits of depositing an Nb film on the inner surface of a castable cavity structure made of copper (Cu) or aluminum (Al). At the system design level, this would exploit the freedom to decouple the active SRF surface from the accelerating structure definition and its cooling, opening the possibility to dramatically change the cost framework of SRF accelerators.

CERN has conducted pioneering studies [1-3] in the field of SRF Nb films on Cu (Nb/Cu) applied to cavities and successfully implemented this technology in LEP-2. Although 1.5 GHz cavities achieving gradients up around 25MV/m [4] were produced, these cavities suffered from significant losses resulting in the significant reduction of Q at accelerating gradients above 15MV/m. Some of the defects were inherent to the magnetron sputtering technique used to produce these cavities.

In the meantime, bulk Nb cavities are approaching their intrinsic limit at $H_{max} = H_c$ (180mT), with breakdown fields close to the de-pairing limit (50 MV/m) [5].

The challenge in developing SRF Nb thin films is to reproduce and go beyond the performance of bulk Nb. While tight correlation with the characterization of real materials has yet to be described, there exists a theoretical framework describing the relevant material parameters of surfaces as they influence SRF properties. Several material factors, highly dependent upon the surface creation conditions, contribute to degraded SRF performance with respect to ideal surfaces. These limiting factors such as intra-granular impurities and lattice defect density, inter-granular impurities and oxidation, surface topography and chemistry, may lead to the reduction of the electron mean free path, thus the reduction of the lower critical field H_{c1}.

Thus, understanding of the film growth dynamics from nucleation to final exposed surface is crucial. The defect density (which determines the electron mean free path) within the RF penetration depth is certainly affected by intragrain contaminants incorporated during the final stage film growth, but it is also strongly affected by the underlying crystal texture, which is in turn developed from the initial film nucleation process, which necessarily is strongly influenced by the substrate. The development of every stage can be expected to depend strongly on the kinetic energy distribution of the arriving Nb ions. Although the thickness corresponds to the very top 40 nm of the Nb film, this final surface is dictated from its origin, i.e. the substrate, the interface, and deposition technique (ion energy, substrate temperature…).

The results on Nb films presented in this contribution are for the most part the fruit of a collaboration between JLab, surrounding university partners and Alameda Applied Science Corporation Inc. (AASC). These films have been prepared by magnetron sputtering, and energetic condensation via electron cyclotron resonance (ECR) and coaxial energetic deposition (CED™).

SUBSTRATES

In thin films, one is dealing with heterogeneous nucleation. By opposition to homogeneous nucleation (where a solid forms homogeneously from a liquid), in heterogeneous nucleation [6], a new solid phase forms on a pre-existing particle or surface which catalyzes the nucleation event. The nucleation is driven by nucleation centers such as defect, impurities on the substrate surface or simply by the orientation of the underlying substrate.

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MAGNESIUM DIBORIDE FILMS FOR SRF CAVITY APPLICATIONS

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Abstract

We have explored magnesium diboride films for applications in SRF cavities. MgB_2 has a high T_c = 40 K and low surface resistance that, even in polycrystalline films, is comparable to niobium. It also shows the potential for higher power handling than niobium because of the higher critical fields. We report the results of measurements of the surface resistance and power handling in films deposited by the reactive-evaporation method. The measurements were made using both a stripline-resonator at 2 GHz and with a dielectric resonator at 10.7 GHz. The best results for surface resistance are 14 micro-ohm at 10.7 GHz, which scales to 0.5 micro-ohm at 2 GHz. The maximum rf magnetic field of the best film has been measured to be 300 Oe, limited by the available amplifier. We have also demonstrated a successful surface-passivation method of atomic-layer-deposited (ALD) films of Al_2O_3 and Zr_{O2}. We have also demonstrated evidence that one of the two energy gaps shows unconventional symmetry with a six-fold-symmetric nodal order parameter. The implications for applications of these findings of the basic physics of the material will be discussed.

CONTRIBUTION NOT RECEIVED

HOT TOPIC: MEDIUM FIELD Q-SLOPE AND PATHS TO HIGH-Q OPERATION

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Abstract

Superconducting RF cavities for accelerator application offer, at least in principle, the perspective of large accelerating gradients and low RF losses. Both qualities must proceed reciprocally. Therefore, consequent to the achieved increase in accelerating gradient during recent years, the RF losses must be reduced accordingly, in order to keep the cryogenic installation at reasonable size. However, the Q-value, which describes the RF losses, did not follow the improved accelerating gradient as wished or required. The reasons are physical mechanisms, only partly understood, on top of the residual losses, that provoke a more than quadratic increase of the RF losses with the accelerating gradient (Q-slope). Cures have been identified experimentally to some extent, but both the theoretical understanding and a complete elimination of the"Q-slop" are lacking. The hot topic discussion should open the floor for a new and deeper understanding of the"Q-slop".

CONTRIBUTION NOT RECEIVED

DEVELOPMENT OF QUALITY ASSURANCE PROCEDURES FOR THE FAST/SLOW TUNERS ON THE 1.3 GHZ SRF CAVITIES FOR THE SRF ACCELERATOR TEST FACILITY AT FERMILAB

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Abstract

The 1.3 GHz elliptical SRF cavities being prepared for cryomodules of the Fermilab SRF Accelerator Test Facility are equipped with coaxial blade tuners. Quality Assurance tests of these tuners during initial installation, cold testing in the Horizontal Test Stand and during string assembly are described.

CONTRIBUTION NOT RECEIVED

HIGH POWER PULSED TESTS OF A BETA=0.5 5-CELL 704 MHZ SUPERCONDUCTING CAVITY

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Abstract

A β = 0.5 5-cell 704 MHz cavity was developed in the framework of European R&D programs on high intensity pulsed proton injectors. Medium beta elliptical cavities are known to be sensitive to Lorentz detuning, which can become difficult to deal with in pulsed operation. The cavity was optimized to reduce the Lorentz detuning by means of two series of rings welded around the irises, and equipped with a piezo tuning system. In order to test the cavity in pulsed mode, a power coupler with 1 MW capability was connected to the cavity. We report here on the fully equipped cavity tests at 1.8 K carried out in the horizontal cryostat Cryholab at Saclay to study its RF and mechanical behavior in pulsed mode, mostly with 2 ms pulses at a 50 Hz repetition rate. The compensation of Lorentz force detuning has been achieved at an accelerating gradient of 13 MV/m (44 MV/m peak surface electric field).

THE EQUIPPED BETA=0.5 CAVITY

The 5-cell 704 MHz Resonator

The cavity was designed specifically for pulsed operation [1]. The main feature of the cavity is the double series of rings for Lorentz force detuning (LFD) minimization. The stainless steel helium vessel has also been optimized in order to provide stiff mechanical boundaries to the cavities when combined with the tuner. The cavity was previously prepared with standard BCP followed by high a pressure water rinse (HPWR). It was tested in vertical cryostat [2] without and with its helium tank reaching an accelerating field of 15.5 MV/m at 1.8K. Field emission was observed during this test. Then it was installed in the Cryholab horizontal test cryostat [3] in order to test the magnetic shielding designed specifically for this cavity [4]. The low field Qo was measured at 3 10^{10}, proving the effectiveness of the magnetic shielding. Field emission was observed above E_{acc} = 8 MV/m, but could be processed away and a maximum accelerating gradient of 16.5 MV/m was obtained. During a measurement on the 4pi/5 mode of the fundamental passband, field emission resumed and could not be processed in-situ. The field emission onset on the fundamental mode was even reduced to 5 MV/m. This led us to perform an additional chemical etching and HPWR before subsequent tests.

Saclay-V Type Tuning System

The cold tuning system is a based on the same principle as the Saclay II tuner [5] for the slow tuning part. When the main screw rotates, the arms (red parts on Figure 1) communicate a rotation movement to the vertical eccentric spindles. The latter provide a function similar to a cam, so that a longitudinal displacement is created between the two main horizontal beams and the “feet” (in green on Figure 1), leading to cavity elongation. The tuner is attached to the cavity at the beam tube flange. Three supports are used to connect it to the helium tank, one on the piezo side, two on the opposite side. The tuner can lengthen or shorten the cavity by 2.7 mm symmetrically with respect to its neutral point.

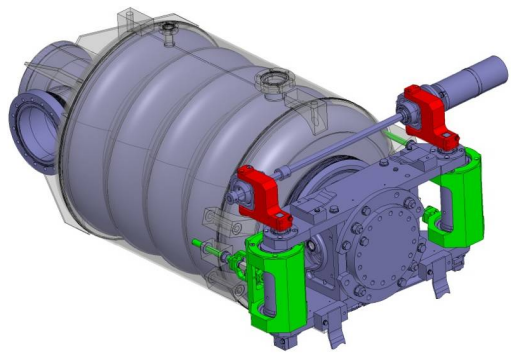


Figure 1: CAD model of the β = 0.5 cavity.

In the previous systems, the mandatory preload force on the piezo actuator was generated by the cavity spring-back force. A minimum elongation of the cavity was necessary in order to preload the piezo element with the correct force. The main improvement in the new tuner is the piezo support which is designed to provide this force independently of the actual cavity elongation needed to bring the cavity on tune.

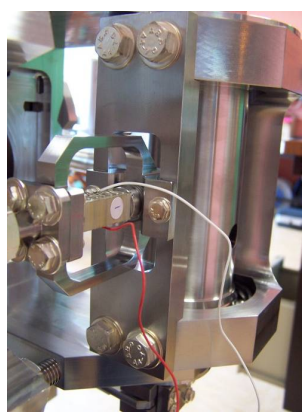


Figure 2: Close-up of the piezo support.

It consists in a stainless steel frame equipped with an adjustment screw acting as a support and a preload spring for the piezo (Figure 2).

In order to provide a force independently of the cavity elongation, the frame stiffness is ten times higher than the cavity stiffness. The piezo elements are 30 mm long

COOLING PROPERTIES OF HOM ABSORBER MODEL FOR CERL IN JAPAN

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Abstract

Two types of the HOM absorber models were designed and fabricated according to results of ferrites and ceramic properties measurement at low temperature. One without HIP ferrite was used to measure thermal property and the other with HIP ferrite to confirm HOM absorption property and thermal tolerance against cooling cycle. Measurement of thermal resistance in inadequate position of comb-type RF bridge suggested that the comb teeth should be modified to reduce the thermal transmission. The HIP ferrite attached to our 9-cell ERL model cavity sufficiently damped HOMs. Several cracks were observed during cooling cycle test.

INTRODUCTION

HOM damping is important for superconducting cavities, especially for high current CW machines such as ERLs. The lower Q-values of HOMs lead to the smaller capacity of a refrigeration system and the higher threshold current against the beam breakup (BBU). Enlarged beam pipes, which have lower cutoff frequencies, are effective to damp monopole and dipole HOMs [1] and the eccentric-fluted beam pipe is effective to damp quadrupole HOMs [2]. Propagating HOMs through the beam pipe are absorbed and damped by the HOM absorbers. Since the HOM absorbers are connected to the superconducting cavities in a cryomodule as shown in Fig. 1, the operating temperature of the HOM absorbers is near liquid nitrogen temperature. The HOM absorbers are required to have high thermal resistance between liquid nitrogen temperature and liquid helium temperature parts to reduce the heat load into the superconducting cavity. The HOM absorption materials are required to have good HOM absorption property as well as good tolerance against cooling cycle.

The HOM absorber models were designed and fabricated to confirm the thermal property and tolerance at liquid nitrogen temperature.

The present paper describes the measured results of thermal property and tolerance at low temperature and HOM absorption property at room temperature .

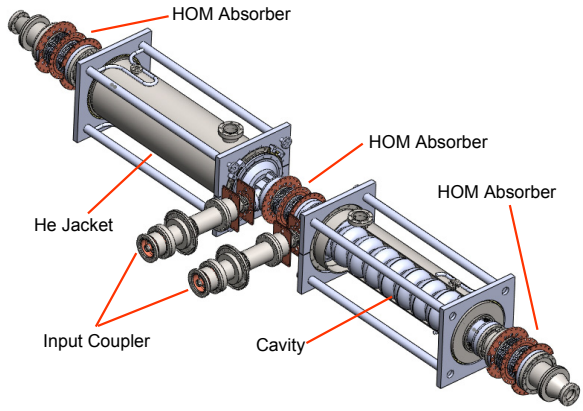


Fig. 1: Layout of HOM absorbers in the cryomodule.

HOM ABSORBER MODELS

The HOM absorber can be divided into three parts. The center part consists of the RF absorber and the 80K-anchor connected to the liquid-nitrogen-temperature line. Both end parts consist of the flange connected to the superconducting cavity and the 5K-anchor. The center part and the end part are connected with a bellows.

HIPped (Hot Isostatic Press) ferrite is attached on the inner surface of the copper base. Since HIP can bond between the ferrite and the copper base firmly, HIP process is adopted to prevent from the ferrite falling off from the copper base. The comb-type RF bridge is adopted at the beam pipe connection between the center and the end parts [3]. The comb-type RF bridge has the advantages of low impedance and small heat conductance compared with the finger-type RF connector. The bellows is used to increase allowance of the flange connection and the heat shrink. The bellows is also used to reduce the heat transmission to the superconducting cavity when the ferrite temperature rises due to HOM power absorption.

Two types of the HOM absorber models were designed and fabricated. One was almost same structure of the HOM absorber except the HIP ferrite (Fig, 2 upper) and the other was a center part with HIP ferrite before machining for teeth of the comb-type RF bridge and the 80K-anchor (Fig. 2 lower). The former was used to measure the thermal property at 80K and the latter to measure the HOM absorption property and the cooling cycle tolerance.

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DEVELOPMENT AND TESTING OF PROTOTYPE FUNDAMENTAL POWER COUPLERS FOR FRIB HALF WAVE RESONATORS*

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Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) requires superconducting Half Wave Resonators to accelerate ions to 200 MeV per nucleon. The Fundamental Power Coupler (FPC) is designed to deliver up to 14 kW of RF power at 322 MHz to the resonator and the beam in CW, and to increase the resonator's control bandwidth for stable operation. With the resonator over-coupled, the mismatch creates a standing wave in the FPC and transmission line downstream of the circulator. The FPC includes an alumina vacuum barrier to allow the resonator to be under ultra-high vacuum. The FPC also serves as a thermal break between the room-temperature transmission line and the resonator at 2 K, with thermal intercepts designed to minimize the heat load to the cryoplant. The FPC design allows for some variation in the coupling, in case a larger bandwidth is needed to mitigate microphonic disturbances. The RF and mechanical design of the coupler and conditioning stand is reviewed, and the results of high power RF conditioning and testing is presented.

DESIGN

Design History and Optimizations

The RF window design for the FRIB coupler takes advantage of existing technology, which has proven record of reliable operation. This design uses the RF windows developed for the Rare Isotope Accelerator (RIA), which had evolved from KEKB, and SNS. [1-3]. The FRIB design incorporates precisely the same methods used for fabrication of the inner conductor window assembly. For reliable operation at FRIB, additional design optimizations are necessary because some of the operating conditions are different.

The FRIB coupling is very high Q (~1e7). Because there is some uncertainty in the extent of the effect microphonics will have on the frequency stability of the cavity, the penetration of the probe into the cavity can be adjusted. This is provided for by the addition of a copper coated bellows on the outer conductor (Figure 1, (D)). A manual adjustment in coupling is done locally by a system of screws, which provides a method to mitigate large microphonic disturbances increasing the control bandwidth.

*This material is based upon work supported by the Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 …
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With a straight coaxial line, the ceramic disc had a direct line of sight to the high electric field region of the cavity, which is an increased potential for problems not realized in the design of the previous couplers. The addition of a tapered region on the inner and outer conductors mitigates this.

A multipurpose copper gasket (Figure 1A) is being developed to serve as the vacuum seal, 4.5 K conduction intercept, and the RF seal. This gasket allows for an excellent heat conduction path from the outer conductor walls, and is applied at the cavity flange.

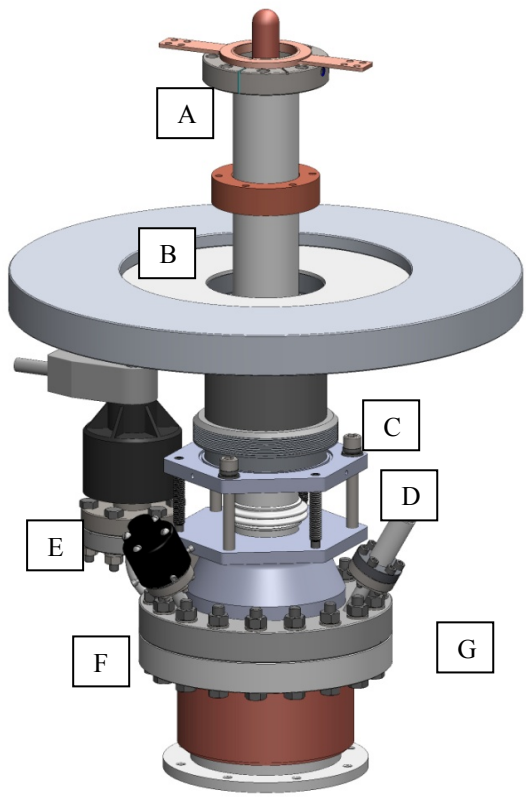


Figure 1: FRIB Prototype Fundamental Power Coupler. (A): 4K intercept, vacuum break ad RF seal, (B) 38 K intercept, (C) Bellows for thermal contraction (D) Bellows for coupling adjustment, (E) Cold Cathode Gauge, (F) Spark Detector, (G) E-probe.

Design Requirements

Two HWR types will be used to accelerate heavy ions from 17 MeV to 200 MeV for uranium. The beam current is low enough that the coupling required for the beam loading may not be enough for to mitigate microphonic

HIGH POWER TESTS OF KEK-ERL INPUT COUPLER FOR MAIN LINAC UNDER LIQUID NITROGEN CONDITION

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Abstract

We fabricated the prototype of an input coupler, which has two ceramic windows to keep the inside of the superconducting cavity clean, for ERL main linac and performed the high power test. Required input power is about 20kW with standing wave condition for the cavity acceleration field of 20MV/m. In this high power test, the one ceramic window, named as a cold window, was installed into the vacuum insulating chamber and cooled by liquid nitrogen. First, the multipacting limited the power level to 10kW. The pulse processing method for 8 hours enabled the final power level to 25kW with standing wave condition. We could also keep 20kW power feeding into the coupler for 16 hours. The maximum measured temperature rises under feeding the 20 kW power to coupler were 120K near the bellows parts and these are not so severe values to operate ERL main linac. After power test, the thermal cycle test of cold window of coupler was done. After 10-times thermal cycle tests between the room temperature and liquid nitrogen temperature, no leaks or cracks were observed. From these results of high power test, this prototype coupler satisfies our thermal and RF requirements.

INTRODUCTION

An input coupler is one of the important items of the superconducting cavity for ERL operation [1]. Table.1 shows the parameters of the input coupler for main linac. Though the mechanism of energy recovery enables to reduce the input power of the main linac, the minimum input power will be restricted by the cavity detuning due to the microphonics from a cryomodule. Therefore, 20kW is needed for our main linac operation.

Table 1: Parameters of input coupler for main linac.

Frequency	1.3GHz
Accelerating voltage	Max 20MV/m
Input power	Max CW 20kW (Standing wave)
Loaded Q (Q_L)	$1x10^7 \sim 4x10^7$(variable)

Fig.1 shows the design of the input coupler for our main linac. Two coaxial disk ceramic windows are set; One, which is called as "cold window", is set on the cold parts at 80K and the other, which is called as "warm window", is on warm parts at 300K for safety against vacuum leak due to window break. Purity of ceramic material is 99.7% to reduce the power loss of ceramic. The impedance of coupler is 60Ω to reduce the power dissipation of inner conductor. Furthermore forced air cooling was applied to inner conductor. Detailed design strategy and parameters are expressed in Ref.[2].

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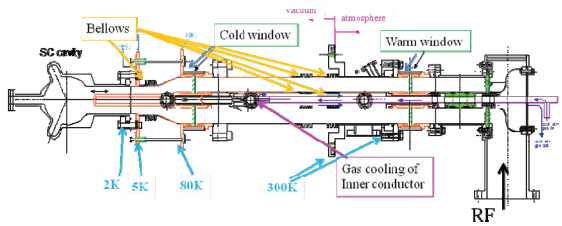


Figure 1: Schematic design of input coupler for main linac

Previously, we fabricated input coupler components, warm ceramic windows with bellows and cold windows, and carried out the high-power test of the components by using a CW 30kW IOT power source. In these component tests, we found the resonance of the dipole mode in ceramic window made the sudden temperature rise and the break of ceramic window as shown in Fig.2 [3][4]. We fabricated the new ceramic window by changing the thickness of ceramic window to escape the resonance mode. We finally achieved 27kW in the high power test by using new ceramic window [5]. The high power test of the components of input coupler was successfully carried out. In this proceeding, we summarized the following tests. First we carried out the thermal cycle tests of old cold ceramic window between 80K and room temperature. Based on this thermal cycle test, we fabricate a prototype of input coupler of ERL main linac (TOSHIBA TETD). Next the high power test of input coupler was carried out under Liq. N_2 cooling. We also carried out the thermal-cycle tests of cold ceramic window by using this input coupler again.

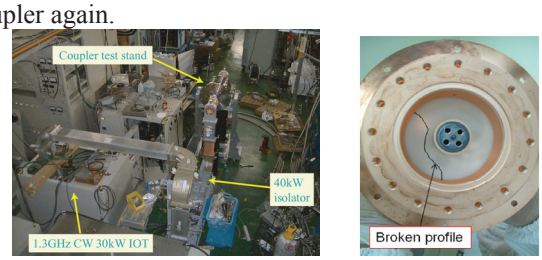


Figure 2: (Left) Setup of the coupler test stand.
(Right) Picture of the cold window with broken profile.

HIGH POWER COUPLERS FOR PROJECT X*

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Abstract

Project X, is a multi-megawatt proton source under development at Fermi National Accelerator Laboratory. The key element of the project is a superconducting (SC) 3GeV continuous wave (CW) proton linac. The linac includes 5 types of SC accelerating cavities of two frequencies, 325 and 650MHz.The highest Beta cavities each consume up to 30 kW average RF power and need properly designed main couplers. This paper describes the requirements and approach to the coupler design for each cavity, presents results of electrodynamic and thermal simulations, and describes new schemes for increasing cost effectiveness.

COUPLERS REQUIREMENTS

The parameters of the five families of cavities in the 3 GeV Project X superconductive linac are presented in Table 1.

Table 1: Cavity Parameters

Cavity	Frequency	Number	Power*	Cryo-loss
SSR0	350 MHz	18	0.7 kW	1.3 W
SSR1	350 MHz	20	1.7 kW	1.7 W
SSR2	350 MHz	40	3.2 kW	3.7 W
LB	650 MHz	36	11.5 kW	24 W
HB	650 MHz	152	17.5 kW	25 W

*Maximal power consumed by the beam.

Using the cavity parameters, and taking into account the necessary overhead and that the coupler must sustain full reflection from the cavities for a short period of time, power levels of 6kW at 325MHz and 30kW at 650MHz have been chosen as the design criteria for the Project X couplers. In addition, the cryogenic loads of the couplers have to be minimized, and the couplers have to allow for assembly to cavities with a vacuum window in a clean room, followed by installation in a cryomodule. Finally, we have designed the couplers to be as simple and as similar as possible to make them cost-effective.

COUPLER CONFIGUTATION AND PARAMETERS

To make coupler production more effective, an approach of maximum unification was chosen. Couplers for both frequencies should contain maximum number of common (shared) parts. Both couplers will have coaxial structures. The outer diameter of coaxial structure is determined by compatibility with previously designed and built 325 MHz cavities. The outer conductor is made from standard seamless 3" stainless tube with its O.D. machined to obtain a 0.8mm wall thickness, and its I.D. coated with an ~10 micron copper layer. The inner conductor is made of 0.5" O.D. oxygen-free copper tube and is air-cooled. The conceptual design of the 2K-300K vacuum part of the couplers is presented in Fig.1.

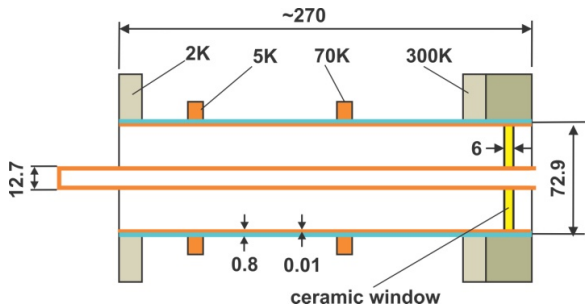


Figure 1: Structure of 2K-300K vacuum part of coupler.

The relatively small diameter of the inner conductor provides a high impedance of 108 Ohm. High impedance has two advantages: it provides lower RF current for fixed RF power and, thus, lower RF loss in outer conductor which is connected directly to low temperature 2K structure. Second, high impedance leads to higher multifactor power threshold and moves it beyond the operating range. Nevertheless, coupler design allows the application of a voltage bias to suppress multifactor if necessary.

The Project X linac is CW machine, so the couplers have a fixed coupling as the penalty for an error in the coupling is a small increase in RF power. Calculations show that the power is not sensitive to mis-coupling: it requires not more than 5% extra power if the coupling varies over the range 0.65 - 1.55, with 1.0 being optimal. It is suggested that cavities be overcoupled from the beginning to decrease microphonic detuning effects.

An antenna tip of a new shape will be used for 650 MHz coupler, Fig.2.

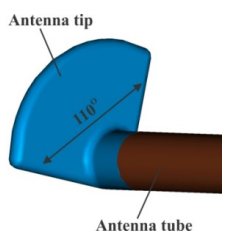


Figure 2: New shape of an antenna tip for 650 MHz coupler.

*Work supported by DOE
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DEVELOPMENT OF STF INPUT COUPLERS FOR ILC

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Abstract

High power tests of the STF-Phase 1 cryomodule was carried out at KEK-STF (Superconducting RF Test facility) in 2008. Vacuum leaks at the cold ceramic window of STF-1 input couplers were found in the disassembly of the cryomodule after warm-up. It was considered that the vacuum leaks might be caused by the thermal cycles. Structures of brazing parts at a ceramic disk was investigated to reduce the thermal strain. The STF-2 input couplers with an improved brazing structure for S1-Global cryomodule was designed after the thermal cycle tests of the sample RF windows. The results of the thermal cycle tests of the sample RF windows and the high power performance of the improved STF-2 input couplers will be reported.

CONTRIBUTION NOT RECEIVED

VERTICAL TEST FACILITY FOR SUPERCONDUCTING RF CAVITIES AT DARESBURY LABORATORY

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Abstract

The Vertical Test Facility at Daresbury Laboratory has been recently relocated to enable it to fulfil its potential of performing high power characterisation tests of Superconducting RF Cavities in the 1.3 to 3 GHz range. The 250 litre, 3 metre dewar is capable of operation from 1.6 K to 4 K and has recently been used to test the first Superconducting cavity produced in the UK. This paper outlines the setup, processes and results of these tests.

INTRODUCTION

As part of the accelerator research and development infrastructure at STFC (Science and Technologies Facility Council), Daresbury Laboratory (UK), a vertical test facility (VTF) for superconducting RF (SRF) cavities was manufactured, commissioned and installed in 2008. However, due to location and shielding issues it was not possible to achieve higher accelerating gradients. Thus as part of a further development programme during 2010/ 2011 the facility was relocated in order to enable high power tests to be performed on newly constructed single cell 1.3 GHz niobium superconducting RF (SRF) cavities. These cavities are the first to be fabricated in the UK and have been manufactured by Shakespeare Engineering [1] as part of collaborative programme of work [2] with ASTeC (Accelerator Science and Technology Centre) at Daresbury Laboratory and Jefferson Laboratory in the US.

SYSTEM DESCRIPTION

The cryostat is 3m tall with an internal diameter of 320 mm and can accommodate liquid helium inventories of up to 300 litres [3]. The cryostat consists of a helium vessel, vacuum containment vessel, internal cavity support structure, instrumentation, radiation baffles and of a number of concentric radiation shields; the radiation shields, baffles, vacuum and super insulation insulate the helium vessel from ambient temperatures, the radiation baffles & shields are cooled using a controlled flow of helium gas through the Dewar neck. Typically, liquid nitrogen is used to perform radiation shield cooling; but using helium gas as the cooling medium is advantageous, as it reduces the risk of experiencing microphonics which result from system generated vibration, that is often caused by being in contact with vigorously boiling liquids. A secondary benefit is a reduction in the logistical burden of managing both liquid helium and liquid nitrogen supplies. The gas cooled shields have proved to be very effective, with the total heat load shown to be approximately 1 W.

The majority of the cryostat system is located below ground level, encased in a minimum thickness of 600 mm of high density concrete and the top section, above ground, is surrounded by a 1 m thick removable radiation shielding block configuration. The cryostat is also enclosed in a specially designed μ-metal shield, the purpose of which is to reduce the effect of the earth's magnetic field to an acceptable level of 15 mG.

The thermometry instrumentation consists of silicon diode temperature sensors, which are required for measuring temperatures down to 1.6 K and PT100s. The silicon diode sensors are attached to the test cavity and support structure, whilst the PT100s are used to monitor the temperatures of the shields. The level of the liquid helium column is measured across the full operating range, by a combination of two 50" overlapping American Magnetic Instruments level probes. Pressure conditions are also monitored and all parameters are recorded by means of data logging system which incorporates a national instrument RIO (reconfigurable I/O) and graphics displayed via Labview.

Cooling from 4.2 K to 2 K is achieved by means of a Leybold Sogevac SV500 rotary vane vacuum pump. A schematic of the setup is shown in Figure 1.

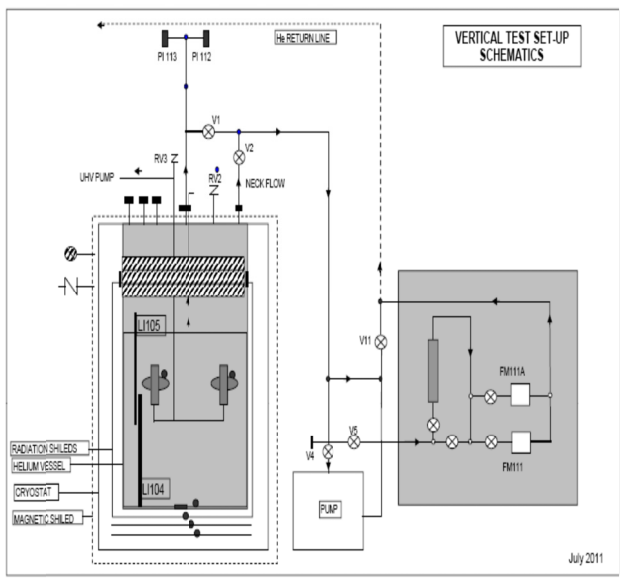


Figure 1: Process schematic.

RF power is applied to the cavity being performance tested using a signal generator via a solid state amplifier (SSA) and is controlled with a Labview based phase locked loop (PLL) system. The PLL system is a National Instruments compact RIO containing a fast; field programmable gate array (FPGA).

HOW TO ELIMINATE A COPPER COATING AND TO INCREASE AN AVERAGE POWER OF MAIN COUPLER*

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Abstract

Idea how to avoid a cooper coating and increase an average power of main coupler by using RF shield is described. RF shield decreases magnetic field at outer wall of coupler, which is connected directly to low temperature superconductive (SC) cavity. Shield has thermal contact with coupler at only one point at 80K, and all RF losses on the shield walls are translated to 80K. Cryogenic losses in the outer wall of a coupler become so small, that there is no need to coat a stainless steel by copper. It decreases a static cryogenic losses as well, simplify technology and promises to make coupler more reliable. More than this, some presented geometries have zero magnetic field around low temperature aria (2K–5K). We can say that coupler "has no dynamic loss" at all.

INTRODUCTION

Main couplers for SC cavities of relatively high average power require special measures to decries a power flow from coupler to low temperature cavity. Among them it is thin copper coating of stainless steel parts. Copper coating is not simple operations and includes several stages. Mechanical and electrical quality of coating does not always satisfy requirements and it causes a malfunction of SC cavity operation. In this paper a new approach is considered, which allows to avoid copper coating and to keep RF cryogenic loss at low level. Calculations show that new couplers have even better thermal properties then coupler with copper coating.

Idea is to use RF shield with good electrical and thermal conductivity which reduces or eliminates fields at coupler stainless steel wall in low temperature aria (2K-5K). At the same tame RF shield has now thermal contact around low temperature, and RF losses are translated to higher temperature (80K) interception.

COUPLERS WITH RF SHIELDING

Simple Sraight Shield

Simple RF shield is presented in Fig. 1. It is an additional copper pipe with thin wall and outer radius slightly less than radius of outer coupler conductor. At one end the copper piper has thermal and electrical contact with stainless tube. Length of copper tube is half of wavelength and it forms slots with the same length. Simulations show that this configuration has no reflection at operating frequency. Maximum fields in slot are the same as in coaxial before and after slot. But in coaxial we have travelling wave and standing wave in slot. By this the RF losses in slot outer wall is twice less then loss in the same wall in coaxial without slot. But real gain can be much more if low temperature area is placed near minimum of magnetic field. In this case the losses in low temperature area, which are most critica, become small. Figure 2 explains this approach. Tables 1 and 2 demonstrate thermal properties of conventional 650 MHz coaxial coupler coated by 10 micron copper and thermal property of coupler with RF shield and without copper coating. One can see that coupler with RF shield has even better thermal characteristics.

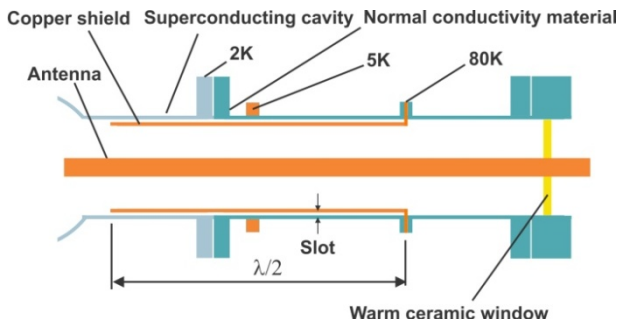


Figure 1: Simple RF shield: l/2λ copper pipe with single mechanical-thermal contact with stainless steel outer pipe.

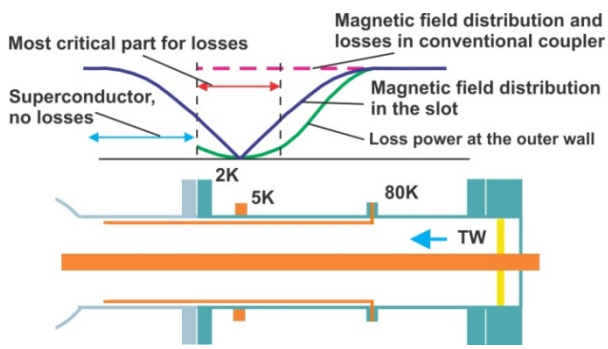


Figure 2: Gain can be much more if low temperature area is placed near minimum of magnetic field.

Table 1: Conventional coupler. Cryogenic losses at different interception point

RF power,	Power 2K,	Power 5K,	Power 80K,
0 kW	0.029 W	1.63 W	8.90 W
30 kW	0.080 W	1.79 W	9.25 W

*Work supported by DOE
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CONDITIONING THE FUNDAMENTAL POWER COUPLER FOR ERL SRF GUN*

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Abstract

The 703 MHz superconducting gun for the BNL Energy Recovery Linac (ERL) prototype has two fundamental power couplers (FPCs), and each of them will deliver up to 500 kW of CW RF power. In order to prepare the couplers for high power RF service and process multipacting, the FPCs should be conditioned prior to installation into the gun cryomodule. A conditioning cart based test stand, which includes a vacuum pumping system, controllable bake-out system, diagnostics, interlocks and data log system has been designed, constructed and commissioned by collaboration of BNL and AES. This paper presents FPC conditioning cart systems and the conditioning process for the BNL GUN FPCs.

INTRODUCTION

The 703 MHz photo-injector is used to produce high current, high brightness electron beam for BNL high current Energy Recovery Linac (ERL) prototype, shown in Figure 1 [1], whose design parameters are listed in Table 1. The 704MHz half-cell superconducting gun requires a total of 1 MW of RF power in order to meet the high current specification (0.5 A, 2 MeV), necessitating two 500 kW fundamental power couplers.

In order to ensure that the FPCs will be able to perform properly in operation, they must be cleaned, assembled, baked and then conditioned with RF power at levels about twice the operating power level. A room temperature test stand has been designed and built by AES in collaboration with BNL for testing and conditioning of the FPCs. The goals for the testing and conditioning include: (1) to help remove any surface imperfections from the fabrication step; (2) to check for, and process through, any multipacting barriers that may be encountered; (3) to ensure the copper plating on the outer conductor is well adhered; (4) to help outgas the UHV components prior to installation on the gun; (5) to ensure the parts are capable of handling the designed power level prior to installation on the gun; (6) to verify the cooling circuits function properly and provide adequate cooling to the respective parts. This paper presents the conditioning test stand and procedures of conditioning for BNL gun FPCs.

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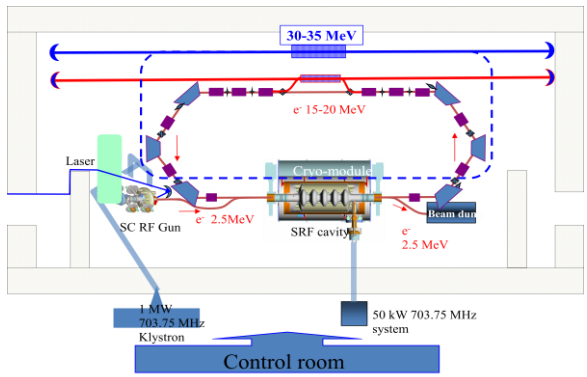


Figure 1: Layout of BNL ERL prototype.

Table 1: BNL ERL prototype parameters

Parameters	High Current	High charge
Bunch charge[nC]	0.7	5
Passes	1	1
Energy max/injection, [MeV]	20/2.5	20/3.0
Bunch rep-rate[MHz]	700	9.383
Average current[mA]	500	50
Injected/ejected beam power[MW]	1.0	0.15
RMS emittances ex/ey, [mm*mrad]	1.4/1.4	4.8/5.3
RMS □E/E	3.5×10^{-3}	1×10^{-2}
RMS Bunch length[ps]	18	31

FUNDAMENTAL POWER COUPLER

Figure 2 shows the scheme of 50 Ω coaxial-line-based fundamental power coupler for the gun cavity. The FPC is separated by a planar alumina window to vacuum side and air side. On the vacuum side, the copper-plated

AUTOMATIC CLEANING MACHINE FOR RF POWER COUPLERS*

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Abstract

Couplers are technological devices that permit RF power matching between RF source and cavities. An high cleaning quality requirement especially for the coupler cold part directly linked to the cavity is needed. Even if the actual coupler preparation procedure at LAL works well, contamination risks remain due to the handling, no repeatability and a too long time duration (5 days) which is not acceptable for machines like ILC where around 16000 couplers would be prepared.

Our challenge is to suppress these weak points, in designing an automatic coupler cleaning machine which give us a lower contamination risk, a full repeatability of the cleaning and only 3 hours of process.

INTRODUCTION

Couplers are technological devices that permit RF power matching between RF source and cavities.

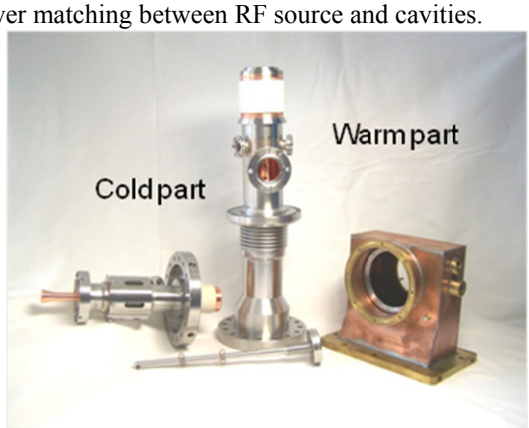


Figure 1: Coupler parts.

As couplers (Fig. 1) are directly plugged on cavities, they have a very high cleaning quality requirement in term of particles contamination. To satisfy this requirement, the following process [1] has been developed: ultrasonic bath in clean room class 1000 with detergent and warm (60°C) Ultra-Pure Water (UPW) for 15 minutes. Then pieces are rinsed by hand with a check of the rinsing water resistivity. After these 2 steps, the pieces are placed on a bench in the clean room class 10 for drying (a minimum of 72 hours of drying is needed). At the end, before mounting, a particle counting is done in order to certify the cleanness of the couplers.

The weak points of the actual cleaning procedure are:

- Contamination risks due to the handling
- No repeatability
- Too long time duration: 5 days

These points are not acceptable for coupler mass production (ILC) where around 16000 couplers would be prepared.

The solution is to use an automatic cleaning system with:

- No handling
- Full repeatability and control of each parameters
- Shorter time duration: 3 hours

Unfortunately, this kind of machine is not available in the industry. Our project is to make one in order to prove that it is possible to clean couplers automatically for mass production.

THE MACHINE

The Process

A cleaning cycle includes the following steps:

- Ultrasonic cleaning with hot UPW & detergent
- Rinsing and resistivity measurement
- Drying with filtered N2 and humidity measurement

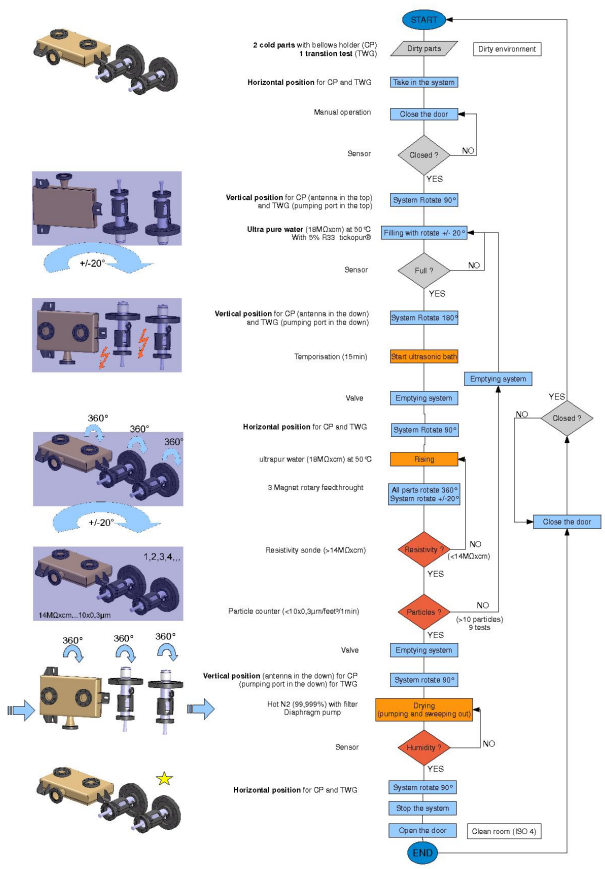


Figure 2: Cleaning steps overview.

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NIOBIUM ELECTROPOLISHING IN AN AQUEOUS, NON-VISCOUS HF-FREE ELECTROLYTE: A NEW POLISHING MECHANISM*

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Abstract

Faraday is working with Jefferson Lab to develop an improved process for electropolishing niobium RF superconducting cavities in an electrolyte free of hydrofluoric acid, to create microscopically clean and smooth niobium surfaces on the cavity interior. Conventional electropolishing of niobium cavities is based on a viscous electrolyte with an approximately 20 micron thick diffusion layer,[1] containing hydrofluoric acid as a depassivation agent. The FARADAYIC Electropolishing process combines pulse reverse electric fields and aqueous, low acid, non-viscous electrolytes to control current distribution and oxide film formation during metal removal. This eliminates the need for a depassivation agent, such as hydrofluoric acid. This program is aimed at understanding this new electropolishing mechanism, and optimizing it to achieve the desired oxide formation, reduced defect density and high performance. The feasibility of the process has been demonstrated using an aqueous sulfuric acid solution in conjunction with the FARADAYIC Process to electropolish niobium to surface finishes below 1 nm over a 2 x 2 micron area.

INTRODUCTION

State-of-the-art finishing for niobium cavities uses chemical polishing or electropolishing.[2] In chemical polishing, a mixture of concentrated nitric, hydrofluoric and phosphoric acids is used: the nitric acid forms a niobium oxide layer, which is dissolved by the hydrofluoric acid, with the phosphoric acid acting as a buffer to prevent high reaction temperatures.[3] Typical removal rates achieved using this technique are about 1 µm/min. However, the resulting surface roughness is an order of magnitude higher than conventional electropolishing and the grain boundaries are enhanced, which may degrade the quality factor.[4]

In conventional electropolishing, an electrolyte of concentrated sulfuric and hydrofluoric acid is used in combination with a constant voltage. Oscillations in the electropolishing process have been observed, which likely correspond to oxide film growth and dissolution. Voltages may be as high as 25 V with current densities of 10 A/dm^2.[5,6,7] Conventional electropolishing achieves metal removal rates up to 0.5 µm/min.[8] Higher rates (e.g. 0.65 µm/min) have been obtained with buffered electropolishing,[4] which uses a lactic, sulfuric, and hydrofluoric acid electrolyte.

Disadvantages of both chemical and conventional electropolishing processes include the use of hydrofluoric acid to achieve breakdown of the passive film on the surface. Ideally, a polishing process for superconducting Nb cavities will have attributes that include the following:

- Electrolyte free of hydrofluoric acid
- Control of surface roughness to a microscale finish, Ra $\leq$ 0.1 µm
- Surface free from contamination after polishing
- Current distribution control that enables uniform polishing across the entire cavity surface
- Controlled removal of at least 100 µm

TECHNICAL APPROACH

Faraday has achieved a technical breakthrough with the demonstration of the feasibility of the FARADYAIC Electropolishing process, which employs sophisticated electric fields to control oxide film formation during metal removal, to achieve Nb polishing without hydrofluoric acid. FARADAYIC Electropolishing differs from conventional electropolishing through the use of a user defined, asymmetric waveform (in comparison to a constant voltage/current) permitting benefits that include:

- Control of oxide film formation,
- Improved polishing uniformity by producing a more homogenous current distribution through the control of process parameters,
- Increased metal removal rates, if desired, and
- The use of low-acid or neutral, aqueous electrolytes.

Pulse and pulse reverse electrolysis have been applied to special applications in edge and surface finishing.[9,10] A generalized pulse reverse electrolysis waveform is shown in Figure 1, and consists of an anodic peak current density, i_a, and associated on time, t_a, a cathodic peak current density, i_c, and associated on time, t_c, and an off time, t_0. (*Please note: voltage control is often preferred for metal removal; however, it is easier to discuss the theory in terms of current control.*) The sum of the on times and off time is the period of the waveform. The anodic, D_a, and cathodic, D_c, duty cycles are the ratios of the respective on times to the period. In contrast to conventional DC processes where the control variable is either constant voltage or current, the FARADAYIC Electropolishing process introduces several key process parameters that are user defined: the peak anodic current density, anodic on time, and duty cycle. The proper selection of these variables is critical for the successful implementation of the process due to the strong

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ASSEMBLY OF THE INTERNATIONAL ERL CRYOMODULE AT DARESBURY LABORATORY

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Abstract

The collaborative development of an optimised cavity/cryomodule solution for application on ERL facilities is nearing completion. This paper outlines the progress of the cryomodule assembly and details the processes used for final cavity string integration. The preparation and installation of the various subcomponents of the cryomodule are also detailed in this paper.

INTRODUCTION

The assembly at Daresbury Laboratory of the Superconducting RF (SRF) cryomodule developed for high current ERL applications, with intrinsic capability for operating at high Q_{ext} and CW operation is nearing its final stages of completion.

Table 1: Cryomodule Design Parameters

Parameter	Value
Frequency (GHz)	1.3
Number of Cavities	2
Number of Cells/Cavity	7
Cryomodule Length (m)	3.6
R/Q (Ω)	762
E_{acc} (MV/m)	>20
E_{pk}/E_{acc}	2.23
H_{pk}/E_{acc} (Oe/MV/m)	46.9
Cryomodule Energy Gain (MeV)	>32
Q_0	>1 x 10^{10}
Q_{ext}	4 x 10^6 – 10^8
Maximum Beam Current (mA)	100
Max. Cavity Forward Power (kW)	25 SW

The international partners who have participated in this collaborative development (Cornell and Stanford universities, STFC Daresbury Laboratory, DESY, FZD-Rossendorf, Lawrence Berkeley Laboratory and TRIUMF) have identified appropriate subsystem solutions to achieve the fundamental requirements for this new cryomodule, which have been reported previously [1,2]. Table 1 highlights the primary design parameters of this optimised cryomodule, which is due to be installed on the ALICE ERL accelerator at Daresbury Laboratory and validated with beam later this year.

CAVITY QUALIFICATION

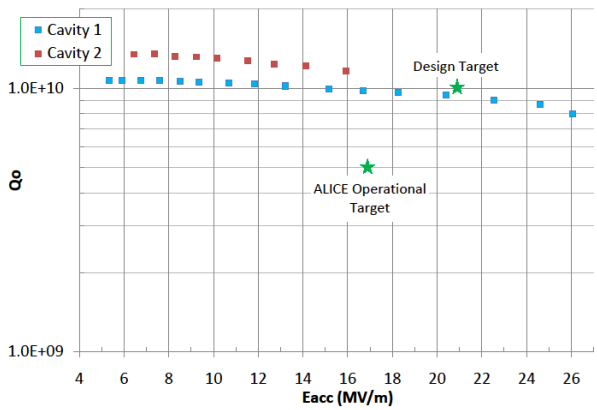


Figure 1: Vertical test results.

After heavy etching (400-500 µm) and a 48h 115°C bake, the vertical tests carried out at Cornell on the two highly modified DESY superstructure cavities showed very good performance and met the ALICE operational specification. The FE limitations observed were ascribed to the difficulty in cleaning the He jacketed cavities. Further improved cleaning, particularly of the central cells, was carried out before shipping to Daresbury, and final performance is expected to be better than the test results shown in Figure 1.

INPUT COUPLER TESTING

As previously reported, the input couplers were high power tested (see Figure 2) to 5 kW CW and 10 kW pulsed with no notable vacuum activity throughout the process [3]. Further tests were carried out following improvements to the coupler test stand HV power supply and RF systems. Temperature rises on the coupler ceramics were detected when attempting to raise the CW power, therefore it was decided to run pulsed power tests.

HIGH GRADIENT RESULTS OF ICHIRO 9-CELL CAVITY IN COLLABORATION WITH KEK AND JLAB

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Abstract

KEK and Jlab have continued S0-study collaboration on ICHIRO 9-cell cavities since 2008. In 2010, we have started S0 study on ICHIRO#7, full 9-cell cavity with end groups. Surface treatments and vertical tests have been repeated at Jlab. Maximum gradient of 40MV/m was achieved so far. We will describe the details of that and further plan of S0-study on ICHIRO 9-cell.

INTRODUCTION

We have succesfully demonstrated the principle proof of 50MV/m with ICHIRO single cell cavities in our high gradient R&D for ILC-ACD at KEK. For ICHIRO 9-cell, we have started S0-study in collaboration with Jlab from 2008. In S0 study, cavities will be exchanged and tested at each laboratory. We can cross check the data and also compare the facilities. In the S0-study on ICHIRO#5, which has no end group, we have achieved 36.5MV/m at Jlab and 33.7MV/m at KEK[1]. End group means HOM couplers, RF input coupler port, and RF pick-up antenna port. We confirmed that our KEK ICHIRO facilities are not so different from Jlab. After ICHIRO#5, we fabricated two full ICHIRO 9-cell cavities with fine grain Nb, ICHIRO#7 and #8. Our top priority is the proof of 50MV/m with full ICHIRO 9-cell cavity, so we decided to do S0-study with Jlab again with ICHIRO#7. Figure 1 shows the image of ICHIRO#7.

COMISSIONING OF ICHIRO#7 AT JLAB

At KEK, we processed ICHIRO#7 by our standard recipe which consists of centrifugal barrel polishing (CBP, ~100μm), light chemical polishing (CP, 10μm), annealing (750°C x 3hrs), electropolishing (EP, 80 + 20μm), flash EP (3μm, fresh acid, no circulation), post EP cleaning [2, 3], HPR, and baking (120°C x 48hrs). Pi-mode gradient was limited by field emission (FE) at 12MV/m. We found a defect on beam tube by inspection after VT; it might be a source of FE. We ground it off by mini-handy grinder before sending ICHIRO#7 to Jlab. KEK staff visited Jlab and had responsibility for process and test.

Installation

We prepared hardware in order to process ICHIRO#7 at Jlab facilities. Jlab's cavity cage was modified to fix ICHIRO#7 with KEK's cage. ICHIRO#7 has MO seal on beam tube flanges [4], so we made adapters between MO flange and EP sleeves. We also made new EP cathode for ICHIRO#7. For HOM ports and Pt port, we used ILC standard Al gasket as sealing. Those ports of ICHIRO#7 were made of Nb. Leak tightness of this combination was successfully demonstrated in this S0-study. Fundamental RF input coupler port was sealed with indium wire because of the difference of flange shape. MO flange was sealed with indium plated Al gasket. Figure 2 shows some hardware installation.



Figure 1: full ICHIRO 9cell cavity #7.

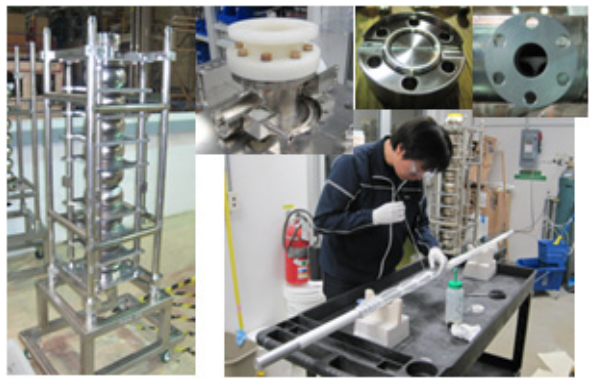


Figure 2: Installation of ICHIRO#7.

VT-1, as received

After shipping, ICHIRO#7 was inspected inside and confirmed flatness of 94%, no degradation during shipping. VT-1, as received test, was done after re-rinsed with ultrasonic cleaning (USC) with Liqui-Nox and HPR. The result is shown with blue dots (■) in Figure 3. Maximum gradient was improved from 12MV/m to 21MV/m; but limited by FE. Mechanical grinding mark still remains on beam tube, so this might have some responsibility for FE limitation. The flatness was kept with 93% through VT-1.

VT-2, after 1st EP (25μm) at Jlab

The processes for 2nd RF test were 25μm EP, post EP cleaning of wiping and brushing on end groups, USC, and 6cycles of HPR in total. Unfortunately, the indium seal at input coupler port was melted and leak was happened because of failure baking process. Cavity inside was contaminated by melted indium. We did nitric acid soaking to remove the indium contaminations and HPR again. Then cavity was baked with 120°C for 48hrs successfully, and tested. The result is shown with purple dots (◪) in Figure 3. Severe FE was induced during the processing around 15MV/m, and gradient was limited

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STANDARD PROCEDURES OF ILC HIGH GRADIENT CAVITY PROCESSING AND HANDLING AT JEFFERSON LAB*

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Abstract

We describe the JLab standard procedures of ILC cavity processing and handling for reproducible high gradient, high Q_0 results. The procedure includes optimized electropolishing (EP), streamlined post-EP cleaning, updated vacuum furnace out-gassing, no-touch bead-pull tuning and slow pumping down for cavity evacuation.

INTRODUCTION

The standard ILC cavity processing recipe [1] consists of, among others, the following steps following the completion of cavity fabrication,

- Light BCP etching (10-30 μm).
- Heavy EP (100-150 μm).
- Vacuum furnace outgassing (600-800 ˚C).
- Tuning for field flatness and frequency.
- Light EP (20-50 μm).
- In-situ baking at 120 ˚C for 48 hours.

The exact implementation varies at different processing facilities. For example, the exact amount of light BCP prior to heavy EP, the exact amount of heavy EP, the exact vacuum furnace heat treatment cycle (temperature, duration and ramp up profile), and the exact light EP amount vary within a rough range as listed above. In this paper, we describe the JLab standard procedures of ILC cavity processing and handling.

The standard JLab procedure has been used in preparation of fine-grain 9-cell ILC cavities since 2009. More recently, it has been also used for processing large-grain niobium and seamless niobium 9-cell cavities. The procedure begins with mixing fresh electrolyte at a molar ratio of $HF:H_2O:H_2SO_4$ in a range that is compatible with that in the original Siemens recipe. Three key process parameters, namely the acid flow rate, the polish cell voltage and the cavity body temperature, are identified and in control. The optimal EP is achieved in the continuous current oscillation mode. The appearance of current oscillation also serves as a sensitive in-situ QA/QC indicator. The "auto polishing" procedure is introduced by continuing the acid flow and cavity rotation after the voltage is shut off. This effectively reduces sulfur-bearing niobium oxide granules, an inherent contaminant of the EP process. An elaborate post-EP cleaning procedure includes low-pressure water rinsing, HOM coupler brushing and ultrasonic cleaning with detergent. Additional ethanol rinsing is applied following the heavy EP to facilitate removal of sulfur deposit on the niobium surface. The vacuum furnace heat treatment procedure is updated. A no-touch bead-pull method is established. Slow pump down is routinely applied to prevent recontamination of the cavity surface. The repeatability of the cavity processing procedure and the reproducibility of high gradient high Q_0 results are much improved as compared to that during the initial period of ILC cavity work at JLab.

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

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ELECTROPOLISHING

Electrolyte Mixing

Electrolyte mixing is done at the EP machine. A volume ratio of 1:10 ($HF(48\%):H_2SO_4(96\%)$) is used for a molar ratio of $HF:H_2O:H_2SO_4$ compatible with that of the original Siemens recipe [2]. Prior to mixing, the electrolyte storage tank and acid piping are flushed with sulfuric acid (96% concentration). This eliminates any possible water left in the system. Then 55 gallon of sulfuric acid (96% concentration) is transferred into the electrolyte storage tank followed by chilling while keeping the acid in circulation (this is done by connecting the cavity acid inlet hose with the cavity acid outlet hose). Addition of the first gallon of hydrofluoric acid (48%) starts when the electrolyte temperature in the storage tank reaches 15 ˚C or lower. Acid circulation is then continued until the electrolyte temperature recovers to 15 ˚C again, followed then by addition of the second gallon of hydrofluoric acid. This process is repeated till 5.5 gallon of hydrofluoric acid is added.

Electropolishing

A horizontal EP [3] machine is used at JLab. Three key EP parameters are identified and are under control,

- Voltage. Nominal at 14.5 V as measured across the body of cavity and the cathode, allowable range 13-17 V.
- Cavity cell temperature (measured at the cavity outer surface near the equator region). Nominal at 25 ˚C, allowable range 20-30 ˚C for final light EP and nominal at 30 ˚C, allowable range up to 35 ˚C for heavy EP.
- Acid flow rate. Nominal at 3-4 liter per minute.

In addition to these key parameters, it is important to keep the purging nitrogen gas flow at the minimum level. We also changed the direction of acid supplying holes in the cathode tube. They face upward instead of downward. This reduces the disturbance of the viscous layer across the acid niobium interface.

STUDY CORRELATING NIOBIUM SURFACE ROUGHNESS WITH SURFACE PARTICLE COUNTS

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Abstract

A study has been initiated at Michigan State University (MSU) to relate the surface preparation of Superconducting Radio Frequency (SRF) resonators and surface particle counts, using niobium samples. During fabrication, undesired surface roughness can develop on the internal surfaces of the resonators. The final cavity finish will be product of material forming, machining, welding, chemistry, high-pressure rinsing, and handling of the niobium material. This study will document niobium samples treated with MSU standard processing procedures; first measuring the surface roughness, then polishing samples with defined techniques, processing, and measuring surface particle counts. The samples will include as received niobium, machined surfaces, welded surfaces, and surfaces with characterized surface imperfections (scratches).

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is an approved ~550M$ project funded by a cooperative agreement between Michigan State University (MSU) and The US Department of Energy (DOE) for advancement in the study of rare isotopes. The driver linac for the FRIB project is an 200 MeV/u superconducting linac with final beam power reaching 400 kW. There are four types of resonators used; two quarter-wave resonators (80.5 MHz, Beta= 0.041 & 0.085) and two half-wave resonators (322 MHZ, Beta= 0.29 and 0.53) [1]. The resonators are house in rectangular, bottom loaded cryomodule with internally built focusing solenoids.

Acquisition strategies have been drafted for the major components of the FRIB linac, including the procurement of the 341 required SRF cavities. As part of the acquisition specifications, a study was initiated to correlate niobium surface roughness with post-processing particle counts and define the acceptance criteria. The study will also establish a mechanical polishing procedure to be used on SRF cavity surfaces as a means to repair surface defects. Surface defects are defined here as surface irregularities occurring from fabrication or processing of the cavities. Surfaces can become damaged as a result of machining (tool marks, tool breaks) electron-beam welding (sputter, undercutting), and cavity mishandling (scratches, dings).

The study will use small niobium samples, measuring both surface roughness and surface particle counts as the samples are exposed to polishing methods and standard SRF cavity processing.

Using a QIII+SPD (Pentagon) surface particle counter, surface particles will be measured before and after the samples are processed. Samples will be prepared in lots of three, with all samples in a lot receiving the same treatments. In addition, a lot of control samples will follow all sample processing runs.

SAMPLE PREPARATION

The initial study will use flat poly-crystal (~50μm), high RRR (>250) niobium samples. Samples will be 2 inches by 2 inches by 0.079 inches thick. The defined polishing technique for a given sample lot will be applied to a 1 inch by 1 inch square, centered area on the sample. Surface roughness measurements will be taken on samples as-received, after polishing, and after processing.

A Fowler Profilameter (54-410-500) was used to measure the surface roughness. Two small holes are used to mount samples to process tooling. A portion of the samples will be halved and electron-beam welded together, with a full penetration weld, to study the welded surface. All samples were processed using the same processing procedures, equivalent to procedures used in standard FRIB cavity processing; see PROCEDURE section. Data will be collected and recorded from all samples tested. Data presented is an average of the data collected from the three samples per lot.

Prior to processing, a selection of samples, with and with outs welds, will receive a surface polish, exploring multiple polishing methods and media. In addition, a selection of samples will be prepared with scratches to define acceptable polishing practices in the event scratches are observed on cavity surfaces. Scratches will be “man-made” using a scribing end mill to produce scratches with uniform width and depth across several samples/lots. Examples of the three types of samples are shown in Figure 1.

DEVELOPMENT AND SCALE-UP OF AN HF FREE ELECTROPOLISHING PROCESS IN SINGLE-CELL NIOBIUM SRF CAVITIES*

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Abstract

The performance of niobium SRF cavities is strongly dependent on a microscopically smooth and clean surface, achieved using buffered chemical polishing or electropolishing, which require a viscous electrolyte containing hydrofluoric acid to achieve niobium oxide breakdown and current distribution control. An ideal polishing process would include: electrolyte free of hydrofluoric acid; control of surface roughness to less than 0.1 micron; surface free from contamination; current distribution control enabling uniform polishing; removal of at least 100 microns. Additional benefits from the use of a low viscosity could enable cavity electropolishing protocol more compatible with industrial scale processes. Faraday and Fermilab are collaborating to develop and scale-up the FARADAYIC Electropolishing process to validate its performance for single-cell cavity electropolishing. FARADAYIC Electropolishing combines pulse reverse electric fields and low viscosity aqueous electrolytes to control current distribution and oxide formation during metal removal. Recent results on coupon polishing will be presented including polishing rates up to 1 micron/min, control of electrolyte temperature to below 20°C, and surface finishes less than 0.2 microns over 4 mm length scales. Construction of a single-cell cavity electropolishing apparatus at Faraday is discussed.

INTRODUCTION

This technology addresses the need for eco-friendly polishing technologies for niobium cavities, that are not dependent on the use of hydrofluoric acid. This program is in response to a request for proposal from Fermi National Accelerator Laboratory (Fermilab) seeking vendors capable of performing fluorine-free bulk material removal and surface polishing of niobium superconducting radio frequency (SRF) accelerating cavities. The SRF cavities may be used as part of a proposed Project X facility to be sited at Fermilab and for the International Linear Collider R&D program. The following specifications are minimum requirements for the process:

- Electrolyte free of hydrofluoric acid
- Control of surface roughness to a microscale finish, Ra $\leq$ 0.2 µm
- Surface free from contamination after polishing
- Current distribution control that enables uniform polishing across the entire cavity surface
- Controlled removal of up to 150 µm

TECHNICAL APPROACH

Faraday has achieved a technical breakthrough with the demonstration of the feasibility of the FARADAYIC Electropolishing process,[1,2] which employs sophisticated electric fields to control oxide film formation during metal removal, to achieve Nb polishing without hydrofluoric acid. The process is generally applicable to electropolishing of other strongly passive materials, such as titanium and nickel-titanium shape memory alloys.[3] FARADAYIC Electropolishing differs from conventional electropolishing through the use of a user defined, asymmetric waveform (in comparison to a constant voltage/current) permitting benefits that include:

- Control of oxide film formation,
- Improved polishing uniformity by producing a more homogenous current distribution through the control of process parameters,
- Increased metal removal rates, if desired, and
- The use of low-acid or neutral, aqueous electrolytes.

Based on the feasibility of electropolishing Nb coupons, this activity is directed towards validating the process for single-cell SRF cavities using existing apparatus developed at Argonne National Laboratory.[4] While this activity is directed towards an eco-friendly process, the use of low viscosity electrolytes could offer added benefits. For example, as recently reported by researchers at Fermilab,[5] non-uniform agitation and temperature effects associated with the current process disrupts the viscous boundary layer and facilitates fluoride anion access to the niobium cavity surface and promotes etching. We presume that the non-viscous electrolyte used in the FARADAYIC ElectroPolishing process would be less susceptible to these process instabilities and could lead to a robust industrial scale process.

A generalized pulse reverse electrolysis waveform is shown in Figure 1, and consists of an anodic peak current density, i_a, and associated on time, t_a, a cathodic peak current density, i_c, and associated on time, t_c, and an off time, t_0. (The sum of the on times and off time is the period of the waveform. The anodic, D_a, and cathodic, D_c, duty cycles are the ratios of the respective on times to the period. In contrast to conventional DC processes where the control variable is either constant voltage or current, the FARADAYIC Electropolishing process introduces several key process parameters that are user defined: the peak anodic current density, anodic on time, and duty cycle. The proper selection of these variables is critical

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UPDATE OF THE DESY INFRASTRUCTURE FOR CAVITY PREPARATION

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Abstract

The clean room, set up in the early 90th of the last century, is the main infrastructure for preparation of superconducting cavities at DESY. This clean room was completely renovated in 2009. The ground plan of clean room class ISO 4 was enlarged from 20 to 53 m² and the areas of ISO 7 of the old clean room were upgraded to ISO 6 and ISO 5 standard. Areas for ultrasonic cleaning, ultrapure water rinsing and chemical surface treatment were upgraded to ISO 4 standards. Multiple vacuum connections were installed to reduce movement of cavities. A 120°C heating chamber was connected to the ISO 4 assembly area and allows the in situ bake out of multi cell super conducting resonators. For industrial cavity production it was shown that a high pressure rinsing unit driven by a turbine pump allows feeding several high pressure rinsing stands in parallel. For cost reduction of ultra-pure water production and for increase of the amount of water in the cavity preparation cycle, a recirculation of rinsing water is under commissioning. Fixtures and tools for the assembly of the Beam position monitor and Quadrupol units (BQU) for the XFEL modules are installed and commissioned.

INTRODUCTION

In the last years an improvement on clean room technology took place. Beside reduction of energy consumption, more homogeneous air distribution by individual filter fan units (FFU) and more effective filters were developed. At DESY, the XFEL project was launched in 2007. Various activities like repair and upgrade of XFEL cavities, assembly of Quadrupol-Beam position monitor packages (QBU) for work package 9 of the linear accelerator consortium and the assembly of a 3.9 GHz module for the XFEL injector will take place in the DESY clean room. For these activities the DESY clean room was upgraded to the standards of 2009 and new improved infrastructure for the tasks within the XFEL project were developed.

UPGRADE OF INFRASTRUCTURE

Cleanroom Air Distribution System

The DESY clean room was built in early 90th. Enlargement of space and upgrade of air quality of this cleanroom was limited by the two central fan units installed. In 2009 the clean room air distribution system and the clean room walls were replaced and the work spaces were adapted to the new activities (Table 1). Filter Fan Units (FFU´s) and an air shower were added and a new energy saving air condition unit was installed (Fig.1). That set up allows a flexible increase of space and air quality as required for the projects.

Table 1: Overview on ground plan and actual installed clean room air quality

Clean room part	Before refurbishing	After, refurbishing
ISO 4	20 m²	53 m²
ISO 5	112 m²	82 m²
ISO 6+7	ISO 7...65 m²	ISO 6…65 m²
Chemistry area	ISO 7...55m²	ISO 5 ...55 m²
Ultrasonic cleaning / UP rinsing	ISO 7	ISO 4
HP rinse 1+2	ISO 4	ISO 4

The FFU´s are self-controlling and can be set individually. These units are controlled by facility management software with online control of the homogeneity of the air flow volumes and distribution as well as air condition parameters. The FFU´s allow regulating and adapting the air volumes to keep the air flow conditions (laminar flow) constant, when air pressure and air distribution are disturbed by opening of doors.



Figure 1: Main clean room area (ISO 4/5) before installation of FFU´s.

Alarms are generated to inform the cleanroom crew when the FFU´s are not able to keep that laminar flow conditions any more. For power saving the air flow can be reduced during night or weekends.

FABRICATION, TUNING, TREATMENT AND TESTING OF TWO 3.5 CELL PHOTO-INJECTOR CAVITIES FOR THE ELBE LINAC

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Abstract

As part of a CRADA (Cooperative Research and Development Agreement) between Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and Thomas Jefferson Lab National Accelerator Facility (TJNAF) we have fabricated and tested two 1.3 GHz 3.5 cell photo-injector cavities from polycrystalline RRR niobium and large grain RRR niobium, respectively. The cavity with the better performance will replace the presently used injector cavity in the ELBE linac [1].

The cavities have been fabricated and pre-tuned at TJNAF, while the more sophisticated final field tuning; the adjustment of the external couplings and the field profile measurement of transverse electric modes for RF focusing [2] was done at HZDR.

The following standard surface treatment and the vertical test were carried out at TJNAF's production facilities. A major challenge turned out to be the rinsing of the cathode cell, which has small opening (Ø10 mm) to receive the cathode stalk. Another unexpected problem encountered after etching, since large visible defects appeared in the least accessible cathode cell.

This contribution reports about our experiences, initial results and the on-going diagnostic work to understand and fix the problems.

INTRODUCTION

The development of the superconducting photo-injector at HZDR started in 1998. A very successful demonstration of an electron beam from a superconducting gun in 2002 led to the present injector design for the ELBE LINAC (**E**lectron **L**inear accelerator with high **B**rilliance and low **E**mittance).

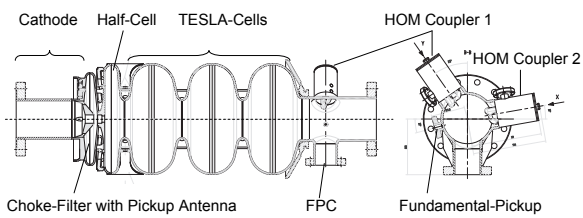


Figure 1: Cross-section of the modified 3.5 cell SRF-Gun cavity.

The injector cavity is shown in Figure 1. It consists of three cells with the TESLA cell shape and one velocity optimized half cell. The cathode insertion was designed for an easy exchange and precise positioning of Cs_2Te cathodes. Additionally, a resonant superconducting choke filter surrounding the cathode is needed to prevent RF leakage out of the cavity. Two TESLA type HOM dampers and one 10 kW CW input coupler, developed at HZDR are attached to complete the design.

The commissioning of the cavity started in September 2007 and even though the cavity performance in the vertical test showed some respectable values, it became obvious that in the injector configuration the cavity was limited by field emission, limiting both the Q-value and the achievable gradient [3]. Therefore this project described here was launched with the idea to hopefully replace the present injector with a better performing cavity.



Figure 2: Both fabricated SRF-Gun cavities made from fine (left) and large grain material (right).

CAVITY FABRICATION AND TUNING

We fabricated two units: one cavity was made from polycrystalline (fine grain: FG) niobium of RRR~300 and the second one was made from large grain ingot material of RRR~300 (LG). This material from CBMM was previously used for single cell cavities, which performed very well [4]. The nomenclature [LG, FG] describes only the cell structure; beam pipes, coupler ports, HOM dampers and stiffeners, were made from polycrystalline niobium which was of lower RRR-value (~40). Beam line flanges, fundamental power coupler flange and HOM – probe flanges as well as helium vessel end dish were made from NbTi. The TESLA shaped cells and a part of the half cell was deep drawn from sheet by standard practices; the components beyond the 3½ cell structure

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CURRENT STATE OF ELECTROPOLISHING AT ANL*

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Abstract

An electropolishing system for 1.3 GHz elliptical single- and 9-cell cavities is in full operation at the joint ANL/FNAL Superconducting Cavity Surface Processing Facility (SCSPF) located at Argonne. Currently, the facility is processing an average of one cavity per week. Single-cell cavities are routinely achieving accelerating gradients exceeding 35 MV/m and several recent 9-cell cavities have operated in the region of 34-35 MV/m. Process improvements are continuing with the intent to improve overall yield at 35 MV/m and to improve cavity Q-values. Electropolishing on dressed 9-cell cavities is being explored as a technique for recovering previously good performing bare cavities where performance has degraded, for example, after RF processing. A new electropolishing tool for co-axial half- and quarter-wave cavities has been recently commissioned and work is ongoing to adapt this new tool for 650 MHz elliptical shaped cavities for Project X.

INTRODUCTION

The SCSPF is a 200 m^2 facility that houses a pair of class 100 clean rooms for HPR and clean assembly, a class 1000 anteroom, and two separate chemistry rooms along with a 3000 scfm air scrubber to remove hazardous fumes generated from electropolishing (EP) and buffered chemical polishing (BCP) processes [1]. The facility has now been electropolishing 1.3 GHz elliptical shaped superconducting niobium RF cavities for the International Linear Collider (ILC) since May of 2008. Currently, the SCSPF is electropolishing 1.3 GHz cavities at an average pace of one cavity per week with a total of 42 processes in 2010. A second EP tool, along with a new high pressure rinsing (HPR) tool, were designed and built to process quarter-wave resonators (QWR) for the Intensity Upgrade of the Argonne Tandem Linac Accelerator System (ATLAS). Both the new EP and HPR tools were built with the flexibility to accommodate cavities of various geometries, such as 650 MHz tesla shaped cavities for Project X.

ILC

Evolution of EP Parameters

Since the inception of the elliptical cell EP tool at the SCSPF, continuous process improvements and system upgrades have subsequently led to an evolution of our EP parameters. The original parameters were chosen based on what was known to reliably produce good performing cavities at the time [2]. These original parameters steered the electropolishing process by controlling the acid return temperature, which is the temperature of the acid exiting the cavity.

Discussions with KEK, JLAB, and FNAL in March 2010 led to adjustments in some of our EP parameters. The EP process was then operated at a lower voltage and driven by controlling the cavity surface temperature instead of the acid return temperature (see Table 1). An increase in accelerating gradient and a decrease in Q_o were immediately observed for several cavities electropolished under these adjusted conditions. One explanation for this observation is that by lowering the voltage, the process is no longer occurring on the current-limited plateau region of the I-V curve; therefore the cavity was not receiving optimum polishing.

Table 1: Evolution of EP Parameters.

	Original Parameters	Adjusted Parameters	Current Parameters
Voltage	18 V	14.5 V	18 V
Acid Return Temp	30-35°C	No Longer a Control Parameter	
Cavity Equator Temp	N/A	Bulk: 30-35°C Light: 25-30°C	Bulk: 30-35°C Light: 25-30°C

Reverting back to the original EP voltage of 18 volts while still regulating the process by cavity surface temperature improved Q_o and has now become part of the standard EP parameters used to process all 1.3 GHz cavities for the ILC.

1.3 GHz Cavity Results

The SCSPF has recently processed numerous single- and 9-cell cavities that have surpassed the ILC cavity performance specification of E_{ACC} = 35 MV/m at $Q_o = 8 \times 10^9$.

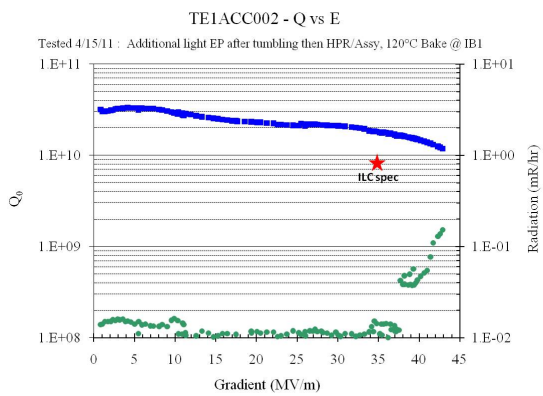


Figure 1: Cold test results for TE1ACC002.

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EFFECTS OF CATHODE SHAPES ON BEP AND EP DURING VERTICAL SURFACE TREATMENTS ON NIOBIUM*

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Abstract

This paper reports the research results of effects of cathode shapes during buffered and conventional vertical electropolishing treatments for single cell superconducting radio frequency (SRF) niobium cavities. Several different cathode shapes such as, for instance, bar, ball, ellipsoid, wheel, etc. were employed. Detailed electropolishing parameters at different locations inside a single cell SRF cavity were measured using a unique JLab home-made demountable cavity, including I-V characteristic, removal rate, surface roughness, polishing uniformity and so on. It was demonstrated that optimal polishing results could be achieved by changing the cathode shape for both BEP and EP. Implications on the electropolishing mechanism of Nb cavities for both BEP and EP based on the obtained experimental results are discussed.

INSTRUCTION

Previous study shows that reactions at different locations of the cavity may be different especially during BEP process [1]. This paper mainly focused on the effect of cathode shape on the process of BEP. Detailed parameters at different locations inside the demountable cavity such as, I-V characteristic, removed rate, surface roughness, polishing uniformity, and so on were measured by a demountable cavity. It was revealed that cathode shape had dominant effects on the inhomogeneous polishing rates between the equator and iris in an Nb SRF single cell cavity for buffered electropolishing (BEP). The conventional electropolishing (EP) appeared to have the same tendency. This study demonstrated that a more homogeneous polishing result could be obtained by optimizing the electric field distribution inside the cavity through the modification of the cathode shape given the conditions that temperature and electrolyte flow were kept constant.

EXPERIMENTAL SETUP

The experimental setup mainly includes four parts: 1. Demountable cavity; 2. Electrolyte circulating system; 3. Data acquisition system; 4. Cooling system. With the chemical fume hood, they constitute the whole setup. Besides, several cathodes of different shapes are tried as now in figure 1. More details please see the paper TUPO033 in this proceeding.

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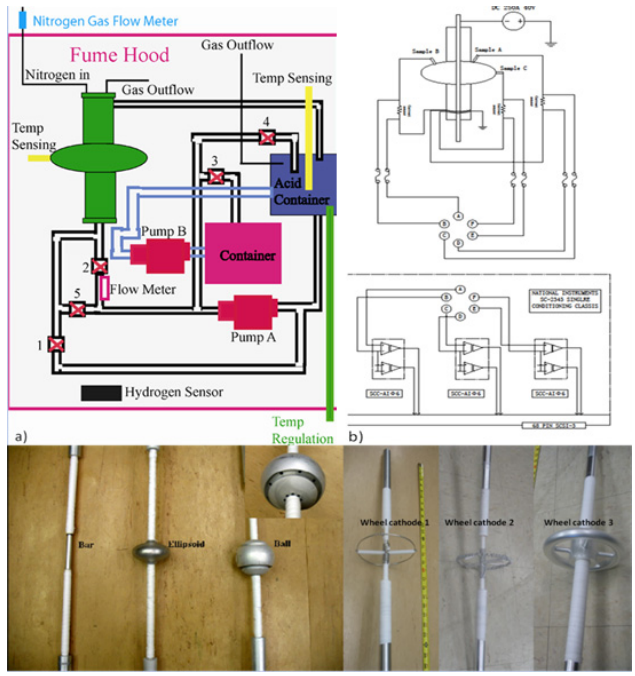


Fig. 1: Schematics of (a) the flow chart of BEP system and (b) the data acquisition system of the vertical BEP system for Nb SRF single cell cavities and the cathodes used in this study.

RESULTS AND DISCUSSION

Effect of Cathode Shape on I-V Characteristic

An electropolishing system consists of mainly three parts: anode, cathode and electrolyte. So, research on the effect of cathode becomes one of critical points in the whole electropolishing treatment study. In this part, we will mainly discuss the effect of different cathode shape on the I-V characteristic, and try to find the way on how to apply the experimental findings in real EP and EP processes. The effect of cathode in BEP process will be firstly discussed, and then we will talk about EP process.

This study was done through the measurements of a series of I-V curves with different cathode shapes in BEP experiments. In the experiments of BEP-2, BEP-6, BEP-8, BEP-13 and BEP-14, the cathodes used were thin bar, ellipsoid, ball, wheel cathode 3 and thick bar cathode, respectively. Most of them are shown in figure 1. As shown in figure 2, I-V curves from the different cathodes show great differences. They can be obviously distinguished in the etching region. The one with the smallest slope in the etching region is obtained by thin bar

DEVELOPMENT OF THE SUPERCONDUCTING CAVITY FOR ILC AT TOSHIBA

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Abstract

TOSHIBA has been developing the superconducting cavity for International Linear Collider (ILC) in cooperation with High Energy Accelerator Research Organization (KEK) since 2009. A 9-cell superconducting cavity was fabricated at TOSHIBA in 2010. Surface preparation and RF test of the cavity were performed at STF/KEK. The 2nd 9-cell cavity is just about to be fabricated now. This paper presents the status of superconducting cavity development for ILC at TOSHIBA.

INTRODUCTION

ILC is the next-generation particle accelerator and it is planned to have a collision energy of 500 GeV initially. Consisting of two linear accelerators that face with each other, the ILC will collide electrons with positrons, at nearly the light speed. Scientists and engineers around the world are collaborating to build the ILC.

KEK constructed Superconducting RF Test Facility (STF) to develop the cryomodule including high performance cavities and to establish the industrial design of a Main-Linac unit for ILC [1][2][3]. Development of the superconducting cavity is performed at TOSHIBA for the purpose of clarifying technical subjects and quality control to industrialize superconducting cavities through the collaboration with KEK.

9-CELL SUPERCONDUCTING CAVITY

The 9-cell superconducting cavity without HOM couplers was fabricated at TOSHIBA based on the STF Baseline cavity. Its main specifications are shown in Table 1. Figure 1 shows a drawing of the 9-cell cavity and figure 2 shows a completed 9-cell cavity.

Table 1: Specifications of 9-cell cavity

Frequency	1.3 GHz
Active length	1.038 m
Iris diameter	70 mm
Beam tube diameter	80 mm
R/Q	1036 Ω
Geometry factor	270 Ω

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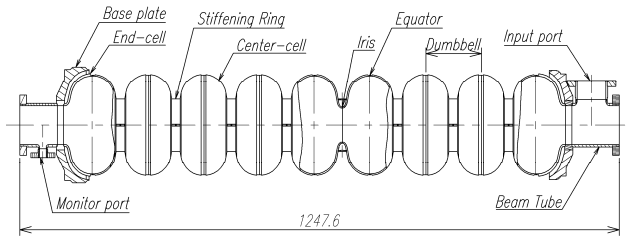


Figure 1: Drawing of 9-cell superconducting cavity without HOM couplers.



Figure 2: 9-cell superconducting cavity with supporting jig.

Cavity Fabrication

The half-cells shown in Figure 3 were formed from high purity niobium disks of thickness 2.8 mm by deep drawing. Figure 4 shows a dumbbell electron beam welded two half-cells at iris. To increase the stiffness of the cavity, stiffening rings were welded to the outside of iris. Two dumbbells were electron beam welded at equator as shown in Figure 5. Equator welds were all full penetration welds from the outside. 4-cell dumbbell is consists of two 2-cell dumbbells welded at equator, and 8-cell dumbbell is consists of two 4-cell dumbbells welded at equator. The 9-cell cavity was completed by welding two end-groups to the either ends of 8-cell dumbbell respectively. Figure 6 shows the end-group consisted of a niobium end-cell, a titanium base plate, a niobium beam tube welded the flange, and an input port welded the flange. All flanges are made from niobium-titanium. End-cells were formed from high purity niobium disk of thickness 3.7 mm by deep drawing.

SULFUR RESIDUES IN NIOBIUM ELECTROPOLISHING*

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Abstract

Electropolishing (EP) in sulfuric/hydrofluoric acid mixtures affords significantly greater surface smoothness than the incumbent buffered chemical polishing (BCP), making it attractive as the future baseline technology for SRF cavity manufacture. However, reported observations of particulate sulfur residues raise concern. One hypothesis is sulfate reduction to elemental sulfur at the cathode, where the measured potential drop is thermodynamically sufficient. We explored these possibilities under standard EP conditions in a small three-electrode laboratory cell. Hydrogen generated on the cathode also plays an important role as a strong reductant. We varied aluminum cathode area to obtain different current densities (and thus overpotentials) at constant cell current. We substituted platinum, an excellent hydrogen activating catalyst, for aluminum in some experiments. Surface of cathodes was examined with Scanning Electron Microscope (SEM). Surface composition was analyzed by Energy Dispersive X-Ray Spectroscopy (EDS) and X-Ray Photoelectron Spectroscopy (XPS).

INTRODUCTION

In Nb EP process, the main reaction at the cathode is hydrogen evolution: $2H^+ + 2e^- \leftrightarrow H_2$. However, the large amount of concentrated sulfuric acid in the electrolyte cannot be neglected when considering chemical reactions. The form of sulfur species in the solution varies under different combinations of pH and potential (E), as shown in the E-pH diagram in Figure 1.

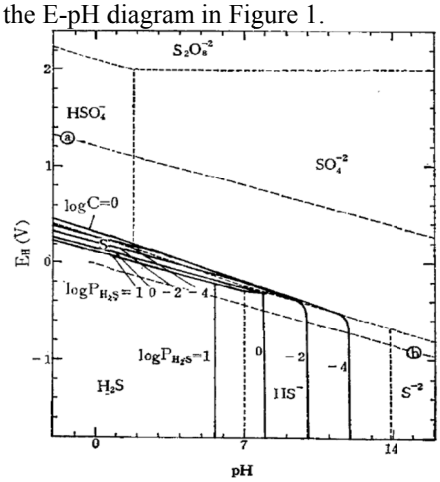


Figure 1: E-pH diagram of S-H_2O system at 25°C [1].

As the potential at the cathode becomes more negative, assuming the pH is near 0 or negative in the highly acidic solution, H_2S is more stable than other forms of sulfur species in the system.

H_2S is produced from H_2SO_4 reacting with the H_2 generated from the main reaction:

$H_2SO_4 + 4H_2 \rightarrow 4H_2O + H_2S$

H_2S can produce elemental sulfur and SO_2 by reacting with H_2SO_4:

$H_2SO_4 + H_2S \rightarrow 2H_2O + SO_2 + S$ [2]

In terms of kinetics, potential (E) drives the reaction, and current density (i) indicates how fast the reaction runs. The slope and intercept of i-E curve can be related to the resistance of a reaction [1].

According to existing reports, sulfur species was found on Nb coupons, in cavity EP tubing [3] and Teflon mesh wrapped around Al cathode [4]. No existing report used a technique giving chemical state information indicating it is elemental sulfur, sulfate or sulfide. Analysis indicates that sulfur species generate near the cathode and travel along with the electrolyte. However, the focus of existing studies is on either Nb anode [5] or the electrolyte [6, 7], no detailed characterization on Al cathodes has been reported. We carried out a series of experiments to help understand how different cathode sizes and materials affect sulfur generation and the mechanism behind it, so as to find ways to reduce it. The range of surface area ratio of anode and cathode we studied covered the typical ratio (about 10) for elliptical shaped 9-cell SRF cavities.

EXPERIMENT

Nb anode was fine grain square with reactive surface area of 3.6 cm^2 fully immersed into the electrolyte. The reactive size of Nb anode was the same for all of the experiments. Three different sized Al samples were used as the cathode. The area ratio between Nb and Al were 0.6, 9 and 18, named Al0.6, Al9 and Al18 in this paper. Pt was also used as cathode for comparison study, and the area of Nb vs. Pt was 18, named Pt18 in this paper. For potential measurement three-electrode setup was used with a saturated mercury mercurous-sulfate electrode (MSE, 0.65V vs. NHE) as reference electrode (RE). The distance between anode and cathode was 7 cm, and 0.5~1 cm between the cathode and the RE. The electrodes were immersed in 300 ml electrolyte (HF: H_2SO_4=1:10, vol.%).

An Agilent E3634A DC power supply was used to apply voltage to the EP cell. A Keithley 617 Programmable Electrometer and a HP 3478A multimeter were used to measure potential and current respectively. Current-potential (I-E) curves of the cathode were recorded when applying 0~15 V voltage to the two electrodes, the voltage step was 0.25 V and time interval between data points was about 5s. Current-time (I-t) curves of EP process were recorded, with 14 V power

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CAVITY PROCESSING RESEARCH LABORATORY AT FERMILAB: SRF CAVITY PROCESSING R&D

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Abstract:

A center for cavity processing R&D at Fermilab, called the Cavity Processing Research Laboratory, is currently in the final stages of installation and commissioning. This facility contains centrifugal barrel polishing, a horizontal electropolishing tool, a 1000°C vacuum furnace, a high pressure rinse tool utilizing ultrapure water, ISO class 4, 5 and 6 clean rooms for cavity assembly work and various other associated pieces of support equipment. All the operations are designed for single cell and nine cell 1.3 GHz Tesla type cavities except for the electropolishing tool which will initially be only for single cell use. Upgrades are currently being examined for single and five cell 650 MHz cavities. The current status of the facility and plans for future work are discussed.

INTRODUCTION

Performance specifications are becoming more stringent for next generation particle accelerators. As requirements on accelerating gradients and quality factors increase, it becomes essential to fully understand how each process affects the cavity's performance. This is especially important at Fermilab where the International Linear Collider (ILC) and Project X are both of interest. The ILC has a high accelerating gradient requirement while Project X has a high quality factor requirement [1,2]. These two different performance specifications likely mean the cavities will follow different processing paths.

The Cavity Processing Research Laboratory (CPL) is a facility dedicated to the R&D of the processes and materials needed to consistently produce cavities with sufficient performance characteristics of next generation particle accelerators. This paper will discuss the CPL and some of the work that will be done in it.

CPL LAYOUT

Fig.1 shows the general layout of the CPL. The CPL contains all the operations needed for cavity processing in a small area. The layout was designed based on a processing concept thought to be beneficial for SCRF cavities called "tight loop" processing.

There are five general areas in the CPL that are labeled and each is represented by a different color in Fig. 1. The green is the centrifugal barrel polishing (CBP) area. The pink area is for chemistry operations including horizontal electropolishing (EP). The light blue area is a utilities area for equipment associated with the clean rooms and high pressure rinse (HPR) process. The orange area is a suite of clean rooms for high pressure rinsing and preparation of the cavities for cold testing. The red area contains a 1000°C vacuum furnace and loading fixture for the furnace.

1) The black lines represent the tight loop process flow path with letters being major unit operations and numbers being decision points. The path that a cavity might go through is as follows: Cavity enters process at (0)
2) Cavity goes for bulk material removal at (1) [either (a) CBP or (b) EP]
3) If cavity receives CBP it gets an additional rinse (c) and light EP (b) before proceeding
4) Cavity goes for ultrasonic rinse at (c)
5) Cavity goes for hydrogen degasing at (d)
6) Cavity goes for light EP at (b)
7) Cavity goes for ultrasonic rinse at (c), HPR at (e), assembly for cold test at (f)
8) Cavity goes for cold test at IB1—leaves tight loop processing area of IB4

This is a standard path that a cavity might follow, but deviations from baseline processing can occur. One specific example is shown. If a cavity were to have a high quality factor and gradient, but also show signs of field emission, simply doing another HPR and cold test is often appropriate. This is shown in Fig.1 by a second entry point (entry points are shown as (0)) into the cavity processing loop just upstream of the clean rooms and HPR (shown as (e)).

NINE - CELL TESLA SHAPE CAVITIES PRODUCED FROM HYDROFORMED CELLS

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Abstract

Production of two types of seamless niobium tubes for hydroforming of RF cavities has been developed. The first type of tubes, developed at DESY, have been spun from sheets and flow formed. The second type of tubing was developed by Black Laboratories in collaboration with the company ATI Wah Chang. These longer length tubes were extruded from a heavily deformed billet, processed for a fine-grained microstructure and flow formed. Several seamless three cell units have been produced by hydroforming at DESY. Some of the units have been treated by buffered chemical polishing and RF tested at JLab. The accelerating gradient Eacc of the units exceeded in most cases 30 MV/m. Three of the 3-cell units from the first type of tubing were combined to three 9-cell niobium cavities at the company E. Zanon. The 3-cell units from extruded tubing are welded together to the fourth 9-cell cavity at JLab. All cavities are in preparation for the RF tests at DESY and JLab. Up to now two of the cavities are electropolished and tested at DESY. The first cavity reached an accelerating gradient of Eacc of ~30 MV/m, the second one ~35 MV/m.

CONTRIBUTION NOT RECEIVED

A NEW HOME FOR SRF WORK AT JLAB–THE TECHNOLOGY AND ENGINEERING DEVELOPMENT FACILITY

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Abstract

A project is underway at Jefferson Lab to fully renovate all of the SRF research, development, fabrication, processing and assembly facilities. Initiated in 2009 and funded by the US Department of Energy's Science Laboratory Infrastructure program, this work together with construction of a new building to house JLab's Engineering Division and detector electronics group is collectively known as the Technology and Engineering Development Facility (TEDF) Project. The majority of the SRF facilities will be consolidated in a new building with 30,000 square feet (3300 m^2) of work space attached to the existing Test Lab. The purpose-built facility integrates fabrication, chemistry, and cleanroom suites and cryomodule assembly lines for convenient, yet flexible operations serving multiple projects in parallel. A robust ultra-pure water system and integrated hazardous materials transfer and neutralization system are included in the project. Construction is underway and move-in is scheduled for early 2012. Project details will be presented.

CONTRIBUTION NOT RECEIVED

QUALIFICATION OF THE SECOND BATCH PRODUCTION 9-CELL CAVITIES MANUFACTURED BY AES AND VALIDATION OF THE FIRST US INDUSTRIAL CAVITY VENDOR FOR ILC*

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Abstract

In the past several years, Jefferson Lab (JLab) in collaboration with Fermi National Accelerator Laboratory (FNAL) has processed and tested all the 9-cell cavities of the first batch (4 cavities) and second batch (6 cavities) production cavities manufactured by the Advanced Energy System Inc. (AES). Four out of the six 9-cell cavities of the second production bath achieved a gradient of 36-41 MV/m at a Q0 of more than 8E9 at 35 MV/m. This result validated AES as the first "ILC certified" industrial vendor in the US for ILC cavity manufacture.

INTRODUCTION

One of the major goals of ILC SRF cavity R&D is to develop industrial capabilities of cavity manufacture and processing in all three regions. In the past several years, JLab in collaboration with FNAL has processed and tested all the 9-cell cavities of the first batch (4 cavities) and second batch (6 cavities) production cavities manufactured by the Advanced Energy System Inc. (AES). These cavities are manufactured for FNAL. Over the course, close information feedback was maintained, resulting in changes in fabrication and processing procedures. Some mechanical features originally observable on the RF surface at the stiffening ring radius even after complete EP processing were successfully eliminated by improvement in forming and welding procedures. A light buffered chemical polishing is introduced, removing the weld splatters that cannot be effectively removed by heavy EP alone. An 800 Celsius 2 hour vacuum furnace heat treatment procedure replaced the original 600 Celsius 10 hour procedure. Four out of the six 9-cell cavities of the second production bath achieved a gradient of 36-41 MV/m at a Q0 of more than 8E9 at 35 MV/m. This result validated AES as the first "ILC certified" industrial vendor in the US for ILC cavity manufacture.

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Presently with AES
Presently with Jefferson Lab

BRIEF REVIEW OF FIRST PRODUCTION BATCH CAVITIES

AES manufactured four 9-cell ILC cavities (AES1, AES2, AES3 and AES4) for FNAL in the first production batch. All of the four cavities are processed and RF tested at Jefferson Lab [1]. According to the then ILC S0 protocol, each of these cavities were repeatedly processed and tested. The gradient results achieved in all tests of these four cavities are shown in Fig. 1. No cavity passed the ILC vertical test specification (35 MV/m at Q_0 8E9). In contrast, two 9-cell ILC cavities (manufactured by an experienced European vendor) processed in parallel with these cavities both passed the ILC vertical test specification.

All these four cavities passed 15 MV/m during the first processing and testing cycle. One cavity ultimately passed 30 MV/m after four cycles of processing and testing.

Some cavities (AES1 and AES3) were quench-limited at a gradient < 20 MV/m by the same cell without detectable X-rays. The limitation is insensitive to repeated EP, suggesting that the quench-causing defects are of permanent nature. Further investigation located the responsible defects with geometrical features [2][3].

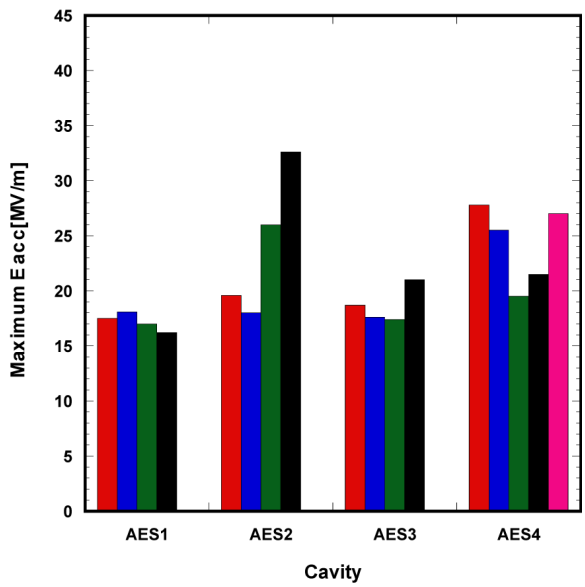


Figure 1: Gradient performance of 9-cell ILC cavities from the first AES production batch.

GRADIENT IMPROVEMENT BY REMOVAL OF IDENTIFIED LOCAL DEFECTS*

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Abstract

Recent experience of ILC cavity processing and testing at Jefferson Lab has shown that some 9-cell cavities are quench limited at a gradient in the range of 15-25 MV/m. Further studies reveal that these quench limits are often correlated with sub-mm sized and highly localized geometrical defects at or near the equator weld. There is increasing evidence to show that these genetic defects have their origin in the material or in the electron beam welding process. A local defect removal method has been proposed at Jefferson Lab by locally re-melting the niobium material. Several 1-cell cavities with known local defects have been treated by using the JLab local electron-beam re-melting method, resulting in gradient and Q0 improvement. We also sent 9-cell cavities with known gradient limiting local defects to KEK for local grinding and to FNAL for global mechanical polishing. We report on the results of gradient improvements by removal of local defects in these cavities.

INTRODUCTION

Recent effort in pushing gradient for reproducible realization of high gradient SRF cavities for ILC improved quench limit understanding [1][2][3][4]. A major conclusion is that the quench limit in real 9-cell cavities (with a surface area of about 1 m^2) is caused by ***highly localized defect***. Furthermore, the quench limitation can be roughly characterized by two types,

- Type-I: quench limit occurs at a gradient in the range of > 25 MV/m. There is normally no observable feature at the quench site through high-resolution optical inspection. Often times, a second EP effectively improves the quench limit to more than 30 MV/m.
- Type-II: quench limit occurs in a gradient range of 15-25 MV/m. It is often correlated with sub-mm sized geometrical defects (mostly pits but bumps are also observable) at or near the equator electron beam welding. Repeated EP has no or little effect in improving the quench limit, suggesting the permanent nature of these defects.

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
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More than 20% 9-cell cavities are limited by type-II quench. The failure rate tends to be higher for cavities built by new vendors. In order to achieve the ILC gradient yield goal of 90% at 35 MV/m, it is necessary to understand the origin of quench causing defects.

Guided repairing (grinding) has been used in labs for a long time as a means of recovering sub-standard cavities. More recently, improvement of the local grinding and development of new local repair methods have attracted a lot of attention. The value of these efforts is in two folds: (1) Help understand the origin of the quench causing defect, which in the long run will tell us how to improve the fabrication process for reliable mass-production, which is important for large-scale projects like ILC; (2) Provide useful means of recovering expensive cavities in a cost-effective manner. This may be very important for medium- or small-scale projects.

At Jefferson Lab, we have developed a local repair method by using electron-beam re-melting. Several 1-cell cavities with known local defects have been treated, resulting in gradient and Q0 improvement. We have been also collaborating with KEK and FNAL in development of 9-cell cavities repair method of local grinding (KEK) and global mechanical polishing (FNAL) techniques.

LOCAL ELECTRON-BEAM RE-MELTING

Development by Using Flat Niobium Samples

We first developed the procedure and parameters of local electron-beam re-melting by using flat niobium samples with the same thickness as compare to that of a real niobium cavity. Fig. 1 shows a photo of such a sample with man-made pits (~200 μm in diameter) on its surface after local electron-beam re-melting. It is evident that these pits are completely eliminated.

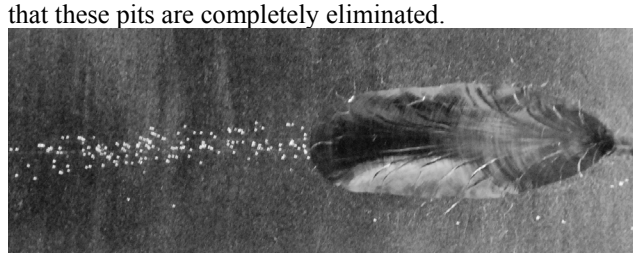


Figure 1: Effect of local electron-beam re-melting. Man-made pits (~200 μm in diameter) are seeded in the central surface region of a niobium sample. Pits are visible in the left area (without re-melting) and are completed eliminated in the right area (with re-melting).

STATUS OF THE 9-CELL SUPERCONDUCTING CAVITY R&D FOR ILC AT HITACHI

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Abstract

Hitachi is developing 9-cell superconducting cavities for ILC project in collaboration with KEK. In 2010, Hitachi's first 9-cell cavity without HOM couplers was completed successfully. Surface treatments and performance test of the cavity were carried out at KEK and its accelerating gradient reached 35.2MV/m. We have undertaken our next 9-cell cavity with HOM couplers since January 2011. This paper outlines the fabrication flow and test result of our first cavity, and describes a current status of next cavity briefly.

INTRODUCTION

Hitachi participated in the construction of STF (Superconducting RF Test Facility) cryomodules at KEK, which aims for versatile development oriented toward ILC (International Linear Collider) project [1,2]. The cryostats were subjected to several performance tests and found to be reliable for this study. We also began to develop superconducting cavities for STF, and we completed our first 9-cell cavity without HOM couplers in April 2010, successfully. We have focused on electron beam welding (EBW) and plastic forming techniques, engineering of jigs, so that we have obtained valuable technology and know-how to fabricate a cavity. On the other hand, some technical issues to the next step are cleared, it make us recognize the importance of improving fabrication technology.

FABRICATION OF HITACHI'S FIRST CAVITY

At first this paper describes the structures and specifications of our first cavity briefly. The motivation for developing our first cavity was to establish basic fabrication techniques and to recognize issues for fabricating a cavity.

Structures and Specifications

The main feature and dimension of our first cavity is shown Figure 1. And major specifications of our first cavity are shown in Table 1.

The shape of center cell is based on STF Baseline cavity. Almost all cavity parts are made of niobium (RRR~300), and its flanges are made of Niobium-Titanium (NbTi), which can be directly welded to niobium by electron beam welding. Both the tensile strength and the hardness of NbTi are comparable to those of stainless steel and better than pure niobium. Baseplate which are welded the jacket with bellows are made of titanium (Ti). All of the parts are electron-beam (EB) welded together in a vacuum chamber.

To clear validity of center cell part productivity, we fabricated 9-cell superconducting cavity without HOM couplers, which remove beam induced power from cavity in order to avoid beam instability.

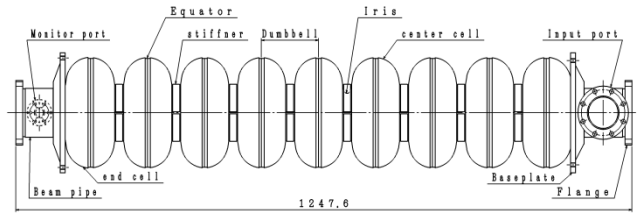


Figure 1: 9-cell superconducting cavity without HOM couplers.

Table 1: Basic Specifications for superconducting cavity

Items	Unit	Spec.
Material	-	Niobium (RRR~300)
Total length	mm	1247.6
Equator diameter	mm	205
Iris diameter	mm	70

Fabrication Flow and Development Items

In order to confirm the basic fabrication techniques of a cavity, we covered the most commonly used fabrication procedures, forming half-cells from sheet niobium. Fabrication flow is as follows.

(1) Deep drawing and trimming, chemical polishing (CP) of center cells
(2) Pressing and machining of stiffener
(3) Dumbbell Electron beam welding (EBW), that is, half-cell iris parts welding.
(4) Multi-dumbbell EBW, that is, dumbbell equator parts welding.
(5) Deep drawing and trimming, CP of end cells
(6) Machining and CP, EBW of baseplates
(7) Machining and CP, EBW of beam pipe.
(8) Assembling (EBW) end cells and baseplates, beam pipe.
(9) Assembling (EBW) center cells and end parts.

In order to achieve the desired high gradients, the superconducting cavity must have clean surfaces especially on the inner surface and therefore have to undergo special treatment and assembly procedures. The important development items are summarized as follows.

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UPDATE ON THE R&D OF VERTICAL BUFFERED ELECTROPOLISHING ON NIOBIUM SAMPLES AND SRF SINGLE CELL CAVITIES*

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Abstract

Electropolishing (EP) has become a popular choice as the final step of the surface removal process during the fabrication of Nb superconducting radio frequency (SRF) cavities. One of the major reasons for the choice is that Nb SRF cavities treated by EP tend to have a better chance to reach an accelerating gradient of 30 MV/m or higher than those treated by buffered chemical polishing (BCP). This advantage of EP over BCP can at least be partially attributed to the smoother Nb surfaces that EP can produce. Recently a Nb surface removal technique called buffered electropolishing (BEP) was developed at JLab. The root mean square of the Nb surfaces treated by BEP can be as smooth as 20nm over a surface area of 200X200 μm^2. In this contribution, R&D efforts of vertical BEP on Nb small flat samples and SRF single cell cavities since the last SRF conference in 2009 will be updated. It is shown that under a suitable condition, BEP can have a Nb removal rate as high as 10 μm/mim that is more than 25 and 5 times quicker than those of EP and BCP(112) respectively. Possible mechanisms responsible for the high Nb removal rate are proposed. Clues on the optimization of vertical BEP and EP treatments on Nb SRF cavities from recent experimental results obtained on a Nb single cell demountable cavity and Nb single cell cavities will be discussed.

INTRODUCTION

Buffered electropolishing (BEP) was firstly proposed in 2001 by scientists at JLab [1]. Although several vertical electropolishing systems were built starting in 2002 for both BEP and conventional electropolishing (EP) [2], the main research focus of BEP then was on Nb small and flat samples using a bench top experimental setup. In 2008, it was realized that research on small samples could never substitute the R&D work on Nb SRF cavities [3]. Then more serious work on Nb SRF single cell cavities was launched formally. A much improved vertical treatment system with better temperature stability together with a computer data acquisition system was constructed recently as reported in Ref.4. Due to the limited manpower and funding, the R&D on BEP has been carried out in an on-off fashion over the last decade. So far it has been demonstrated that BEP can produce much smoother surface finish as compared with those treated by EP and buffered chemical polishing (BCP). The polishing rate of BEP can be as high as 10 μm/min. Sulphur precipitation should be much less (if any) from BEP than that from EP, since most of H_2SO_4 is replaced by $C_3H_6O_3$ in the electrolyte. The highest accelerating gradients of Nb single cell cavities have reached 32 MV/m on a large grain cavity of ILC shape and 28.4 MV/m on a fine grain cavity of cebaf shape.

In this contribution, the R&D on BEP since the last SRF conference in Berlin is reviewed. Effort has been put on the systematic understanding and optimizing of the polishing parameters and treatment procedures of BEP on a demountable Nb single cell cavity and normal Nb single cell cavities employing the improved vertical polishing system as reported in Ref. 4. Several cavities of cebaf shape treated by BEP have reached the highest accelerating gradients ever achieved on these cavities in the neighborhood of 25 MV/m. Mechanism has been suggested to explain the high polishing rate of BEP [5,6]. A new cavity fabrication procedure based on BEP was proposed in a collaborative effort between JLab and Peking University (PKU).

OPTIMIZATION OF CATHODE SHAPE

Early experiments had shown that cathode shape could affect the polishing results of Nb SRF cavities for both BEP and EP [1], whereas the effect on BEP was much more serious. With the help of a demountable cavity, a more systematic study on this topic has been carried out for both BEP and EP [7]. Cathodes of various shapes such as, for instance, straight bar, ellipsoid, ball, and various wheels have been employed in the experiments. It was demonstrated that preferential polishing on the inner surface of a cavity could be realized by changing the cathode shape. Surface areas that showed a large electric field in the stationary electrolyte condition normally had a higher Nb removal rates.

To better understand the experimental results, it is useful to see how the demountable cavity looks like. Figure 1 shows the demountable cavity. This demountable cavity

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UPDATES ON R&D OF NONDESTRUCTIVE INSPECTION SYSTEMS FOR SRF CAVITIES

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Abstract

We are developing high resolution eddy current scan and high density T-map and X-map instruments. The high resolution eddy current scan recognizes a 100 μm diameter hole with 50 μm depth that was drilled on a Nb plate. The surface mount printed circuit technology is applied to the high density T-map and X-map devices, where 1024 T-sensors can be distributed on a cell with ease of installation. In addition, radiography using X-rays and neutrons are also under study.

INTRODUCTION

After the success of the superconducting cavity endoscope[1], nondestructive inspections for sc cavities have been regarded as even more important tools than before. Among many such nondestructive inspection items, we are developing high resolution eddy current scan[2,3] and high density T-map and X-map instruments. The former eddy current scan system inspects Nb sheets before the press and records the data. This enables us to screen out suspicious Nb sheets at the early stage and every completed cavity will have their histories on the material, which should help to raise the production yield at high field gradient. The latter T-map and X-map are used in vertical tests, which will enable us to locate defects by detecting heat spot positions and/or high radiation areas with high spatial resolution. In addition to these items, radiography techniques using X-ray and neutrons are also under study.

EDDY CURRENT SCAN

Fig. 1 shows the completed eddy scan table. While the turn table rotates the Nb sheet on it, the probe head moves from outside to inside. The path is a spiral with 100 μm spacing from radial position of 135mm to 25mm. The relative speed is 1m/s and the sampling spacing is kept less than 50 μm while the timing is given by a rotary encoder installed on the table shaft. By keeping the velocity constant, the rotation speed goes up during a scan (about 5 times). A differential probe is used to detect the signal, using a pair of 0.3 × 0.25mm ferrite needles with sharpened tips and each needle having a pickup coil to detect the signal (see Fig. 2). The set of the needles is wound with an excitation coil whose frequency is a range of 1kHz to 2MHz. The excitation current and the signal processing are provided by ASWAN JSAID-3X200 (ASWAN E.S. Co.,Ltd). Both I and Q signals are recorded through 16-bit ADC (AIO-163202FX-USB), whose acquisition rate is up to 500 ksps. A test Nb sheet with 19 drilled holes was prepared to evaluate the resolution (see Fig. 3). The diameters of the holes are 500, 300, 200, 100 and 50 μm. The depths are 500, 300,



Figure 1: Eddy Current Scanner.

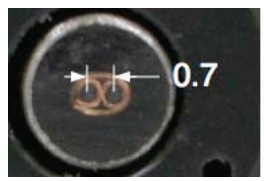


Figure 2: Eddy current probe sensor head. Differential sensor has two pickup coils wound on an excitation coil.

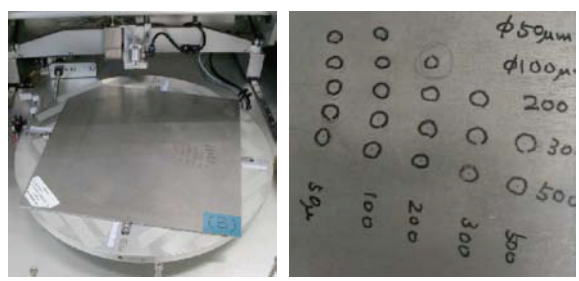


Figure 3: Nb test sheet.

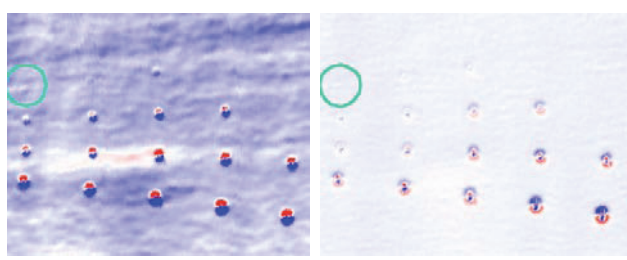


Figure 4: I-Q signals at the drilled holes area. ø100μm x 50 μm depth is barely detected in this run (marked by the circle).

STUDY OF I-V CHARACTERISTICS AT DIFFERENT LOCATIONS INSIDE A DEMOUNTABLE NB CAVITY DURING VERTICAL BEP AND EP TREATMENTS

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Abstract

For a normal superconducting radio frequency (SRF) cavity, it is hard to obtain detailed information of an electropolishing process. So, a demountable cavity was firstly made by JLab to resolve this problem. This paper reports the measurements of I-V characteristics at three different locations inside the demountable cavity during buffered electropolishing (BEP) and electropolishing (EP) treatments. The polishing plateau appeared earlier on the surface areas close to iris and later on those near equator. To find the reason for this phenomenon, the electric field distribution in the cavity was considered and simulated by means of Poisson-Superfish. Correlations were found between the measured I-V characteristics and the simulated results. This implies that electric field distribution inside a SRF cavity has an important effect on the polishing processes during vertical BEP and EP.

INSTRUCTION

Surface condition plays a critical role in the performance of a SRF cavity [1]. Since SRF niobium cavities are born, researches on surface treatment for SRF cavities have not been stopped. As the technique of surface treatments on Nb SRF cavities evolved from buffered chemical polishing (BCP) to electropolishing (EP), the performance of SRF cavities improved greatly [2-5]. The performance of SRF cavities improved greatly. However, the yield of the nine-cell cavities surpassing the required 35 MV/m for the ILC is still not high. The variability of cavity performances has emerged as a major challenge. On the other hand, the low polishing rate about 0.38/min of EP is another problem. Usually a thickness of 150μm is needed in order to remove the surface damage layer of Nb. Therefore, a method for SRF cavity treatment called buffered electropolishing (BEP) is developed by Jefferson Lab and have shown some advantages in small sample experiments, such as a much smoother niobium surface (about 50nm) and faster polishing (2.5μm/min) [6, 7]. Thus, further research of BEP on single cell SRF niobium cavities is launched.

As a R&D work, study is firstly focused on the anode polarization characteristics by employing a JLab home-made demountable cavity. With the help of small button samples on the demountable cavity, the characteristics at different locations of the cavity are obtained during BEP process. Experimental results shows that the reaction processes at different locations may be different if an unsuitable work point is chosen for BEP. In the EP process, the similar tendency also appeared but not as obvious as that in BEP. The reasons for the difference of the reaction at different locations are analyzed. It could be understood as due to the different resistance of electrolyte for the different locations because of the variation in distance from cathode. However, further simulation with Poisson-Superfish reveals that the distribution of electric field can help us better understand this phenomenon and provide a method to resolve it.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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EXPERIMENTAL SETUP

For the study, a vertical electropolishing system is built. Since it is home-made, we will do a little more introduction to this setup. As shown in figure 1, it mainly includes four parts: 1. Demountable cavity; 2. Electrolyte circulating system; 3. Data acquisition system; 4. Cooling system. With the chemical fume hood, they constitute the whole setup. The details are introduced in the following:

The upper right image in figure 1 is a CCD picture of the demountable cavity. The whole cavity is made of two half cells and three small niobium button samples. There are three sample holders in one of half cells at locations close to equator, midway between the equator and iris, and close to iris. The niobium button samples will be mounted in the holders, and electrically insulated from the cell. In this way, it allows the measurements of I-V curves at the three locations independently. At present, a new demountable cavity with two more buttons on the other half cell has been just made. The new demountable cavity will be very helpful for the further study on the effect of gravity in the vertical polishing process.

The image in the lower middle of the figure 1 is the schematic of the electrolyte circulating system of the vertical polishing system for SRF single cell cavities. For polishing, Pump A will be turned on and Valves 2 and 4 are open. The flow rate of the electrolyte is regulated via Valve 2 with a range from 0 to 10 L/min. Valve 4 is installed to branch out the electrolyte in order to avoid labouring of Pump A. Higher flow rate is possible by opening Valve 5. Draining will be achieved by opening Valves 1 and 3 and closing Valves 2, 4, and 5. For rinsing, DI water will be introduced to the acid container. Then Valves 2 and 5 are open and Valves 1, 3, and 4 are closed. In the polishing process, dry nitrogen is introduced to mix

A FLEXIBLE SYSTEM FOR THE HIGH PRESSURE RINSING OF SRF CAVITIES*

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Abstract

The Physics Division SRF group at Argonne National Laboratory has built a new, high pressure rinse system for the joint ANL/FNAL Superconducting Cavity Surface Processing Facility (SCSPF). The rinsing tool can be easily reconfigured vertically or horizontally to process a variety of SRF cavity shapes and sizes including elliptical, spoke, quarter- and half-wave cavities. The system has been commissioned with a new 72 MHz β=0.077 quarter-wave cavity as part of the ATLAS Intensity Upgrade at ANL. The tool is also designed to rinse 1.3 GHz elliptical single-cell and 9-cell cavities, as well as the new 650 MHz elliptical cavities under development for Project-X and Fermilab.

INTRODUCTION

A high pressure rinsing system was needed for post electropolishing (EP) processing of the new quarter-wave resonators (QWR) for the ATLAS Intensity Upgrade at Argonne National Laboratory (ANL). Post EP high pressure rinsing (HPR) of niobium can result in a >99% reduction in surface particulates [1], reducing the chance of field emission. The locations of the four cavity ports and two beam ports make it necessary for an HPR tool with the flexibility to accommodate those locations. Therefore the HPR tool was designed with both a rotating cavity mount and a spray wand which was attached to a variable positioning arm. These two features enable the tool to accommodate virtually any type of cavity, including QWR, half-wave resonators, elliptical cell, and spoke cavities.

TOOL DESIGN

2-Hinged Arm

In order to accommodate the various locations of ports on different cavity types, the HPR wand was mounted on a 2-hinged arm (see Figure 1). The two pivot points allow the wand to be positioned anywhere within the 26" radius of the arm base. Once the wand has been located properly, two wing nuts are tightened down, locking the wand in a fixed position for cavity rinsing. All moving parts are located below the cavity, minimizing particulate contamination.

The arm was made out of aluminium because of its strength and light weight. These qualities minimize the deflection of the wand due to the weight of the tool. After machining, the aluminium was clear anodized to make it resistant to the de-ionized (DI) water used to rinse the cavities.

The hinge pins located in the two pivot points of the arm are made of 316 stainless steel. PEEK bushings are inserted between the pins and the aluminium arms, providing high strength and low friction.

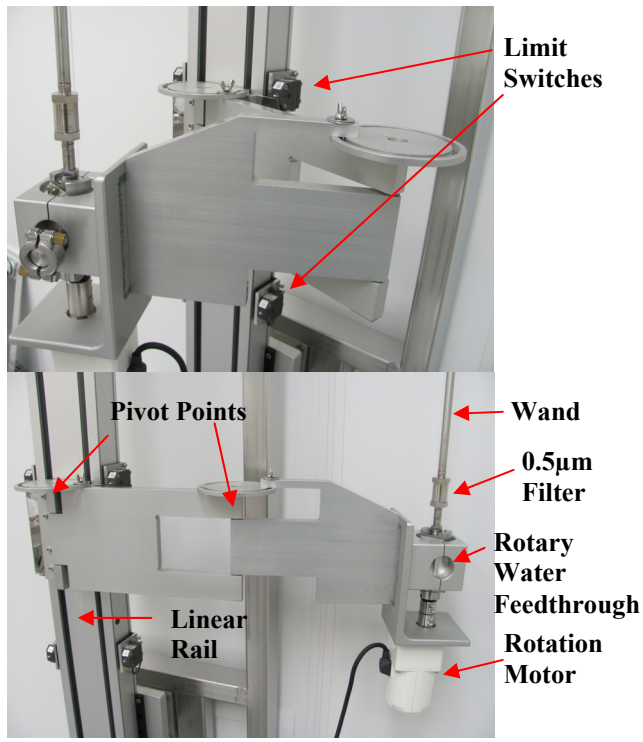


Figure 1: Mounting the HPR rinse wand on a 2-hinged arm allows for the rinsing of any port within the 26" radius.

Wand

Different cavity geometries require different spray patterns in order to adequately rinse the cavity rf surface. Spray patterns can be changed by simply changing the wand on the HPR tool. Currently, the bottom of the wand is welded to one half of a filter. This filter half can be unscrewed from the other half, and the wand can be switched with another wand with a different spray pattern (see Figure 1). Fabrication is already underway on a new, cleaner, method of attachment which uses sanitary fittings instead of threaded fittings. The filter halves will no longer need to be unscrewed in order to switch the wand out; rather just a single sanitary fitting will need to be undone. All welds are full penetration welds in order to eliminate even small dead zones which may promote the growth of bacteria.

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CRYOGENIC TEST OF A TWO-CELL PASSIVE SRF CAVITY FOR NSLS-II

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Abstract

In collaboration with Brookhaven National Lab (BNL), Niowave, Inc. has built and performed the first cryogenic test on a two-cell passive SRF cavity for controlling electron bunch lengths at NSLS-II, the new 3rd generation synchrotron under construction at BNL. The structure is resonant at 1500 MHz, the third harmonic of the accelerating RF frequency. Because the cavity is powered by the beam itself, however, many frequencies could potentially be excited and higher-order modes must be strongly damped. Further, only one of the two cavity fundamental modes is used for the bunch length control, and the other mode has been carefully tuned so that it will be minimally excited by the electron bunches. The first cryogenic test has been performed to demonstrate a successful cooldown of the cavity in its cryomodule and to show that the cavity can be tuned to its operating frequency while the proper spacing between the two fundamental modes is maintained. A brief discussion of the cavity design will be presented along with some results from the cavity tuning and cryotest.

CONTRIBUTION NOT RECEIVED

MATERIAL FOR EUROPEAN XFEL RESONATORS

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Abstract

Twelve different types of semi-finished products will be provided by DESY to producers of European XFEL superconducting resonators. Work on material for XFEL cavities is divided into three phases (prototyping, pre-series and series production). Two new companies (Ningxia OTIC and Plansee Metal GmbH) have been qualified as XFEL suppliers. Material is contracted to 4 companies (Ningxia OTIC, Plansee Metal GmbH, Tokyo Denkai and W.C. Heraeus). Procurement of semi-finished products includes: acceptance on producer's site, eddy current scanning of the sheets, testing for required parameters (RRR, interstitial impurity analysis, metallic impurities analysis, metallography, tensile test, hardness HV, dimensional check, surface roughness), documentation using the DESY EDM-System, marking, delivery to companies. Semi-finished products for pressure bearing sub-components of cavities have to be fabricated according Pressure Equipment Directive 97/23/EC. Qualification of material and the certification of the material producers were done by a "notified body". Appropriate infrastructure and logistic for guiding through more than 20.000 of semi-finished products has been build up.

CONTRIBUTION NOT RECEIVED

STUDY ON ELECTRO-POLISHING PROCESS BY NIOBIUM-PLATE SAMPLE WITH ARTIFICIAL PITS

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Abstract

The Electro-polishing (EP) process is the best candidate of final surface-treatment for the production of ILC cavities. Nevertheless, the development of defects on the inner-surface of the Superconducting RF cavity during EP process has not been studied by experimental method. We made artificial pits on the surface of a Nb-plate sample and observed the development of the pit-shapes after each step of 30um-EP process where 120um was removed by EP in total. This article describes the results of this EP-test of Nb-sample with artificial pits.

INTRODUCTION

The bad performance of Superconducting RF (SRF) accelerating cavities are mainly caused by quench and field-emission. One of candidates to cause the quench is the existence of visible defects on the inner-surface of cavity. Recently, the Electro-polishing (EP) process is the best candidate of final surface-treatment for the high accelerating-gradient cavity. However, there is a natural question that if the EP process is enough to cure the visible defects on the inner-surface of cavity. In such situation, there has been no systematic study on the development of defects on the inner-surface of the SRF cavity during EP process by a clear experimental method. In order to answer this question, we performed EP process on a niobium (Nb) plate sample which has some artificial defects/pits on the surface, in the collaboration of KEK and JLab. We performed the EP process step by step with removal thickness of 30 um by 4times, i.e. 120 um in total. In each step, the development of pit-shape was observed by a laser optical micro-scope. This article reports the results of this experiment.

NIOBIUM-PLATE SAMPLE WITH ARTIFICIAL PITS

The preparation of Nb-plate sample with artificial pits was done in JLab. Many hard alumina micro-balls in the size ranging from a few tens to a few hundreds microns were pressed on the surface of Nb-pate sample. The alumina balls were embedded into the surface of the Nb-plate sample and these balls were molten in following Buffered Chemical Polishing (BCP) process. After melting all alumina balls, pits were created on the surface of the Nb-plate sample. The Nb-sample was sent from JLab to KEK. A picture for the Nb-plate sample with these artificial pits is shown in Fig. 1. We made four scratching lines around pits to make it easier to identify the position of each pit. Then we named seven pits as pit 1 – 7 as shown in Fig. 1.

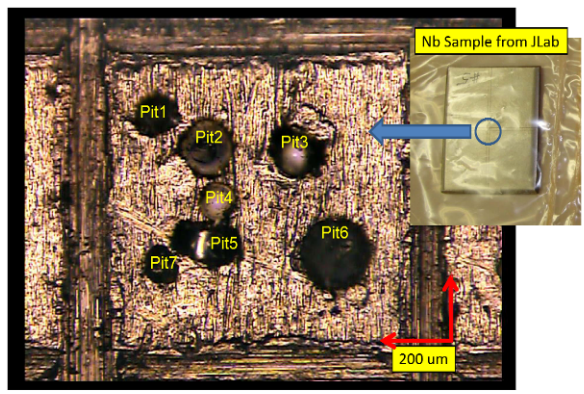


Figure 1: A picture on the surface of the Nb-plate sample with pits by an optical micro-scope.

LASER OPTICAL-MICROSCOPE

We utilized a laser optical-microscope: KEYENCE VK-8500. We could take optical micro-scope images in the format of digital files by this tool. And we could also make 3-Dimensional (3D) contour plot of observing surface of object by laser scanning with changing the focus of optical system automatically. Pictures of the laser optical micro-scope are shown in Fig. 2.

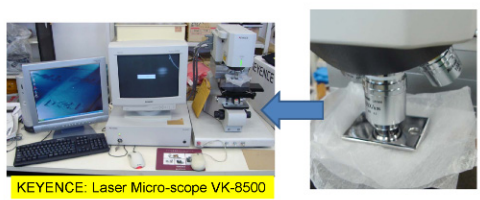


Figure 2: Pictures of the laser optical micro-scope: KEYENCE VK-8500.

BCP PROCESS OF NIOBIUM-PLATE SAMPLE

After receiving the Nb-plate sample at KEK, all pits were observed by the laser optical micro-scope. As the result, we found some small alumina balls were still remaining at the bottom of some pits. We added BCP process by 30 um to remove the alumina balls completely and also this cleaned up the surface of Nb-plate sample before EP process. The BCP process was done at KEK

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SUPERCONDUCTING RF CAVITY DEVELOPMENT WITH UK INDUSTRY

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Abstract

As part of a STFC Industrial Programme Support Scheme (PIPSS) grant Daresbury Laboratory and Shakespeare Engineering Ltd have fabricated, processed and tested a single cell 1.3 GHz superconducting RF cavity, in collaboration with Jefferson Laboratory. The overall aim of the project through a knowledge exchange programme was to develop the capability of UK industry to fabricate and process a single cell niobium superconducting cavity, as part of a long term strategy to enable UK industry to address the large potential market for superconducting RF structures. As a means of measuring the performance of the fabrication and processing an objective of the programme of work was to achieve an accelerating gradient of greater than 15 MV/m at an unloaded quality factor of 1.0 x 10^{10} or better. Three cavities were fabricated by Shakespeare Engineering, and electron beam welded at Jefferson Laboratory in the USA. Processing and testing of the cavities was then performed both at Jefferson Laboratory and at Daresbury Laboratory. The fabrication and process methods are discussed in this paper along with the results obtained from the testing performed in the vertical test facilities.

INTRODUCTION

Three single cell 1.3 GHz niobium superconducting RF cavities have been manufactured by Shakespeare Engineering Ltd [1] as part of a joint programme of work between ASTeC (Accelerator Science and Technology Center) Department at Daresbury Laboratory and Shakespeare Engineering Ltd. The work has been performed in collaboration with Jefferson Laboratory in the US, who has provided their technical expertise throughout all the stages (design, manufacture, processing and testing) of the project. The machining and forming of the cavities was performed by Shakespeare Engineering whilst the electron beam welding of the cavities was performed at Jefferson Laboratory. The Buffered Chemical Polish (BCP) etching and High Pressure Rinse (HPR) and testing of the first cavity were performed at Jefferson Laboratory, whilst all preparations for the second cavity were performed at Daresbury Laboratory. The third cavity is presently awaiting qualification. The tests on the first cavity were performed to provide a benchmark for the processing and testing performed at Daresbury Laboratory.

CAVITY DESIGN & MANUFACTURE

The cavity design utilised the standard TESLA geometry incorporating steps at the equator and beam-pipe interfaces to ensure easy interlocking and location of adjacent parts. Tooling was designed and manufactured using tool steel to ensure durability for repeated processes and to reduce the likelihood of stray material being picked up, thus minimising the transfer of impurities to the surface of the niobium sheets.

Successful trials using a 60 tonne press to produce cavity half cells were performed firstly using copper, as its malleability is similar to that of niobium. The forming dies were polished, to ensure that there was no contamination of the niobium parts. However, the first attempt to produce a niobium cavity half cell was unsuccessful, as the niobium sheet dragged in the press producing a deformed half cell. An investigation determined that the cause was due to the fact that the material thickness was greater in places than the pressing tools had been initially designed for; 3.26 mm compared to 3.1 mm. Modifications were made to the tooling to account for the extra material thickness. The dies were then re-polished and a second attempt to produce a niobium half cell was subsequently successful.

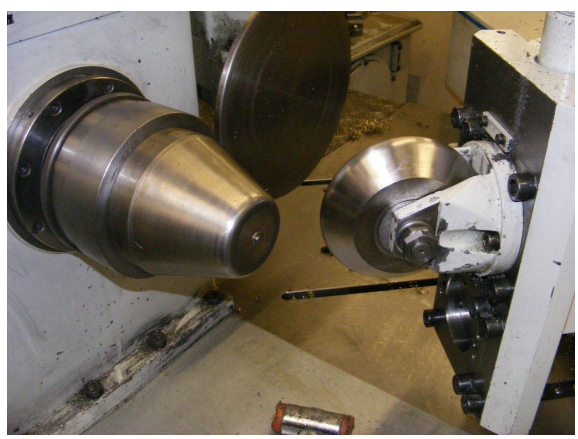


Figure 1: Beam-pipe spinning at Shakespeare Engineering

The beam-pipes were spun on a CNC (computer numerical control) lathe to eliminate the need for performing an electron beam (EB) weld along the seam of a rolled sheet of niobium, as is typically performed. The niobium sheet was spun into a cone (Figure 1), and with successive heat treatments and spinning operations, the cone was eventually transformed into a cylinder and formed on a mandrel. A thickness reduction in the

LONG-TERM MONITORING OF 2ND –PERIOD EP-ELECTROLYTE IN STF-EP FACILITY AT KEK*

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Abstract

We have constructed an Electro-polishing (EP) Facility in the Superconducting RF Test Facility (STF) at KEK at the end of 2007. We have been operating the EP facility since January 2008 and have performed the EP processes of cavities about 140 times up to the present. During this period, we replaced EP-electrolyte in the 2,000L tank twice. Consequently, now we are performing EP processes with the 3rd–period EP-electrolyte. In this report, we present the long-term monitoring results of the 2nd–period EP-electrolyte used from May 2009 to July 2010.

INTRODUCTION

In the EP facility at KEK, the capacity of the EP-electrolyte reservoir tank is 2,000 L (Figure 1). This size is relatively large if compared with EP facilities in other laboratories. It means that the quality control of EP-electrolyte is more difficult than other laboratories because the status of EP-electrolyte changes as we use the EP-electrolyte for many EP processes and the aging of EP-electrolyte proceeds. In the real EP-process operations, we circulated the EP electrolyte of 1,100 L which was firstly delivered into the tank in January 2008 and was disposed in May 2009 [1]. The tank was refilled with fresh EP-electrolyte in May 2009 and the 2nd-period electrolyte was used until July 2010.

The chemical compositions of EP-electrolyte change gradually when using it repeatedly and this aging effect gives some influences to the EP process of cavity. Therefore, it is very important that we monitor the chemical compositions of EP-electrolyte in the tank periodically. In this article, we report the monitoring results of the 2nd-period EP-electrolyte which was used from May 2009 to July 2010.

MONITORING MATERIALS AND ANALYSIS METHODS

We monitored the concentrations of niobium, aluminium, and fluorine in the 2nd-period EP-electrolyte. Niobium is the material of cavity, aluminium is the material of cathode, and fluorine is the component of the EP-electrolyte. We used the ICP (Inductively-Coupled Plasma emission spectrometry) method to measure the concentration of niobium and aluminium (Figure 2). The dilution ratio of EP-electrolyte for niobium measurement is 1/500 and that for aluminium measurement is 1/50. The number of samples for each measurement was three (n=3). Each sample of niobium measurement has the EP-electrolyte volume of 100 ul and it is diluted to 50 ml. Each sample of aluminium measurement has the EP-electrolyte volume of 1 ml and it is diluted to 50 ml. Hydrofluoric acid was added to the samples for niobium measurement until the volume becomes 0.04 mol in order to prevent the hydrolysis.

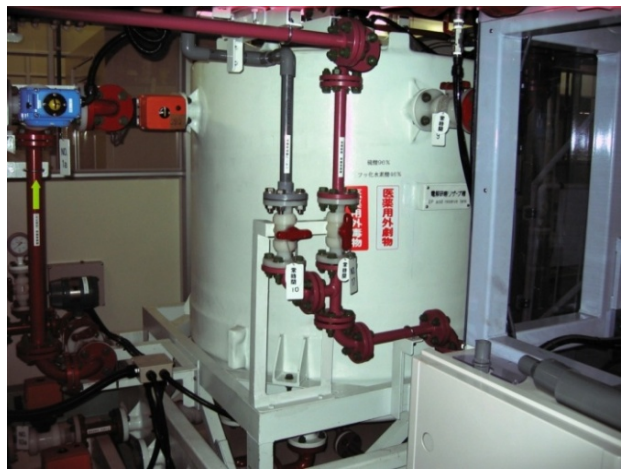


Figure 1: Reservoir tank of EP-electrolyte (2,000 L) in STF-EP facility at KEK.

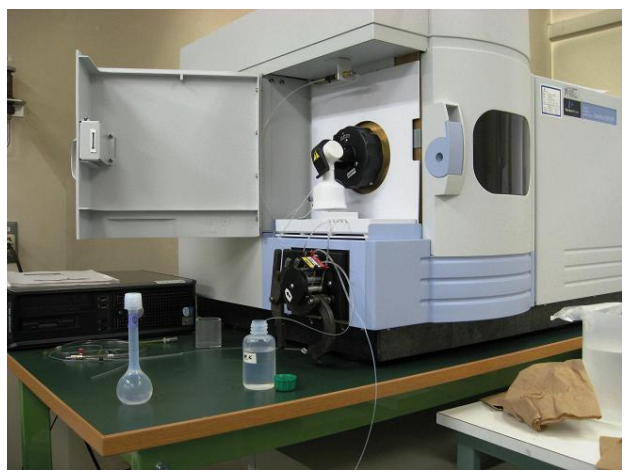


Figure 2: Picture of ICP analyzer used in the measurements.

Chemical Forms of Fluorine in Fresh EP-Electrolyte

Figure 3 shows the result of Ion Chromatograph (IC) analysis for the 1/1000 diluted fresh EP-electrolyte. The fluorine in the diluted solution is separated into the forms

INVESTIGATION ON MODULE ASSEMBLY AND REPAIRS

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Abstract

At DESY several cavity strings for modules of the FLASH accelerator and studies on XFEL prototypes are completed. In some modules cavities have been exchanged for upgrade of applicable module gradients or exchange of resonators showing performance degradation in the module test. Assembly and repair sequences and quality control plans for cavity string are developed and applied. From module string PXFEL3 six out of eight cavities are removed and handed over to CEA Saclay for training of string and module assembly. On two of these cavities the procedures for assembly and exchange of cavities in cavity strings are crosschecked. These cavities are tested at 2 K as removed from string without additional treatments to cross check assembly and repair sequences.

INTRODUCTION

Several cavity strings for modules are set up at DESY. In the modules No 1 to 3 cavities equipped with niobium lips on the sealing area are exchanged to cavities with the actual Niobium- Titanium flange design. On the modules 3**, 6, 8 and PXFEL3 cavities showed gradient degradation between vertical test and RF test on the module test bench (CMTB) [1], [2]. For repair or upgrade of these modules several cavities needed to be exchanged without re-processing of all cavities. Investigations are made to find procedures allowing exchanging individual cavities or cavity sub-units in a module string without re-treatment and a new vertical test of all resonators.

ASSEMBLY SEQUENCES FOR MODULES

All components in use for string assembly in ISO 4 are cleaned in respect to particle contamination [3]. After qualification in an RF test at 2 K in the DESY test area the cavities are cleaned for ISO 4 cleanroom application by ultrasonic cleaning, and ultra-pure water rinsing. Before installation to the cavity string an intensive quality control of cleanliness takes place [4].

After that cleaning process the RF input antennae are exchanged from high Q antenna to the power coupler cold part antenna (PCA) for string assembly. No post-assembly cleaning by high pressure rinsing (HPR) can be applied here without losing the conditioning of the power couplers.

The standardized assembly procedure for string assembly (Table 1) starts with integration of Beam Position Monitor (BPM), quadrupole and gate valve to a Beam Position Quadrupole Unit (BQU). These units are qualified by particle count control and vacuum leak check before installation. Eight resonators, one BQU and a gate valve are connected by bellows at the beam tubes inside ISO 4 cleanroom and build up the cavity string.

Table 1: Generalized assembly steps for sting assembly of DESY / XFEL Cavity strings

1	Align cavity #1 and gate valve on rail
2	Vent cavity to normal air pressure
3	Connect gate valve to cavity #1
4	Pump down and leak check unit
5	Vent cavity and gate valve to normal air pressure
6a	Align cavity #N on rail
6b	Align bellow and beam tube flange long side
6c	Clean beam pipe flange cavity long side
6d	Remove beam tube flange
6e	Connect bellow to beam tube long side
7a	Clean beam tube short side flange
7b	Align bellow and beam tube flange short side
7c	Remove beam tube short side
7d	Connect bellow to beam tube side short
8	Repeat step 6a to 7d for cavity #2 to #8 and BPM Quadrupole unit
9	Adjust coupler distance
10	Pump down string and leak check unit
11	Vent string to normal air pressure

Cavity beam position monitors were in use for the module No 1 to 8. These cavity BPMs are equipped with welded-on bellows. This design leads to limited space for assembly at the connection to cavity 8. The alignment and connection to the cavity string was done manually, without assembly tools being applicable.

The XFEL prototype BPM installed to module PXFEL1 to PXFEL3 is designed with a separated bellows unit. These bellows is of identical geometry as in use for the cavity to cavity connection. This set-up allows making use of the identical tools and handling processes as applied for the cavity to cavity connections.

The refurbished DESY cleanroom [5] allows improvements in preparation and assembly steps of the string assembly. The assembly of XFEL BQU takes place independent from the string assembly itself [5].

Before assembly to the cavity string each part is qualified by controlling particle contaminations with blowing with ionized air guns towards air particle counters [6].

REPAIR SEQUENCES

Preparation for Strings upgrade

During module installation and module test, the exterior of the cavities is exposed to normal air and contaminated by particulates and other residues of the assembly

SLAC/FNAL TTF3 COUPLER ASSEMBLY AND PROCESSING EXPERIENCE*

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Abstract

The TTF3-style coupler is typically used to power 1.3 GHz TESLA-type superconducting cavities. For the US ILC program, parts purchased in industry for such couplers are received at SLAC where they are inspected, cleaned, assembled as pairs in a Class 10 cleanroom, pumped down, baked at 150 °C and rf processed. The pairs are then shipped to FNAL and installed in cavities that are tested at input power levels up to 300 kW. This paper describes the coupler results to date, including improvements to the preparation procedures and efforts to understand problems that have been encountered.

INTRODUCTION

The International Linear Collider (ILC) will contain about 16,000 superconducting cavities. Each cavity will have a power coupler that transports ~ 300 kW, 1.6 ms, 1.3 GHz rf pulses at 5 Hz from a waveguide feed at room temperature through a coaxial line to an antenna that protrudes into the 2 K cavity beam pipe. Fig. 1 shows the TTF3 coupler design [1], which was developed by the TESLA Collaboration and is being used for ILC cavity R&D in Europe and the US and for the European XFEL project. The design is complex due to requirements on thermal expansion, heat load, vacuum, Qext adjustability and high voltage isolation. In particular, four thin bellows are used to allow flexibility and adjustability, the inner stainless surfaces are plated with a thin copper layer to reduce rf losses while limiting heat loss and the windows are TiN coated to suppress multipacting.

The cryomodule program for the US ILC effort is centered at FNAL, and SLAC is providing TTF3 couplers for the cavities that are being 'dressed' there. So far, all couplers have been purchased from one vendor. They were fabricated using brazing and e-beam welding techniques, and then shipped to SLAC where they were inspected, cleaned, assembled in a Class 10 room, pumped down, baked at 150 °C and then rf processed [2]. The first couplers were rf processed in 6/09, and this paper discusses the progress and the lessons learned since then.

PROCESSING HISTORY

To date, 18 couplers have been inspected, assembled and rf processed at SLAC, and shipped to FNAL where 16 have been installed in cavities that have been tested in their Horizontal Test Stand (HTS). At SLAC, the couplers are rf processed at room temperature in pairs using a specially designed disk-shaped cavity to couple the power between the pairs via their antennas. For this processing, the input power is slowly increased up to 1.3 MW, paced by the outgassing level (limited to 10^{-6} Torr), at progressively longer pulses (20, 50, 100, 200, 400, 800 and 1050 μs). At 800 us and 1050 μs, the power is kept below 650 kW to limit average heating, although for the most recent pair, the repetition rate was lowered to 1 Hz for the 1050 μs operation and the power ramped to 1.3 MW to better match the long pulse SW operation at FNAL.

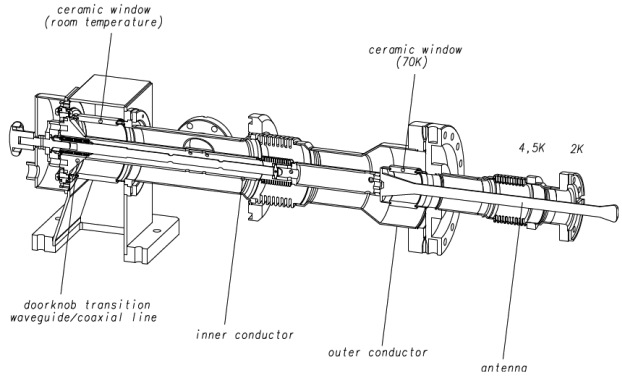


Figure 1: TTF3 L-Band Power Coupler.

The integrated periods of power-ramping were typically 10-20 hours for the nine pairs, although they were operated up to 50 hours including fixed power periods to verify that the monitored signals (vacuum, light in the air-filled waveguide and electron probes in the coupler vacuum) continue to decrease over time. The electron probe signals, which are monitored using an electronics module designed at FNAL [3], indicate strong multipacting during the initial power ramp-up, which is to be expected. This activity tapers off during processing as the surface gas layer is removed. No rf breakdown has been observed at the high power levels, which is not surprising given the low surface fields.

At FNAL, the couplers need to be rf processed again after installations on the cavity (cold section) and in the HTS (warm section), as the inner surfaces are exposed to air. This is first done at room temperature where the rf power is fully reflected. A similar conditioning protocol as that described above is used, except that the power is limited to 280 kW, the maximum pulse length is 1.3 ms and all operation is at 2 Hz. It usually takes 25-40 hours to complete the processing. The factor that most limits the conditioning time is the intense degassing in the warm part of the coupler, which causes vacuum spikes above the interlock value.

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OPTIMIZATION OF PLASMA PARAMETERS FOR ETCHING OF SUPERCONDUCTING RADIO FREQUENCY CAVITY SURFACE IN Ar/Cl_2 PLASMA

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Abstract

We are pursuing the development of low cost environmentally friendly dry etching of superconducting radio frequency (SRF) cavities in Ar/Cl_2 discharges. It has been proven with flat samples that the bulk Niobium (Nb) removal rate and the surface roughness after plasma etchings are equal to or better than wet etching processes. The plasma properties inside the single cell SRF cavity depend on frequency, pressure and power. To understand the plasma properties and chemical kinetics of the plasma etching process inside the single cell cavity, we are using a single cell cavity with 20 sample holders symmetrically distributed over the cell. These holders are being used for niobium coupon etching as well as diagnostic ports for optical measurements. Multiple optical probes with optical fibers have been utilized for optical emission spectroscopy measurements. A power supply in the radio frequency regime (100 MHz) and another power supply in the microwave frequency regime (2.45 GHz) are used to produce the plasma inside the cavity. The plasma parameters at different pressure and power levels in combination with the analysis of the niobium sample etched will be used to determine the adequate frequency regime for plasma etching of Nb cavities.

INTRODUCTION

To improve the RF performance of the SRF niobium cavities, the cavity surface must be prepared by a process that improves surface roughness, removes impurities and creates less sharp grain boundaries. Currently used technologies are buffered chemical polishing or electro polishing. These technologies are based on the use of hydrogen fluoride in liquid acid baths, which poses major environmental safety concern. HF-free plasma-based ("dry") technologies are a viable alternative to wet acid technologies as they are much more controllable, less expensive and more environment-friendly. We have seen that plasma etching technology has replaced the wet etching process in the semiconductor industry

While the results with flat samples were very encouraging, with etching rates up to 1.7 μm/min and surface roughness down to below 100 nm, the two parameters could not be achieved with the same treatment. Results are indicative of competitive character of the surface smoothness and etching rate. In every case, however, the surface roughness of plasma etched sample is equal or better than the chemically etched samples [1].

SINGLE CELL CAVITY EXPERIMENT

In order to test the RF performance, plasma processing has to be applied to a single cell cavity. Cavity shape is defined by the resonant low-loss requirement for generating the accelerating gradients. This design does not favor the electric configuration on the surface that is optimal for plasma etching. Therefore, the generic etching configurations are capacitive coupled radio frequency or a coaxial microwave discharge. A specially designed diagnostic cell has been used for preliminary testing on homogeneity of plasma and surface processing performance. The cell has a set of 20 sample holder holes that can be used as plasma observation windows or small sample holders for etching tests. After completion of the tests with the diagnostic cell, a set of standard single cells will be prepared for cryogenic RF performance testing.



Figure 1: Single cell cavity with sample holders.

To verify the non-uniformity and other plasma parameters of the plasma in the cavity, a fibre optic diagnostic system was developed. The driven electrode is 2.6 mm in diameter 17.2 cm long niobium rod and the

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CORRECTIONS OF A SUPERCONDUCTING CAVITY SHAPE DUE TO ETCHING, COOLING DOWN, AND TUNING *

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Abstract

Corrections of shape needed for an SRF cavity after fabrication are presented in a convenient form with a possibility to take into account different technological procedures, such as etching, cooling down and pre-loading.

INTRODUCTION

Optimization of the cavity shape consists mainly in a search of the final shape in a cooled-down state after all the technological procedures including etching and preliminary loading. The preloading is needed with a goal to get rid of backlash when the cavity is being tuned to the work frequency. So, the drawing dimensions should differ from these final dimensions if we want to end up with the calculated dimensions. Moreover, it is a question, whether these dimensions are dimensions of elliptic arcs routinely used for description of the cavity shape. It would be useful to find a convenient form of taking into account all of these changes of shape. It is even more important to keep the designed dimensions if the cavity is optimized for minimal BBU parameter, because the higher order modes responsible for beam break up - are even more sensitive to distortion of dimensions than the fundamental mode.

MATRIX DESCRIPTION OF THE CAVITY SHAPE

If we look at any multicell cavity shape, we can note that it can be presented as a chain of elliptic arcs connected with straight segments tangent to them, Figure 1. So, a full description of the final dimensions of such a cavity excluding the lengths of end pipes can be presented as:

$$\text{dim_}f = \begin{pmatrix} x1 & x2 & \cdots & x\text{n} \\ y1 & y2 & \cdots & y\text{n} \\ a1 & a2 & \cdots & a\text{n} \\ b1 & b2 & \cdots & b\text{n} \end{pmatrix}.$$

"Final" means that the cavity is cooled down after all technological preparations which can change the dimensions (etching and, possibly, tumbling), and preloading. In the first line of the matrix are longitudinal coordinates of the centers of the elliptic arcs, in the second line – the radial coordinates of the centers, in the third and fourth – longitudinal and radial half-axes of the ellipses, respectively.

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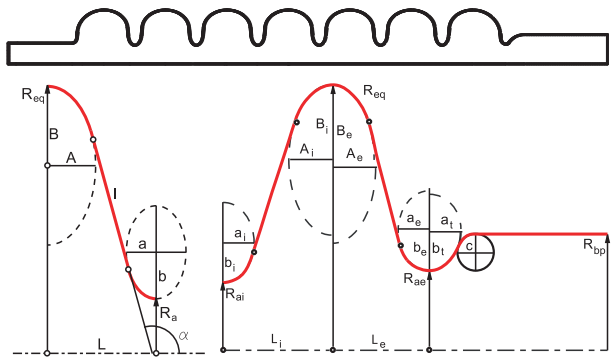


Figure 1: A multicell cavity (upper picture) and its presentation as a chain of elliptic arcs connected with straight segments: inner half-cell and end cell (lower pictures). End cells can have an additional iris: compare the right and left ends.

If shrinkage only due to Nb thermal contraction from 293 K to 0 K is considered, the starting dimensions of the cavity should be bigger by the factor of $1+kT = 1+1.43\cdot 10^{-3}$ [1]:

$$\text{dim_}s = \text{dim_}f \cdot (1 + kT).$$

If etching only is taken into account, then

$$\text{dim_}s = \text{dim_}f - \text{Etch},$$

where the matrix Etch looks like

$$\text{Etch} = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ ex1 & ex & \cdots & ex\text{n} \\ ey & ey2 & \cdots & ey\text{n} \end{pmatrix},$$

where positive values in the third and fourth rows correspond to concave surfaces (equatorial ellipses) and negative values of ex or ey are for decreasing half-axes (irises). Here we can take into account different values of etching for equatorial and iris regions if they are known from experiment (different ellipses = different columns) and even for lower and upper parts of the ellipses (for different axes = different rows). Now, if only compression (or stretching) of the cavity should be accounted, we can write

$$\text{dim_}s = \text{dim_}f - \text{P}\cdot\Delta L,$$

where P is the matrix of "pliability":

INVESTIGATIONS TO UNDERSTAND THE ORIGIN OF DEGRADATION OF SUPER CONDUCTING CAVITIES FOUND IN ACCELERATION MODULES AT DESY

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Abstract

In the last decade the degradation of cavity acceleration gradients is observed frequently in module RF tests, after the assembly and installation of complete accelerator modules. In some cases no explanation for these degradations could be found from quality control records, assembly procedure protocols or notes from observers. On the PXFEL 3 module quench limitations without indication of field emission loading is observed at two cavities. Boundary conditions like storage of resonators, cleaning process for ISO 4 clean room as well as the assembly processes and handling of the resonators are under investigation. The two degraded cavities of module PXFEL 3 are removed from the cavity string and studied intensively. The actual status of our research is presented.

MOTIVATION

During the last decade several accelerator modules were assembled at DESY for prototype development and FLASH linac operation. Cavity strings are assembled in the DESY ISO 4 cleanroom. Even if the procedures for string assembly are well established, some of the module cavities show degradation of acceleration gradient (Eacc) cavities installed into module strings do not undergo a further high pressure rinse (HPR). Limitation by field emission may be explained by statistical errors origin from infrastructure problems or nonconformities during the assembly, which might be removable by HPR. Some cavities show low gradients limited by quenches without detectable X- rays. The origin of degradation without electron loading is under investigation. Two cavities, Z88 and AC127 in module PXFEL 3 show this effect and were removed from the string for studies.

ANALYSIS OF DATA

In eight out of ten cavity strings assembled, a degradation of resonators was observed. In some cases degradation is combined with increased emission of X-rays. At seven resonators gradient reduction without field emission is observed at DESY (Table 1). Minor non conformities are recorded for these cavities during string assembly. The applied preparation sequences (BCP flash; EP) do not seem to be correlated to the degradations (Table 1), even though more cavities treated by EP are affected. No strong correlation on position and degradation of cavities inside modules is found, even though positions 3 and 6 show an increased number of degraded resonators (Table 2).

Cavity AC113

Cavity AC113 installed to module PXFEL 1 showed degradation of Eacc. when the cavity was tested horizontally in CHECHIA (Fig. 1). No further reduction was found after installation to module PXFEL 1. One non conformity before CHECIA test is reported.

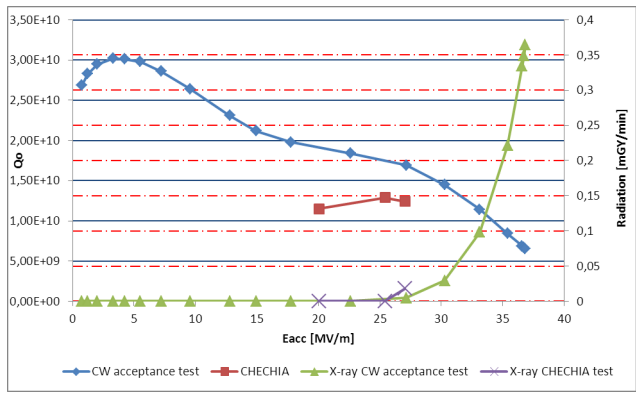


Figure 1: RF Test results of cavity AC 113.

During tank welding procedure the field measurement system had to be exchanged due to a vacuum leak.

Z88, Z108 and AC127

Cavity Z88 and AC108 have been used in module 8 before. Reduced gradients with field emission loading were observed.

Table 1: Summary of resonators showing reduced performance without field emission in DESY modules. The last column shows the gradient before module assembly.

Module	Cavity	Pos.	Final treatment	Drop (MV/m)	Start Gradient (MV/m)
6	Z85	5	EP	12	35
	Z92	6	EP	12	35
8	Z109	2	BCP +EP	8	30
PXFEL1	Z100	7	EP	11	39
PXFEL2	Z133	3	BCP flash	11	27
PXFEL3	Z88	3	EP	11	31
	AC127	6	EP	8	28
S1 global	Z108	3	EP	12	32

After retreatment the gradients recovered to 30,4 and 31,3 MV/m respectively without field emission in the

RESULTS ON LARGE GRAIN NINE-CELL CAVITIES AT DESY: GRADIENTS UP TO 45 MV/M AFTER ELECTROPOLISHING

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Abstract

Since 2009 a series of eight nine-cell cavities (AC151 – AC158) of TESLA shape fabricated of large grain (LG) niobium material [1] is under preparation and test at DESY. In a first step all cavities were tested after a BCP treatment. In a second step additional electropolishing is applied to all cavities. In this paper the treatment will be discussed and present results will be reported.

MATERIAL AND FABRICATION

Development of LG disc production was done within the framework of the European XFEL driven R&D program of DESY [2] and the company W. C. Heraeus. One of the particularities was the presence of a single crystal with a diameter larger than 150 mm in the disc's central area. This was essential for avoiding necking and tearing at the iris areas during deep drawing.

The developed multi-wire slicing procedure allows keeping the high residual resistance ratio (RRR) of the melted ingot in the discs. The surface of the sliced discs has a high quality; the roughness was small compared to conventional fine grain sheets.

Three cavities (AC151 – AC153) have been fabricated from material with RRR of about 420. For five cavities (AC154 – AC158) the RRR of the material was about 350. More details about the material are presented in [3].

For the cavities AC155 and AC156 the steps at the grain boundaries, which appeared after deep-drawing, were smoothened by grinding the RF surface of the half-cells.

The complete fabrication was done by Research Instruments GmbH (RI).

CAVITY SURFACE PREPARATION

For all cavities the preparation at DESY started with a mechanical and electrical entrance check. The inner surface of the cavities was visually inspected with a camera system developed at KEK/Kyoto University [4].

BCP Treatment (Figure 1)

The main inside surface removal of about (100 – 110) μm as well as the outside removal of about 10 μm was done by BCP (volume $HNO_3 : HF : H_3PO_4$ 1:1:2) at RI. Inside BCP took place in the RI closed loop system, while outside BCP was done by dipping with protected NbTi-flange surfaces. The subsequent final treatment at DESY started with the standard 800°C firing for 2 h at a pressure < 10^{-5} mbar. After tuning to a field flatness of better than 95 % the final inside BCP of (20 – 30) μm (volume $HNO_3 : HF : H_3PO_4$ 1:1:2) followed in the closed loop DESY system including ultrapure water rinse and first High Pressure Water Rinse (HPR). Flange and pickup assembly followed by final six HPR cycles (2 h each) [5] and helium leak check were done in the cleanroom of class ISO 4. The low temperature heating ("baking") of the evacuated cavity took place at a temperature of 125°C - 130°C for about 48 h in a heating stand outside of the cleanroom.

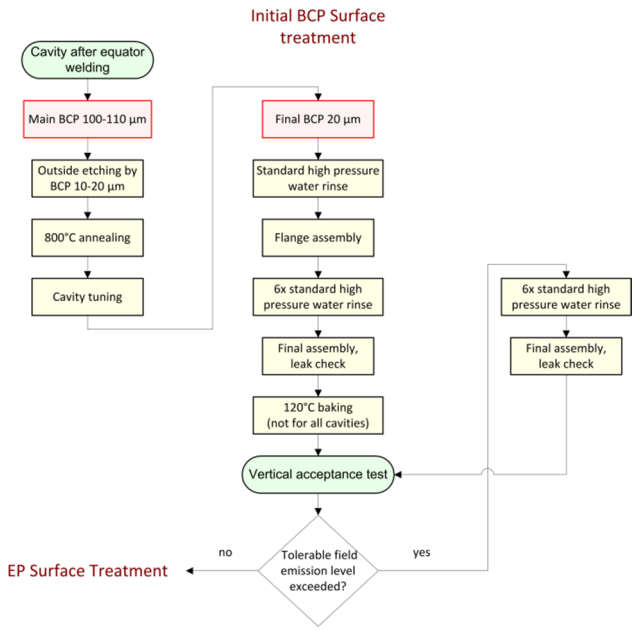


Figure 1: Flow scheme of BCP treatment.

EP Treatment (Figure 2)

After the first vertical acceptance tests (described below) the possible removal with respect to frequency and tolerable length was calculated. Therefore two different procedures were applied:

- For six cavities a main EP at DESY [6] of about (60 – 70) μm was done, followed by an ethanol rinse and an additional standard 800°C firing for 2 h at a pressure < 10^{-5} mbar for hydrogen degassing. Before final EP, the field flatness was checked again and, if necessary, tuned to better than 95 %. The final EP removal was about 48 μm. Ethanol rinse [7], flange assembly, final six HPR cycles and helium leak check took place in the cleanroom of class ISO 4.
- For two cavities (AC151, AC155) the main EP was not possible. Their tolerable length in the cryo-module at the operating frequency would be exceeded due to the additional removal. Therefore, after tuning only the final EP followed by the above

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COMMISSIONING AND UPGRADE OF AUTOMATIC CAVITY TUNING MACHINES FOR THE EUROPEAN XFEL

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Abstract

For more than 20 years DESY has gained experience in tuning cavities of TESLA [1] shape nine cell cavities for FLASH [2] to field flatness and concentricity.

Based on this experience four automatic cavity tuning machines were developed and built by a collaborative effort among FNAL, KEK and DESY [3] to support the high throughput of series cavity productions necessary for new projects like the European XFEL [4], the ILC project, Project "X" and further SRF based future projects.

In the meantime two machines were delivered to the collaborative partners KEK and FNAL. The remaining two machines at DESY, are regularly used since several months. A large number of cavities of different types and at different production stages have been automatically tuned for FLASH and also in preparation for the European XFEL series cavity production starting this summer.

INTRODUCTION

Typical tuning methods [5] are based on special tooling to manually obtain plastic deformation of every cell by an expert operator. This is a very time-consuming procedure. It is not adequate for cavity series productions needed for SRF-based projects like the European XFEL.

Four completely new designed machines were developed, built and successfully commissioned until 2009 at DESY by a close teamwork with FNAL.

Due to this operational experience and the requirements of the European XFEL cavity specification, it became necessary to improve and upgrade several components of the automatic cavity tuning machines and their control software [6].

These upgrades mostly impact the accuracy and the diversity of machines to get the ability to tune cavities in different production stages – from the semi-finished, just electron beam welded cavity, over the completely prepared and chemically treated cavity with welded ring and bellow, up to the completed cavity, welded in helium tank.

These upgrades have a multiple influence on the safety concept of the machines.

All changes of the machines have to comply with the essential health and safety requirements and have to be designed, built and documented in accordance to the Machinery Directive of the European Community (EC). In June 2010 the 2nd revised version of the Machinery Directive of the European Community (EC) was validated. Because of the delayed official delivery date of machines to the cavity vendors new safety measures had to be taken into account.

In the following the several upgrades with their reasons and targets to the functionality of the automatic cavity tuning machines are described in detail.

MAJOR UPGRADE OBJECTIVES

From the gained experience we decided on several necessary upgrades.

The functionality of machines was expanded by:

- Tune a cavity with welded ring and bellow.
- Accomplish a bead pull measurement on a cavity welded in a helium tank.
- Enable machines to operate an automated calibration procedure.

It is well known that the welding procedure of a helium tank changes the field flatness by deformation of a cavity in a slight but not irrelevant percentage. To guarantee planed accelerating gradients, the field flatness - after welding of ring and bellow - needs to achieve 98% before tank welding.

To obtain these aims it is necessary to increase the accuracy not only for feedback measurements during the entire tuning procedure but even for the cell tuning and alignment itself.

The accuracy of machine was enhanced:

- Total resolution of eccentricity measurement device better than 0.1mm.
- Increase precision of entire tuning frame.
- Enhance plastic deformation range of jaw units.
- Increase precision of cavity alignment tool.

TUNING FRAME UPGRADE

The tuning frame is designed modularly. All assemblies including electronic enclosures are mounted to an aluminum alloy cast base plate. The plate itself only captures the weight of subassemblies. The entire design is done in a way that no counter forces are applied to the base plate.

Figure 1 shows the tuning frame with the base plate and the three vice units. The tuning frame consists of three equal vice units, arranged in a 120°angle. Each vice unit has two tuning arms mounted on a rotary axis. Via a stepper motor and two gearboxes the distance between the

Q_0 IMPROVEMENT OF LARGE-GRAIN MULTI-CELL NIOBIUM CAVITIES BY USING JLAB'S STANDARD ILC PROCESSING*

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Abstract

As reported previously at the Berlin SRF conference, applying the JLab standard ILC electropolishing (EP) recipe on initially buffered chemical polishing (BCP) etched fine-grain multi-cell niobium cavities results in improvement both in gradient and Q_0. We recently had the opportunity to further experiment with two 1300 MHz 9-cell large-gain niobium cavities, one manufacture by JLab and the other by Peking University. Both cavities were initially BCP etched and further processed by using JLab's standard ILC EP recipe. Due to fabrication defects, these two cavities only reached a gradient in the range of 20-30 MV/m. Interestingly, both cavities exhibited significant Q_0 improvement in the gradient range of 15-20 MV/m. At 2K, a Q_0 value of 2E10 is achieved at 20 MV/m. At a reduced temperature of 1.8K, a Q_0 value of 3E10 is achieved at 20 MV/m. These results suggest that a possible path toward raising Q_0 in the medium gradient range is to use the large-grain material for cavity fabrication and ILC-style recipe, namely furnace heat treatment, light EP and low temperature bake for final processing.

INTRODUCTION

Pushing the unloaded quality factor (Q_0) of SRF cavities has received lot of attention in recent years. This development is driven by two classes of SRF cavity applications:

- CW machine operated at a medium gradient, such as CEBAF 12 GeV upgrade, Cornell ERL, FNAL Project X.
- Pulsed machine operated at very high gradient, such as ILC 1 TeV upgrade.

For a CW machine at GeV energy range, high Q_0 is needed to keep both the size of the cryo plant and the cryogenic operation cost at reasonable levels. For a pulsed machine at TeV energy range, pushing gradient is important to keep the machine length at a reasonable level; however, to make the higher gradient economically attractive, the cavity Q_0 value must be further pushed beyond the state-of-the-art.

Although there are candidate alternative materials that offer the perspective of lower surface resistance and hence a higher Q_0, it is still premature to plan a future SRF project based on a material other than niobium. In fact, Cornell ERL, Project X and ILC are all based on niobium technology at frequencies in the range from 650 MHz to 1300 MHz. It is therefore of interest to explore methods of improving Q_0 of niobium cavities.

As reported in Ref. [1], applying JLab's standard ILC processing recipe [2] onto an initially BCP etched multi-cell fine-grain niobium cavity resulted in improvements both in gradient and Q_0. Besides the two 7-cell 1497 MHz cavities HG006 and HG007 reported in Ref. [1], a third 7-cell 1497 MHz cavity HG008 was also successfully processed and tested, re-confirming the benefit (Fig. 1).

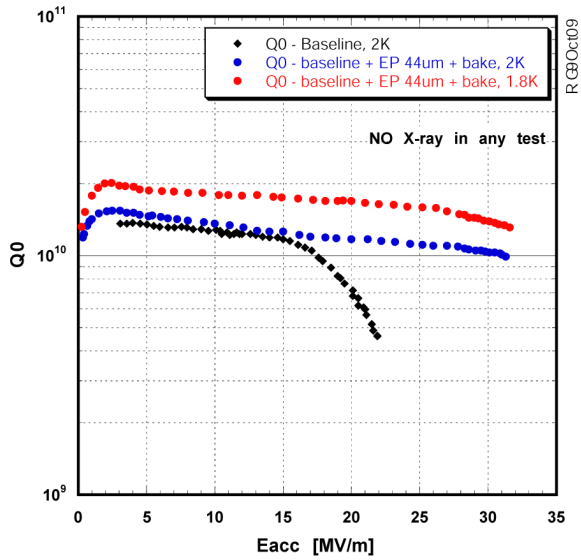


Figure 1: Test results of 1497 MHz 7-cell fine-grain niobium cavity HG008.

These encouraging results with fine-grain multi-cell niobium cavities were followed by further experiments with large-grain multi-cell niobium cavities. In this paper, we will report on the results of two 1300 MHz 9-cell large-grain niobium cavities. We will also analyze the new and previous data in an attempt to understand the physics behind the Q_0 improvement.

CAVITIES AND RESULTS

JLAB LG#1

This cavity was fabricated at JLab using CBMM large-grain material [3]. It was initially tested after BCP etching with a quench limit at ~ 20 MV/m at Q_0 8E9. Following a light EP with 35 μm removal and 120 °C 48 hour bake, the cavity quench gradient was improved to 30 MV/m at Q_0 of > 1E10 [1]. Through T-mapping measurements and optical inspection, a weld repair at the equator EBW of the center cell was found to be responsible for the quench limit. The cavity JLAB LG#1 was then sent to KEK for

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STUDIES ON TRANSPORTATION OF SUPERCONDUCTING RESONATORS AND BEAM POSITION MONITOR - QUADRUPOL UNITS FOR THE XFEL PROJECT

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Abstract

For the XFEL project industrial companies in Germany and Italy are in charge of the cavity fabrication and preparation. For the radio frequency acceptance test these cavities have to be transported to the DESY site in Hamburg without losing the performance. The XFEL Beam Position Monitor and Quadrupol Units (BQU) are completed in the DESY clean room. The cavities and the BQU are handed out in the status "ready for assembly" to the string assembly site at CEA Saclay in France. These components have to be transported without risk of damages or reduction of performance. To ensure that the transports over European routes do not influence the performance of cavities or are origin of particulates inside the BQU, individual transport boxes for super conduction cavities and transport fixtures for the BQU are designed and tested.

INTRODUCTION

The cavity fabrication and surface preparation for the XFEL project is contracted at two industrial companies, E. Zanon in Schio, Italy and Research Instruments in Bergisch-Gladbach, Germany. The assembly of the module strings, consisting of eight cavities and one BQU will take place in the cleanroom of CEA Saclay in France. For transports between these companies, standard trucks will be used. Some frequent transport distances will exceed 1000 km.

Test equipment for transportation studies on valuable goods can be found at the Institute BFSV in Hamburg Germany [#1]. Beside damage-free transportation, DESY has to ensure that the performance of resonators will not be influenced by these transportations. Commercial available transport cases as well as a special designed transport unit for BQU were studied on a test bench and during real transport to validate safe transportation procedures.

TRANSPORT CONDITIONS

For the XFEL in the 17GeV version 100 modules have to be assembled at CEA Saclay. 800 resonators in batches of up to four cavities need to be transported from Italy, respectively middle of Germany to the test bench at DESY as pay load. Batches of eight tested resonators and one BQU will be sent to CEA Saclay. For these transports a maximum of technical safety at a minimum of costs is required, On the test bench of the BFSV institute in Hamburg it was shown that cavities and accessories like High Q- or HOM antennas can be exposed individually to shock waves of up to 6 g without affecting the mechanical properties (geometry of the cavities) [1].

Transport Conditions

The cavities are handed to DESY in the status ready for acceptance test. The surface treatment by final EP or BCP flash [2] is completed at industry. The cavities are equipped with their Pick up antenna and HOM antennas that remain on the cavity in the module. For the vertical test at 2K a high Q test antenna is installed on the power coupler port (Fig. 1). These antennas, as well as the beam tube flanges, remain on the resonators until the string assembly.

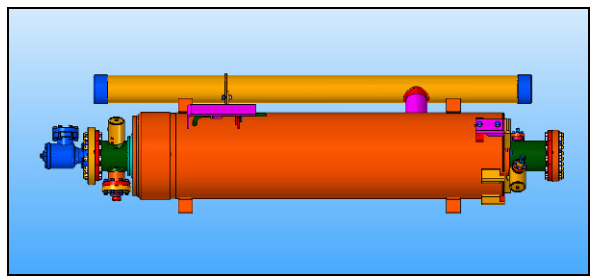


Figure 1: XFEL cavity in helium tank full equipped.

The BQU units are completed in the ISO 4 area of the DESY cleanroom (Fig. 2). A cleaning for ISO 4 clean rooms of the sophisticated BQU cannot be done in an economical way.

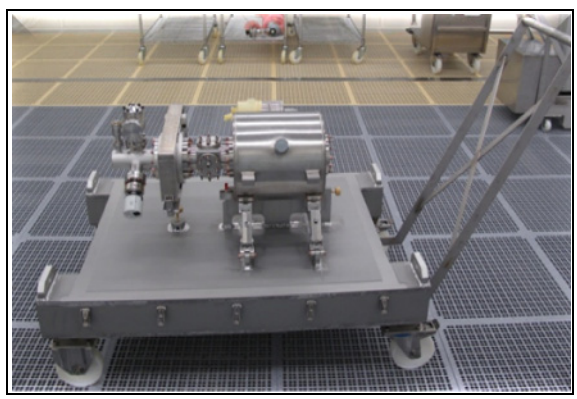


Figure 2: BQU completed inside ISO 4 cleanroom.

The unit is hermetically closed by a cover hood inside DESY ISO 4 area at DESY (Fig. 3). To ensure that the box will be free from differential pressure at any time, even when heated up during cleaning processes, an inline particle filter is connected to the hood.

HIGH-TEMPERATURE HEAT TREATMENT STUDY ON A LARGE-GRAIN NIOBIUM CAVITY*

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Abstract

Improvement of the cavity performance by a high-temperature heat-treatment without subsequent chemical etching has been reported for large-grain Nb cavities treated by buffered chemical polishing (BCP), as well as for a fine-grain cavity treated by vertical electropolishing [1]. Changes in the quality factor, Q_0, and maximum peak surface magnetic field achieved in a large-grain Nb single-cell cavity have been determined as a function of the heat treatment temperature, between 600 °C and 1200 °C. The highest Q_0 improvement of about 30% at a peak surface magnetic field of 90 mT was obtained after heat-treatment at 800 °C – 1000 °C. Measurements by secondary ion mass spectrometry on large-grain samples heat-treated with the cavity showed large reduction of hydrogen concentration after heat treatment, compared to samples treated by BCP.

INTRODUCTION

A high temperature heat treatment (HT) at 600 °C for 10 h or 800 °C for 2 h in a ultra-high vacuum (UHV) furnace is part of the standard preparation procedure for SRF cavities made of bulk niobium. This treatment is done after cavity fabrication and heavy chemical etching to provide some stress-relief in the material and degas interstitial hydrogen from the bulk to avoid the so-called Q-disease [2]. Because of the re-absorption of residual gases in the furnace into the Nb cavity during cool-down to room temperature and possible surface contamination with foreign materials during HT, about 20 µm of Nb are typically removed from the inner cavity surface by either Buffered Chemical Polishing (BCP) or Electropolishing (EP) after the heat treatment. Nevertheless, measurements on Nb samples [3-5] show surface hydrogen concentrations of up to about 40 at.% after such chemical treatments. Such high concentrations are also to be expected from the theoretical point of view [6]. High concentrations of hydrogen near the surface can degrade the SRF properties of Nb, for example by increasing the residual resistance and therefore lowering the Q_0 of the resonator.

Initial studies were carried out at JLab to evaluate the performance of single-cell cavities after HT at 800 °C for 3 h, without subsequent chemical etching [1]. In some cases, a low-temperature (120 °C for 12 h) bake was also included in the heat-treatment, after the hold-out at high temperature. Significant improvement of the Q_0-value after HT without BCP/EP was measured in cavities made of large-grain niobium. Sample measurements by Secondary Ion Mass Spectrometry (SIMS) [1] revealed much reduced hydrogen content after heat treatment.

In this contribution we present the cavity test results and SIMS data on samples after heat-treatments at different temperatures and durations, in the range 600 °C – 1200 °C for 2 – 10 h to evaluate the parameters which would give the largest Q_0 improvements. Initial data have shown that lower residual resistance values can be already achieved using large-grain Nb, instead of fine-grain Nb, using standard cavity preparation procedures. Therefore we are focusing on this material to develop a cost-effective preparation procedure to obtain cavities with high Q_0 at peak surface magnetic field, B_p, of the order of 90 mT (accelerating gradients of about 20-25 MV/m). This would be beneficial for the use of new Continuous Wave (CW) accelerators for a variety of applications.

CAVITY PREPARATION AND TEST RESULTS

Cavity Preparation

The cavity used for this study is a 1.47 GHz single-cell of the original CEBAF shape and was made of large-grain Nb from Ningxia, China. This cavity was also used for the initial study of Ref. [1]. The treatment and test sequence was as follows:

- ~3 µm removal by BCP 1:1:2
- RF test (baseline 4)
- ~30 µm removal by Barrel Polishing followed by ~27 µm removal by BCP 1:1:2 and HT at 1000 °C/3 h + 120 °C/12 h
- RF test
- ~17 µm removal by BCP 1:1:2
- RF test (baseline 5b)
- HT at 1200 °C/2 h + 120 °C/12 h
- RF test
- ~16 µm removal by BCP 1:1:2
- RF test (baseline 6b)
- HT at 600 °C/10 h + 120 °C/12 h
- RF test

Common to the preparation steps mentioned above are: ultrasonic degreasing for 30 min prior to BCP or HT and after HT, High Pressure Rinse (HPR) with DI water for 30 min, after BCP or HT. After HPR the cavity is dried for ~3 h in a class 10 clean room and stainless steel blanks with pump-out port and RF antennae are assembled on the cavity flanges with In wire. The cavity is then evacuated

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THE FABRICATION OF BEPCII 500MHZ SUPERCONDUCTING CAVITIES

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Abstract

Since Nov. 2006, the 500MHz SRF system of Beijing electron positron collider upgrade (BEPCII) has been running stably. But there's a hidden danger for no spare cavity is existed. If there's any serious trouble happened on either one of the two operating cavities and cannot be recovered in time, it will affect the operation of BEPCII facility. Spare cavities began to be investigated since 2009. Now three cavities are developed and two of them have been vertical tested at Jan and July 2011, respectively. This paper will briefly present the manufacturing, post-processing and vertical test performance of the cavity.

INTRODUCTION

All parts of a BEPC Ⅱ 500MHz spare cavity, including two half cells, large beam pipe, small beam pipe, the support of the coupler are formed by spinning technique and welded together by electron beam welding (EBW). A schematic layout of the cavity is shown in Fig. 1.

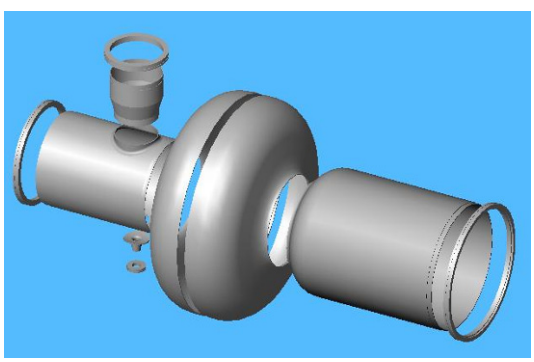


Fig. 1: Layout of the BEPC Ⅱ cavity.

Surface processing is very important for a superconducting cavity. After a certain post-procession procedure, the cavities reveal good properties during vertical test.

FABRICATION TECHNIQUES

Spinning is a simple force-forming technique which is widely used on metal bodies with rotational symmetry structure [1].

Many parameters will affect the final shape of the workpiece, mainly including the fillet radius of the roller, the headstock rotation speed, the roller feed speed, the gap between the die and the roller, even the lubricate method. Choosing a set of right parameters is essential to achieve best spinning quality.

High purity niobium (Nb) has good properties for spinning [2], but there's no experience on Nb spinning for domestic industry before. The cold hardening of this material puzzled us a lot before finding a set of optimized annealing parameters.

Table 1: The mechanical parameter

Annealing status	Tensile strength R_m（MPa)	Yield strength $R_{0.2}$(MPa)	Elongtation (%)
Original no spinning	167.2	88.7	57.3
no annealing	206.2	159.6	40.2
750°C	198.2	151.4	43.7
800°C	196.4	138.7	41.4
850°C	199.6	117.3	45.5
900°C	180.1	93.6	48.7

OPTICAL INSPECTION OF SRF CAVITIES AT FERMILAB

E. Toropov*, D. A. Sergatskov#, FNAL, Batavia, IL 60510, U.S.A.

Abstract

The production of a SRF cavity includes a string of multiple treatments at different facilities before the cavity can be RF-tested in a cryogenic system. Many of the processing steps change the cavity surface and affect the RF performance of the cavity. Interjection of optical inspections between these steps provides us with an instant feedback on the processes involved as well as gives us new insight on the mechanisms responsible for forming surface abnormalities. The major drawback of inclusion of frequent optical inspections is the increased amount of time and labour in the cavity production cycle. An optical inspection of equatorial and iris welds of a 1.3GHz TESLA-shape cavity produces about two thousand pictures. We developed an automated procedure where a computer takes over the most of the routine operations including adjusting the camera focus. With that automation, the inspection currently takes about three hours and little operator time. We will describe the developed system including the focusing algorithm and discuss ways to further optimize the procedure.

INTRODUCTION

The technology of manufacturing SRF is steadily improving. However, cavities often do not achieve the performance goals due to the quality of the inner surface. An optical inspection system developed by Kyoto University collaboration allows us to obtain high-resolution images of inner surface of SRF cavities [1].

The system was originally designed to closely inspect a certain area of interest on the surface. In order to make a full inspection of a cavity, an operator must perform operations of switching between cells, changing rotation angle, and adjusting the focus. Special software was designed to take over these operations.

The main problem of developing an automated system is creating a mechanism that would keep the surface in focus. This includes three independent components: an algorithm for performing autofocusing, a method to apply it efficiently, and a way to check/correct mistakes of autofocus.

Optical inspection has to deal with problems such as long inspection time, low image quality, and necessity for calibrations. Inspection time depends on the mechanical design of the system, the camera speed, and the camera field of view. The indicator of image quality is image resolution. It is determined by two factors – the camera and the optics resolution. Finally, differences in outer diameters of equators and tuning of cavity length make it necessary to employ calibration prior to inspection.

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MECHANICAL SETUP

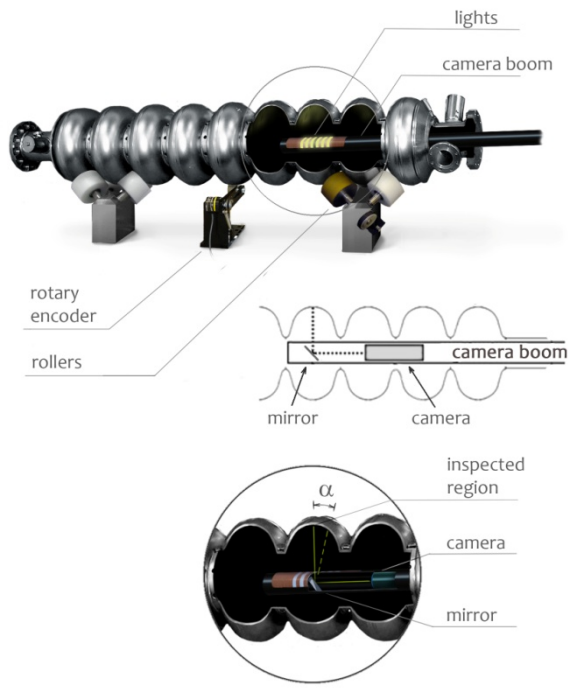


Figure 1: Optical inspection stand.

Fermilab has two optical inspection systems, which are referred to as the production and R&D systems. The production system is used to inspect bare 1.3 GHz cavities while R&D system was designed to inspect dressed and 650 MHz cavities.

The optical inspection system is used to study the inner surface of a SRF cavity with an optical camera. A system consists of a base, a camera boom – a plastic tube with a camera inside, four motors, a rotary encoder, and a computer. The boom can move along a cavity (see Fig.1.)

The first motor moves a cavity along the stand, thus changing the inspected cell. The second motor changes the angle of rotation – this is accomplished by either rotating a cavity (production system) or by rotating the camera boom (R&D system).

Fig.1 depicts the inner design of the boom. The camera has a constant focal length but it can focus on the surface by moving along the boom by the third motor. The mirror tilt is changed by the fourth motor. The lights installed on the boom are controlled by separate control electronics.

INSPECTION SEQUENCE

A typical optical inspection of a 9-cell cavity includes inspecting all the equators and irises welds and heat-affected zones. At first, equators are inspected, after that – irises.

CAVITY SURFACE TOPOGRAPHY FROM OPTICAL INSPECTION

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Abstract

Characteristics of the cavity surface geometry such as roughness affect cavity performance. The optical cavity inspection system at Fermilab allows us to obtain pictures of cavity surface at different lightning conditions. By analyzing the images of some fixed location inside a cavity taken while the light source moves progressively along the axis we can deduce some topographical information of that surface. In the large-grain cavities after BCP, grains are oriented at distinct angles to the surface and, therefore, reflect light in different directions. We developed a simple algorithm to calculate the angle distribution of the grains and thus to estimate the roughness. We discuss this method and the results of the analysis of the actual cavity surface.

INTRODUCTION

Rough niobium surface can cause field emission during cavity testing. Several studies were conducted on niobium coupons to explore surface geometry and to learn how different cavity treatments (EP, BCP) change the geometry. [1], [2], [3]. However, it is not possible to explore surface inside a cavity.

Angles between grains in large-grain cavity surface give some information about geometry at large scales. An optical inspection system, such as described in [4] can be used to study these angles if they are distinguishable on optical inspection images. The system allows us to illuminate the surface from different angles and we can see that different grains reflect more light at certain angles. This information leads us to calculating angles between grains and to consequently make an estimate of surface roughness.

The method can be a quick supplement to optical inspection procedure. However, it can be used only on large-grain cavities, new or after BCP. The limitations are discussed at the end of the paper.

SURFACE MODEL

We use a simple model for cavity surface. We assume that the surface is made up from grains oriented at different angles to the surface plane. The grains are considered flat. You can see the 1D model of such a surface in Fig. 1. The surface roughness is determined by angles between grains and grain sizes. No special assumptions about angle and grain size distribution are made at this point.



Figure 1: Surface model.

EXPERIMENTAL SETUP

The new TB9ACC015 cavity was installed onto the inspection system and moved to an equator region. The mirror tilt was adjusted so that the inspected area was aligned with the camera focus plane. We used a camera with 20 um resolution. That put a limit on the size of grains that could be distinguished and analyzed. In our case this minimum grain size is ~100 um.

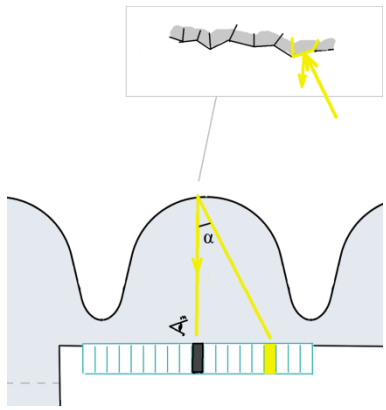


Figure 2: Experimental setup.

The system has 20 LED lights located at both sides of the camera aperture. We sequentially turned each of them on and off. The angle α ranged from -40 to 40 degrees (see Fig. 2.) Accordingly, angles of grains relative to the surface plane range approximately from -20 to 20 degrees. You can see grains at different angles in Fig. 3.

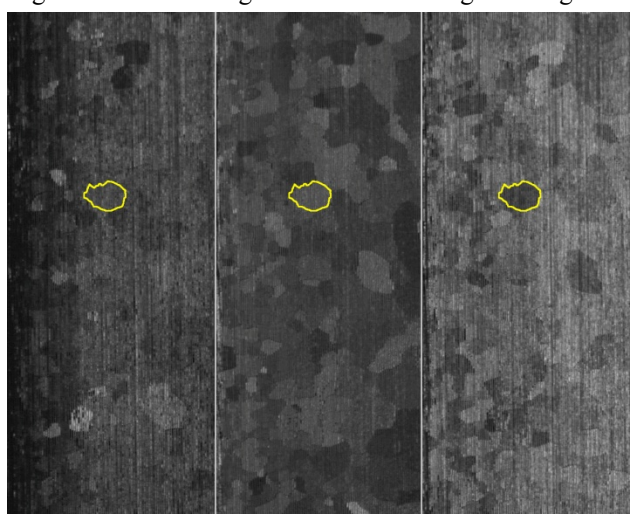


Figure 3: Snapshots for three different LEDs turned on. Grains have a peak in reflection at some angle (one grain is highlighted.) Vertical stripes are mechanical polishing artefacts.

HORIZONTAL SRF CAVITY TESTING AT FERMILAB*

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Abstract

Fermilab makes use of a single-cavity test cryostat to assess the performance of dressed superconducting RF cavities using pulsed high-power RF before they are assembled into a cryomodule. Cavity performance is evaluated in terms of accelerating gradient, unloaded quality factor, and field emission. The functionality of auxiliary components such as tuners and fundamental power couplers is also verified. The latest results from extensive testing of nine-cell 1.3 GHz cavities are presented here, along with a discussion of future extensions of the horizontal test program to include 650 MHz cavities and continuous wave testing.

INTRODUCTION

Fermilab is engaged in a research and development program to construct high gradient accelerator cryomodules based on superconducting radiofrequency (RF) cavity technology for the International Linear Collider (ILC) and Fermilab's Project X. In order to qualify a cavity for assembly into a cryomodule, it is first tested standalone at Fermilab's Horizontal Test Stand (HTS) [1]. At HTS cavities are tested in a configuration similar to operational conditions in a cryomodule; the cavities are welded inside helium vessels and outfitted with high power input couplers, higher-order mode (HOM) couplers, magnetic shielding, and a mechanical tuning system. These dressed cavity packages are then cooled to 2 K in a test cryostat and are operated strongly overcoupled to a klystron-based 300 kW pulsed RF system.

The HTS was first used to test the 3.9 GHz cavities installed in the ACC39 cryomodule now in operation at DESY [2]. This paper presents results from the testing of nine-cell 1.3 GHz TESLA-style cavities at HTS. The two most important cavity performance metrics are the maximum accelerating gradient E_{acc} and the unloaded quality factor Q_0. The ILC requirements for these quantities are $E_{acc} \geq 35$ MV/m and $Q_0 \geq 0.8 \times 10^{10}$. Of additional interest is the amount of X-rays produced due to field emission as this can have an impact on cryomodule operation.

TEST PROCEDURE

The cavity testing steps are quite similar to those described in [2]. Prior to cooling down the cavity the input coupler is conditioned in a standing wave mode by running off-resonance RF pulses at 2 Hz, up to a ≈300 kW pulse with a length of 1.3 ms. After cooling down to 2 K the cavity's blade tuner is employed to tune the cavity resonance to 1.3 GHz and the Q_{ext} of the input coupler is adjusted to 3 x 10^6 (the position of the input coupler's center conductor is adjustable via an external knob), close to the optimal Q_{ext} value for the ILC. A low power (≈5 kW) RF pulse is used to excite the cavity and the gradient is determined from

$$E_{acc} = 2\sqrt{(R/Q)P_f Q_L}\left(1 - e^{-\frac{\omega t_p}{2Q_L}}\right)/L$$

where L is the active length of the cavity, P_f is the cavity forward power, Q_L is the loaded quality factor (effectively equal to the Q_{ext} of the input coupler), ω is 2π times the cavity frequency, t_p is the pulse length, and R/Q is 1036 Ω for TESLA cavities. As a cross-check, the gradient is also determined from $E_{acc} = \sqrt{(R/Q)P_r Q_{ext}}/L$, where P_r is the power reflected back from the cavity immediately after the RF has been shut off and Q_{ext} refers to the input coupler. These two calculations of the cavity gradient typically agree to within a few percent of each other. The gradient determined at low power is used to evaluate the constant k_t in the relation $E_{acc} = k_t\sqrt{P_t}$, where P_t is the cavity transmitted power. This relation is then used to determine the gradient from the transmitted power for all input powers.

The cavity/coupler system is then conditioned on-resonance at 2 Hz up to a gradient of 25 MV/m and a pulse length of 1.3 ms. When conditioning with pulse lengths longer than 0.5 ms, the cavity is filled at full power for 0.5 ms and then the power is reduced by an approximate factor of four in order to maintain a constant gradient for the remainder of the pulse (the "flat-top" time).

To assess the cavity's gradient and Q_0 performance, ILC-like RF pulse parameters are adopted. Using a 5 Hz repetition rate, the cavity is filled to a given gradient and then a 1 ms flat-top is maintained. In order to reliably achieve high gradients with the limited klystron power available, a 0.8 ms fill time is used. The forward power to the cavity is slowly increased until either the cavity quenches or 35 MV/m is achieved. Figure 1 shows an example of a cavity operating at this gradient.

Since the input coupler $Q_{ext} \ll Q_0$, the cavity Q_0 can only be determined from the heat dissipated by the cavity walls to the helium bath. In particular,

$$Q_0 = \frac{\langle E_{acc}^2 \rangle L^2}{(R/Q)\langle P_c \rangle}$$

where P_c is the dissipated heat and the brackets denote a time average. The time average of the square of the gradient can be shown to be

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BUFFERED CHEMICAL POLISHING DEVELOPMENT FOR THE BETA=0.53 HALF-WAVE RESONATOR AT MICHIGAN STATE UNIVERSITY*

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Abstract

The beta=v/c=0.53 half wave resonator (HWR) is being developed for the Facility for Rare Isotope Beams (FRIB). One prototype resonator has been built completely at MSU and four other resonators have been built by industry. The proposed surface treatment is buffered chemical polishing (BCP) and high pressure rinsing with ultra pure water. The BCP process is being optimized to achieve resonator performance goals during certification testing. Research is focused on the improvement of the damaged layer removal (uniformity), the heat exchanger design, and the quality of BCP acid solution. Several etches have been completed on the HWRs. Process data such as: removal rate, temperature profiles, and niobium concentration in solution have been collected. The process data was studied versus the vertical test results; maximum accelerating voltage, quality factor and field emission onset voltage. The chemistry fixture development and process data versus test results will be presented.

INTRODUCTION

The FRIB project requires a total of 341 certified SRF cavities. This includes 144 of the beta=0.53 HWR type. After final fabrication, the internal surface of the cavity is chemically etched to remove a damaged layer of 100-150 microns. The cavity is then degreased, heat treated at 600 °C for 10 hours for hydrogen degassing. After heat treatment the cavity receives a light etch and high pressure rinse and then is assembled for vertical testing.

The finished cavity with helium vessel weighs 230 pounds (104 kg) and has an internal surface area of about 1.11 m^2. The internal volume is 13 gallons (49L). A standard 1:1:2 BCP recipe of 1 part HF (49%), 1 part nitric acid (79%), and 1 part phosphoric acid (85%) is used. The acid temperature is cooled to and maintained at 13-17 °C, by flowing the acid through a storage tank with a submersed Teflon loop heat exchanger with 10 °C chilled water flowing. The acid flow rate is 8-10 gpm (30-38 lpm) and is continuously filtered in the recirculating loop. Cavities without helium vessels are cooled by wrapping with ice packs, and cavities with helium vessels are cooled with cold water flow through helium space

CHEMICAL PROCESS DEVELOPMENT

Before the cavity is processed, a predicted etch rate is determined by way of an etch rate sample test. Eight 2 mm thick niobium samples are etched for 25 minutes. Weight and thickness measurements are taken before and after etching.

First BCP Set-Up

The cavity is oriented horizontally as shown in Figure 1. The RF ports at the top and bottom. The acid is pumped up through the bottom RF port and exits at the top RF port. The beamports and cleaning ports are sealed with Teflon flanges. A niobium in-situ sample is mounted on one of the beam port blanks.



Figure 1: Orientation of HWR for first BCP etching set-up.

In addition to the etch rate sample test, thickness measurements have been performed on various locations of four HWRs before and after etching. The thickness measurement was performed using an ultra sonic thickness measurement (USTM) device and was used to determine the material removal at a given point. The average of these etch rates resulted in an average for the entire cavity. This etch rate was compared to the predicted etch rate (PER) found by the sample test.

Information from both the predicted etch rate and the thickness measurements is used to estimate an etch time required for the desired average material removal. We found that the removal measured by USTM was 30% of the removal estimated from the predicted etch rate.

The material removed (measured by USTM) at different locations on the cavity indicated the etching was non-uniform. The removal along the beam port quadrants (sides) of the cavity was much higher than desired removal. The removal at the top and bottom (acid in/out) RF ports was much lower than desired. The removal near the inner conductor center was also much higher than desired removal. Very little removal was seen at the top and bottom quadrants.

* This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

CERN SRF ASSEMBLING AND TEST FACILITIES

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Abstract

CERN is currently upgrading and refurbishing its RF and cryogenic facilities in the SM18 assembly hall with the aim of testing SRF cavities and cryo-modules of various provenience. They concern new and spare cavities for the HIE-Isolde upgrade, SPL study and LHC collider. These projects require a redistribution of space, refurbishment of cleanrooms, modification of SRF test stands, of vertical cryostats and of all cryogenic lines. This article presents the specifications of the refurbished facility and the technical choices required for the assembling, processing and testing of superconducting RF cavities.

INTRODUCTION

CERN concentrates on the SM18 building final test operations of accelerator components. From the training of the LHC spare magnets to the assembling and test of the RF cavities, the SM18 building is thus divided in three parts, each of them attributed to the main discipline of super conducting accelerator technology: magnets, RF cavities and cryogenics. Within the RF activities, such as LHC, HIE Isolde and SPL cavities, some improvement and refurbishment of the facilities has been decided. This paper will present the actual facilities dedicated to RF cavities within the SM18 building, from the assembly to the test of the cavities and cryomodules, the upgrades currently in progress and the refurbishment plans.

SRF ACTIVITY OVERVIEW

Four SRF projects are currently running within the RF area in SM18 (Figure 1). Three new LHC spare cavities (400.8 MHz) need to be manufactured, tested and assembled to the one already detained in the purpose of giving to CERN a second spare cryomodule. Moreover, all the facilities remain ready in case of problems with the LHC accelerator cavities.

The HIE Isolde project comprises 32 quarter wave cavities (101.28 MHz) with a nominal gradient of 6 MV/m each, which need to be built and tested, resulting an assembly and tests of 6 cryomodules [1].

The SPL study requires the manufacturing of 4 cavities (5-cell cavities running at 704.4 MHz). These cavities will then be assembled into one short cryomodule. Due to the high gradient of these cavities, 25 MV/m, some improvement of the facilities, especially the cleanroom, need to be done to guarantee the cleanliness of the cavities.

Finally, the quadrupole resonator activity is dedicated to material surface studies (bulk niobium, niobium deposition on copper plate ...). This resonator operates at three frequencies: 400, 800 and 1200 MHz [2].

RF ACTIVITY OVERVIEW

In addition to SRF activities, two normal conducting RF projects use the SM18 facilities: the CLIC Test Facility 3 (CTF3) for which the assembly of their cavities is done in a cleanroom environment, and the LINAC4 project for the RF test inside the SM18 bunker.

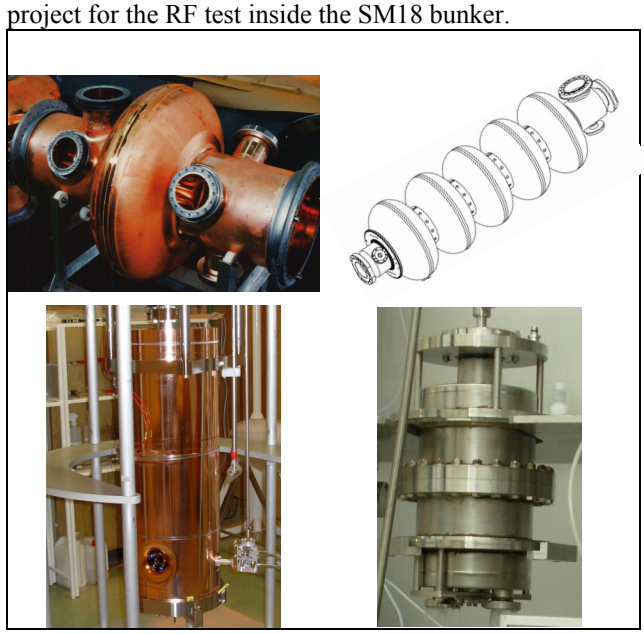


Figure 1: LHC cavity (top left), SPL cavity (top right), HIE Isolde cavity (bottom left), and quadrupole resonator (bottom right).

CLEANROOM FACILITY

Current Facility

The main cleanroom originally designed for the LEP cavity assembly, is composed of three parts, each 15 m long by 4 m large (Figure 2):

- A loading bay allows the positioning of the cryomodule and cavities on the rail system.
- A first class ISO 7 cleanroom (class 10'000), for the cleaning and preparation of the different elements and for the assembling of the CTF3 cavities.
- An assembling room, class ISO 4 (class 10), where cavity assembly into a cryomodule ant the mounting of the power coupler is done (LHC cryomodule).
- Entrance to the assembling room via an air shower.

Next to the main cleanroom, a "baldaquin" (softwall cleanroom), class ISO 5 (class 100), is used for the conditioning of elements that should enter into the main cleanroom, and for the assembly of the HIE Isolde cavity on its test stand.

SRF CAVITY PROCESSING AND CLEANROOM FACILITY UPGRADES AT MICHIGAN STATE UNIVERSITY*

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Abstract

The Michigan State University (MSU) SRF cavity processing and coldmass assembly infrastructure is being upgraded to meet the production needs of multiple SRF projects, including the driver linac for the Facility for Rare Isotope Beams and the MSU Reaccelerator. The objective is to modify the current infrastructure to increase throughput and optimize the process workflow, while minimizing impact to the overall preproduction schedule. Facility upgrades include a cleanroom addition, chemistry room with part etching hood, cleanroom preparation area, and a new ultra pure water system. New handling fixtures and specialized tools are being implemented. Methods are being developed to streamline the workflow, increase repeatability, enhance process safety and reduce cross contamination and waste. The proposed cleanroom layout, process requirements, optimized workflow strategies, and plans for continuous improvement are presented.

INTRODUCTION

The FRIB baseline design requires a total of 341 certified cavities for cryomodule installation [1]. Thirty additional cavities will be fabricated for spare modules. It is assumed 20% of the cavities will be reprocessed resulting in 480 cavity processes. The estimated number of processes is summarized in Table 1.

Table 1: Cavity Quantities for FRIB

Description	Proposed Baseline
Certified cavities required	341
Certified cavities for spare modules	26
Non-performing cavities	10%
Total fabricated cavities for production	400
Reprocess fraction	20%
Number of processes	480
Total number of cold masses	55

The FRIB baseline cavity processing and coldmass schedule encompasses six months start-up and 30 months production. The average process rate is 16 cavities per month over 30 months. An estimate of 20% scheduled downtime and process delay results in 24 months of available process time. To complete 480 cavity processes, the infrastructure will be optimized to achieve a peak throughput of about 21 processes per month. A certification efficiency of 80% yields up to 17 cavities per month installed to a coldmass string. The takt time (eq. 1) for the cavity process workflow is the work time available divided by the number of cavities.

$$Takt\ Time = \frac{132.8\,\frac{hrs}{month} \times 30\ months}{480\ Processes} \cong 1\ \frac{day}{process} \quad (1)$$

PRODUCTION PROCESSING

The upgrade to the processing facility assumes the baseline SRF cavity processing plan (Table 2).

Table 2: Baseline SRF Cavity Processing Plan

Process Step	
Degrease cavity	*Vendor*
Bulk buffered chemical polish (BCP)	*Vendor*
Pure water rinse	*Vendor*
Hydrogen degas	*MSU & JLab*
Degrease cavity & components	MSU
Light BCP (10-30 microns)	MSU
High pressure rinse (HPR) with UPW	MSU
Assemble to test insert (*RF certification*)	MSU
Purge & remove from insert	MSU
Install to cold mass string	MSU

Baseline processing procedures may be modified from results of preproduction cavity testing research (i.e. post certification HPR and low temperature bake-out). The SRF cavity process and test facility will be designed to certify up to one cavity per day. Preproduction cavity processing is planned to begin in middle of 2012, with full production beginning late 2013.

PROCESSING FACILITY UPGRADES

Cleanroom Facilities

The current SRF clean room facility will not accommodate production processing and assembly due to the size of the FRIB coldmasses (up to 20 feet long) and the amount and the volume of work that requires a

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DEWAR TESTING OF BETA = 0.085 QUARTER WAVE RESONATORS AT MSU*

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Abstract

Michigan State University is developing quarter wave resonators (QWRs) for a superconducting linac to reaccelerate exotic ions to 3 MeV per nucleon or higher (ReA3). Eight QWRs with an optimum velocity of $\beta = v/c = 0.085$ and a resonant frequency of 80.5 MHz are required for the third cryomodule, which will complete the first stage of the reaccelerator linac. Approximately 100 additional $\beta = 0.085$ QWRs of similar design will be required for the Facility for Rare Isotope Beams (FRIB). This paper covers Dewar testing of the QWRs, performance issues observed in the tests, and design improvements to mitigate these issues.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) is building a reaccelerator for exotic ion beams [1]. At present, stable ions are produced and accelerated in the NSCL coupled cyclotron facility; in the future, stable beams will be provided by the FRIB superconducting driver linac [2]. In both cases, the primary beam produces a secondary beam of exotic ions by particle fragmentation.

The reaccelerator will consist of a gas stopper to slow down the secondary ion beam, a charge breeder to increase the charge of the ions by removing electrons, a multi-harmonic buncher and radio frequency quadrupole for initial acceleration and focussing, and a superconducting linac to accelerate the beam to a final energy of 3 MeV per nucleon. Two additional cryomodules can be added to increase the energy to 12 MeV per nucleon (ReA12).

The superconducting linac consists of niobium QWRs optimised for $\beta = v/c = 0.041$ [3] and $\beta = 0.085$ [4]. The cavities are housed in rectangular box cryomodules. The first two cryomodules, containing a total of seven QWRs optimised for $\beta = 0.041$, have been installed and thoroughly tested [5]. This paper covers the prototyping work on the $\beta = 0.085$ QWRs which will be used in the third cryomodule for ReA3.

CAVITY DESIGN GOALS

Though the ReA3 and FRIB cavities will share a similar electromagnetic design, the FRIB cavities are required to provide a higher accelerating voltage than the ReA3 cavities. In addition to QWRs, FRIB requires 322 MHz half-wave resonators operating at 2 K. While the ReA3 cavities will operate at 4.5 K, the FRIB QWRs will operate at 2 K, which will increase the safety margin for their accelerating voltage without increasing the overall plant power requirements. With 2 K operation, the intrinsic quality factor (Q_0) for the QWRs will be approximately four times higher than the ReA3 (and previous FRIB) goal for 4.5 K, and frequency detuning due to pressure fluctuations and helium boiling will be reduced. The cavity figures of merit and operating requirements are shown in Table 1.

Table 1: Cavity figures of merit and operating parameters; R_a is the shunt impedance (linac definition), V_{acc} is the accelerating voltage, and E_{peak} and B_{peak} are the peak surface electric and magnetic fields at the specified operating gradient, respectively. The accelerating field (E_{acc}) is defined via the effective length: $E_{acc} = V_{acc}/L_{eff}$.

Parameter	ReA3	FRIB
RF frequency	80.5 MHz	
β_{opt}	0.085	
$L_{eff} = \beta_{opt}\lambda$	317 mm	
R_a/Q_0	408 Ω	
E_{peak}/E_{acc}	6.16	
B_{peak}/E_{acc}	13.9 mT/(MV/m)	
V_{acc}	1.03 MV	1.62 MV
E_{acc}	3.24 MV/m	5.11 MV/m
E_{peak}	20 MV/m	31.5 MV/m
B_{peak}	45 mT	71 mT
Operating temperature	4.5 K	2.0 K
Q_0	5×10^8	2×10^9

DESIGN EVOLUTION

The ReA3 QWR design is based on earlier prototyping efforts for the Rare Isotope Accelerator (RIA). The first 80.5 MHz $\beta = 0.085$ QWR [6] was designed for lower voltage, but Dewar and test cryomodule results showed that higher voltages could be achieved [7]. The design evolution is illustrated in Figure 1, where the third-generation design (Figure 1c) is being finalized. All of the designs include a frictional damper for the center conductor [8], although it is not shown in Figure 1c.

The first-generation design (Figure 1a) has a titanium helium vessel which is welded to niobium-titanium transitions on the cavity using tungsten inert gas (TIG) welding. The weld transitions serve multiple purposes.

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PREPARATION AND TESTING OF THE SRF CAVITIES FOR THE CEBAF 12 GeV UPGRADE*

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Abstract

Eighty new 7-cell, low-loss cell shaped cavities are required for the CEBAF 12 GeV Upgrade project. In addition to ten pre-production units fabricated at JLab, the full set of commercially produced cavities have been delivered. An efficient processing routine, which includes a controlled 30 micron electropolish, has been established to transform these cavities into qualified 8-cavity strings. This work began in 2010 and will run through the end of 2011. The realized cavity performance consistently exceeds project requirements and also the maximum useful gradient in CEBAF: 25 MV/m. We will describe the cavity processing and preparation protocols and summarize test results obtained to date.

INTRODUCTION

At Thomas Jefferson National Accelerator Facility (JLab), the accelerator portion of the Continuous Electron Beam Accelerator Facility (CEBAF) upgrade will be constructed within the framework of the existing CEBAF accelerator. Ten new higher-voltage cryomodules, five per Linac, will be added. Each cryomodule will consist of eight higher performing 7-cell cavities. The 12 GeV cavities have been supplied by Research Instruments (RI). In addition to fabrication, RI completes the bulk chemistry, removing 160 microns, and tunes the cavities to 1497 MHz with greater than 90% field flatness. A 12 GeV C100 cavity is depicted in Figure 1.



Figure 1: A 12 GeV C100 low-loss shape 7-cell cavity.

GROUNDWORK

Several months prior to receiving the first shipment of 12 GeV C100 cavities, a program was established to define and practice the C100 cavity production process and RF test protocols on 7-cell low-loss shaped cavities. Pansophy based data travelers were used to capture all important process data and information [1]. Some production process steps were well established, others, such as electropolishing were not well defined. Over the course, close to 70 process and test procedures and data travelers were created and put into practice. All the documents were uploaded and made accessible through Pansophy. The proposed 12 GeV C100 cavity production process and qualification procedures were exercised full loop on 7-cell cavities for several process cycles.

Pre-Production Cavities

The process and test protocols were further validated and refined using the 7-cell pre-production cavities fabricated at JLab. The pre-production cavities, known as R100, were used to further refine the EP process, characterize the frequency shifts caused by handling and helium vessel welding, and to reduce the number of cold RF test required to qualify the cavities. The R100 and the 12 GeV C100 cavities do not have stiffening rings, which makes the cavities more vulnerable to incidental RF detuning. RF data was collected before and after each process step to characterize the amount of frequency shift due to deformation resulting from processing and handling. Fixtures and tooling were fabricated and procedures modified to minimize the handling and processing induced deformation. Additionally, a detailed characterization was conducted on the effects helium vessel welding had on cavity frequency. A robust welding procedure was developed and changes were made to the warm frequency target to offset the changes induced by helium vessel welding.

The R100 cavities were also used to understand how the presence of a helium vessel would affect qualification data collected during the vertical RF test. The eight R100 cavities were first RF tested without a helium vessel, then again with the helium vessel. The results of the comparison varied cavity to cavity. On average, the maximum gradient achieved and the Q_o at maximum gradient showed no change within the error bars of the measurements. The same process of RF testing before and after the helium vessels were added was repeated on the first eight C100 cavities. The results were similar with the exception of cavity C100-6 which had a maximum gradient of 41.6 MV/m without the helium vessel and 30.4 MV/m with the vessel. The lower gradient is due to the 3-inch diameter helium vessel outlet port reducing the maximum heat that could be rejected from the cavity due to its inherent critical heat flux

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VERTICAL ELECTRO-POLISHING AT CEA SACLAY: COMMISSIONING OF A NEW SET-UP AND MODELING OF THE PROCESS APPLIED TO DIFFERENT CAVITIES

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Abstract

Reproducible operation at high performances of sc cavities is required for superconducting linacs, at least in their high energy section in the case of accelerators for proton beams. High beta elliptical cavities are thus of concern, and, to achieve required performances for such cavities, surface preparation including electro-polishing (EP) is recommended.

Moreover, for large dimension cavities we consider the EP treatment in vertical configuration (abbreviated as VEP) to be more appropriate. For this reasons, a VEP set-up has been designed at Saclay for the electro-polishing of muticells elliptical cavities.

Chosen equipment will make it possible to use a wide range of parameters (voltage, flowrate, temperature, nitrogen inerting) with R&D purpose in mind. Optimization will be done using modeling with COMSOL software for different cavities. As examples, we present some results for the 704 MHz high-beta SPL cavity and the 1300 MHz ILC cavity and show the influence of cathode shape on both acid flow and electric field distribution during the process. At last, importance of the size of the cavity will be commented.

INTRODUCTION

Electro-polishing (abbreviated as EP) is believed to be the most desirable treatment for SRF cavities [1]. EP is an anodic electrochemical treatment carried out in concentrated hydrofluoric - sulphuric (HF-H_2SO_4) acids. Generally, the cavity is electro-polished following a process developed by KEK [1]: A voltage is applied between the cavity and a cylindrical aluminium cathode (set in its centre) while it is placed in horizontal position, rotating, and half-filled with the circulating acid. This process makes it possible to reach high gradients on 9cell Tesla shape cavities and has been chosen for the surface treatment of cavities for the XFEL linac. However, it induces some drawbacks: the rotating seals are more easily prone to leaks, the cavity must be switched full of acid for draining and the footprint of the set-up is rather large. Furthermore, the removal rate in the cavity depends on the location of the cell [2]. To overcome these drawbacks, some laboratories are investigating an alternate process where the cavity is electro-polished in vertical position [3]. Cornell University has proved that VEP with static acid could make it possible to reach high gradients [4], and as VEP is suitable to the treatment of large elliptical cavities, we have developed at CEA-Saclay a VEP set-up sized for surface treatment of the largest high beta and high gradient cavity we have designed, that is to say a 704 MHz cavity for the Superconducting Proton Linac. All other "smaller" cavities, as ILC cavities, fit into the set-up too.

In this paper, this VEP set-up is described as well as results concerning the modeling of VEP for both high beta SPL [5] and ILC cavities. The acid flow and electrical field distribution expected during VEP will be discussed.

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CHARACTERISTICS OF THE SET-UP

Generalities

This set-up is designed to electro-polish a cavity in presence of circulating acid electrolyte. The expected flowrate range is between 5L/min and 40L/min. A constant voltage EP process has been chosen for the treatment of the cavities. The available electric power for the electro-polishing is 30kW (20V – 1500A). The set-up is divided into two distinct ventilated cabinets: The acid storage area and the main treatment cabinet (Figure 1). Insertion of the cathode into the cavity and assembly of connecting pieces are done on a dedicated table close to the set up. The cavity is then transferred in the main cabinet with a specific handling tool.

The acid storage tank is located in a pit connected to the liquid exhaust storage area of the laboratory. The storage capacity is 300L. This capacity has been calculated in order to maintain a niobium concentration in the electrolyte below 10g/L after a bulk EP for SPL cavities.

The cavity is filled up from the bottom by a membrane pump located in the pit. Once the acid reaches the connection tube on the top of the cavity, the acid flows to

ECONOMICAL MANUFACTURE OF SEAMLESS HIGH-PURITY NIOBIUM

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ABSTRACT

Ultramet continues to develop a methodology to fabricate high-performance (RRR>200) seamless niobium superconducting radio frequency (SRF) cavity cells using advanced chemical vapor deposition (CVD) methods. Optimization has resulted in the consistent rapid deposition of RRR>200 niobium at structural thicknesses suitable for accelerator applications. In addition, CVD niobium joining/welding capabilities have been demonstrated as a potential alternative to electron beam welding, and preliminary mechanical and microstructural characterization of the joined area has been performed.

INTRODUCTION

Ultramet manufactures advanced materials by CVD using a broad variety of refractory metals and ceramics for high temperature and/or extreme environment applications. Founded in 1970, Ultramet specializes in the research, development, prototype fabrication, and low- to medium-volume production of advanced materials to meet the needs of government, commercial, and academic customers.

The technical objective of the current ongoing research is to develop an efficient, cost-effective means of fabricating seamless ultrahigh-purity niobium SRF cavities and components suitable for particle accelerator applications.

The work to date, performed under two Small Business Innovation Research (SBIR) Phase I projects for the U.S. Department of Energy (DOE), has demonstrated the suitability of CVD for minimizing current SRF cavity fabrication challenges and the ability to fabricate freestanding CVD niobium cavity structures and to CVD-weld niobium components together. Ultramet's CVD niobium processing has also been optimized to consistently deposit structural high-purity niobium with purity ratings greater than RRR200 [1,2].

NIOBIUM SRF CAVITY FABRICATION BY CVD

The following inherent characteristics of CVD are unique to the process.

- Deposition is not line-of-sight, so uniform coating and seamless forming of freestanding structures on complex-shaped mandrels (e.g. low-beta cavities) is possible. Figure 1 shows a CVD niobium cavity prototype fabricated by Ultramet.
- Low-cost, medium-purity niobium chloride precursor material can be used because CVD is also a metal-refining process; reactions are induced with the metal of interest, which is then transferred to the mandrel for deposition while unwanted elements/impurities in the starting material are left behind. Non-heat-treated niobium has been successfully deposited with RRR values of 213–282.
- Decontamination heat treatments are minimized or potentially eliminated.
- Seamless cavity processing eliminates or substantially reduces the need for expensive electron beam welding.
- High reproducibility and economical near-net-shape fabrication are promoted.
- CVD is a practical and economical approach to fabricate complex and custom one-of-a-kind research cavities and test components, because simple removable mandrel techniques are employed and no fabrication molds are required.
- The need for and/or extent of electropolishing/etching is minimized, so target cavity profile designs are preserved during manufacture. CVD coatings reflect/reproduce/mimic the mandrel surface roughness, and conventional outer diameter mandrel polishing can be used to economically produce inner diameter cavity surfaces with low surface roughness.
- CVD grows inherently large, stress-free grains on a net-shaped mandrel surface. In contrast, mechanical deforming processes create a highly stressed inner cavity niobium surface layer that must be chemically removed during etching, further compromising the final cavity profile and maximum performance potential.
- Flanging features to accommodate joining and CVD welding of components can be fabricated *in situ*, thereby substantially reducing the need for electron beam welding.
- High niobium deposition rate (up to 0.012"/hr) makes formation of large, complex structural components practical.

Niobium CVD Process Optimization

Niobium CVD process optimization has included variations in reactor design, niobium source material, and process conditions (e.g. gas ratio, flow rate, temperature).

RRR Characterization

Multiple CVD niobium deposition runs were performed to fabricate specimens suitable for characterization at Oak Ridge National Laboratory (ORNL, Oak Ridge, TN). The characterization effort focused on determining the residual resistivity ratio (RRR) of the niobium materials deposited (without using a heat treatment purification step), along with that of niobium fabricated by conventional powder processing. The results are presented in Table 1 and show that four of the CVD materials exhibited RRR values ≥213 and one material had a RRR value of 282.

RECENT RESULTS FROM SECOND SOUND, T-MAPPING AND OPTICAL INSPECTION OF 1.3 GHz CAVITIES AT DESY*

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Abstract

DESY is preparing for the delivery of 800 superconducting 9-cell cavities (Fig. 1) for the European XFEL [1]. The review of earlier data and the analysis of data obtained recently helped to define the rules for preparation of cavities and give guidance for the quality assessment of the expected cavity delivery. The experience gained from temperature mapping, the second sound technique [2] and optical inspection [3] will be compared and an overview of the results obtained so far will be given in this report.

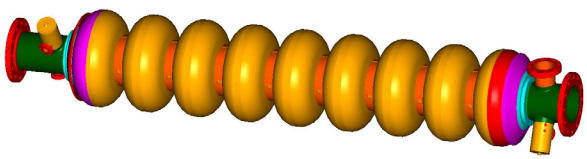


Figure 1: 3D model of a 9-cell 1.3 GHz European XFEL design cavity.

RECENT CAVITY TEST RESULTS

Since the last SRF Workshop 66 cavity tests have been carried out at DESY. Most of these tests have been done with cavities from the 6th and 8th production series. Cavities from production series 7 (3 hydroformed cavities) and 9 (4 cavities in XFEL-design, test of a new fabrication process) have not been included in this report. There were also a few tests with cavities of earlier series, but the status of these cavities including the surface treatment was unclear.

This results in a total number of 48 tests, 30 from the fine grain production series 6, and 18 of the large grain production series 8.

The results are shown in Fig. 2, which shows the maximum field obtained for the various batches. The topmost figures indicate the performance of the two production series whereas the latter three diagrams categorise the maximum field according to cavity treatment. The 6th production shows a broad field gradient distribution between 16 and 38 MV/m. The tests with the low gradients showed strong radiation indicating field emission. For the large grain cavities of the 8th production, there is a series of tests in the range from 20 to 30 MV/m. These are the tests with BCP surface including two EP tests. For the higher gradients, these are EP surfaces only [4].

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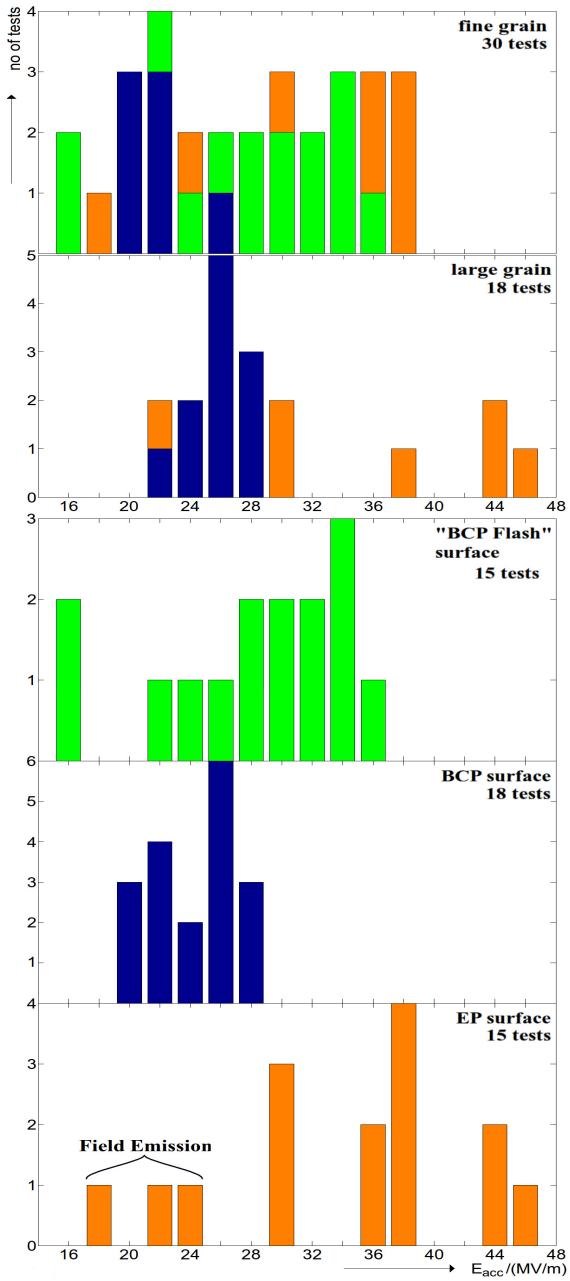


Figure 2: Gradient performance of cavities tested by material and surface treatment – the colors indicate the surface treatment.

Including some more tests from the 6th production, the tests with cavities having a BCP surface achieve up to 28 MV/m. For the EP surfaces there have been gradients achieved up to 46 MV/m and only three tests show gradients below 30 MV/m due to strong field emission. High gradients are thus best achieved with EP treated

ELECTROPOLISHING OF NIOBIUM TO OBTAIN DEFECT FREE SURFACES*

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Abstract

Viscous film formation on an electropolished surface is critical to obtain a good surface finish. Evidence for the formation of this film on niobium was found in electrochemical experiment results and optical observations. The film plays a critical role in the electropolishing mechanism as it was found that the surface is pitted where a stable viscous film cannot be formed. The depth of the surface material removed is also critical to the degree of surface finish obtained. Roughness and profile evolution over polishing time was used to characterize the degree of finish.

INTRODUCTION

Superconducting Radio Frequency (SRF) cavities need to have a good surface finish to achieve a maximum electric field gradient. The set goal for the elliptical shaped TESLA SRF cavities is 35 MVm^{-1}. However, the gradient practically achieved is around 30 MVm^{-1} [1]. The surface condition of the niobium cavities is one major reason preventing the achievement of the target accelerating gradient.

Electropolishing (EP) is so far the most efficient technique to get a good surface finish and is now a standard step in cavity processing sequence. It is very superior to mechanical polishing. Niobium is electropolished by applying a positive potential with respect to a pure aluminium counter electrode in a polishing mixture containing 1 volume hydrofluoric acid (48%) and 9 volume sulfuric acid (96%). The reactions taking place at the electrode are [2]:

At working electrode:

$$2Nb + 5SO_4^{2-} + 5H_2O \rightarrow Nb_2O_5 + 10H^+ + 5SO_4^{2-} + 10e^-$$

$$Nb_2O_5 + HF \rightarrow H_2NbOF_5 + HNbF_6 + NbF_5 + 3\,H_2O$$

At counter electrode:

$$2\,H^+ + 2e^- \rightarrow H_2$$

Niobium gets oxidized to form niobium pentoxide which is then dissolved in the presence of hydrofluoric acid and sulphuric acid to form niobium fluoride and oxofluoride species.

The mechanism of electropolishing is related to current distribution on the surface of the sample. EP of a metal is usually carried out in the plateau region of the polarization curve [3] (Fig. 1). This plateau is obtained because of mass transport limitation. Tian et al. suggested the formation of a compact film of probably niobium oxide on the surface of the niobium. The authors also suggested that the limiting current density region on the polarization curve in the case of niobium is probably due to diffusion of fluoride ions through the compact film [4]. This film is however water soluble and difficult to analyze by ex-situ techniques. A bluish green layer (Fig. 2) is seen to flow slowly down a vertical electrode at the end of electropolishing when the current is switched off. It has not been possible to analyze this film because of this limitation.

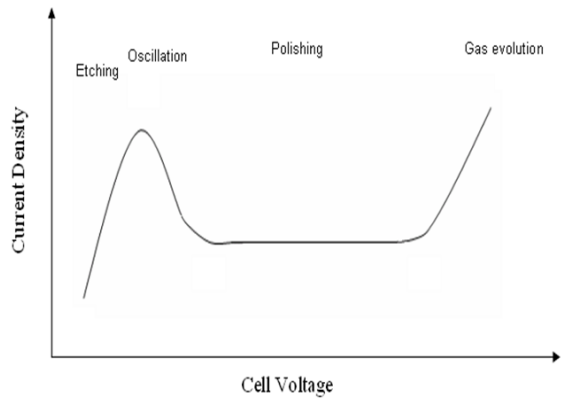


Fig. 1: A typical polarization curve for electropolishing.

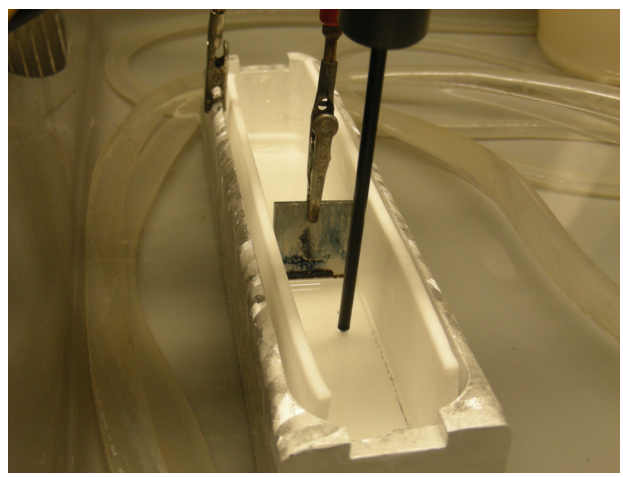


Fig. 2: Bluish green viscous film seen on the surface while electropolishing.

The EP process for processing SRF cavities, however, does not result in defect free surfaces. Pitting is commonly found near the heat affected zone of the electron beam welded region [5]. Pits can be due to a

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QUANTITATIVE EP STUDIES AND RESULTS FOR SRF PRODUCTION*

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Abstract

Cavities and their performance quality are major cost drivers in SRF-based projects. EP is a superior chemical treatment, and now is replacing BCP for producing high gradient SRF cavities. To achieve high performance and reliability, which is essential for Nb SRF cavities production, it is important for us to understand Nb EP in detail so that we can tailor it to the best effect. The analytical tools of electrochemistry and surface topography are the means of developing such understanding. The recent incorporation of analytic electrochemical techniques into the development of well controlled protocols for Nb electroplishing will be reported, such as using three electrode method for polarization curve measurements, electrochemical impedance spectroscopy (EIS) to understand the mechanism of EP, and rotating disk electrode (RDE) to study the diffusion coefficient of active species of F ions, and the related diffusion layers etc. Implications of present basic understanding of Nb electropolishing will be introduced. In parallel, investigations for monitoring scale-dependent Nb surface morphology evolution under cavity production condition will be demonstrated, which is expected to lead to design best EP parameters. Directions for the future are aimed at well control, high reproducibility, efficient, EP process for coming SRF-based projects.

INTRODUCTION

The unique characteristics of Nb SRF cavities have allowed them becoming the building blocks for e charged particle accelerators. A smooth and clean interior surface finishing is paramount to the proper function of SRF accelerator cavities, given that only topmost 40~50 nm layer is directly involved with the rf field [1]. Active acid etching and polishing is required, as is cleaning. EP is an anodic dissolution process. It is characterized by the elimination of micro-roughness (leveling) and the absence of crystallographic and grain boundary attack (brightening) and results in the production of smooth, bright surfaces [2-3], and now is replacing BCP for producing high gradient SRF cavities.

The EP process typically applied to Nb cavities was inherited from Siemens in the 1970's [4], and it has been developed through decade's cavity production practices empirically. Typically, a mixture of hydrofluoric (48~49%) and sulfuric acid (96~98 %) by volume ratio of 1:9 or 1:10 which depends on the weight concentration of hydrofluoric acid and sulfuric acid, is used as the electrolyte.

Typically, EP process used to be conducted at 30°C, and sometimes even at higher temperature during the process practice because the solution itself behaving as a coolant and only the supply and exit flow temperature were monitored not cavity's wall temperature. Recent studies suggest the polishing at lower temperature may present a better surface finishing [5, 6]. For Nb cavity production, applied voltage across the cavity and cathode is 14~15V controlled by power supply and the optimal EP has been done in the continuous current oscillation mode, but the mechanism of current oscillation is still not clearly indentified [7]. For a typical shape of SRF cavity, such as ILC and CEBAF, the internal surface area ratio of the niobium cavity (anode) to the high purity aluminum tube (cathode) is about 10: 1.

To achieve high performance and reliability, which is essential for Nb SRF cavities production, especially for the International Linear Collider (ILC) which requires 16,000 nine cell cavities intended to perform at 31.5 MV/m historic high accelerating gradient. Therefore, it is important for us to understand the kinetics of surface smoothing of Nb EP in detail so that we can tailor it to the best effect. The analytical tools of electrochemistry and surface topography are the means of developing such understanding. Recent and ongoing research is yielding new insights that enable a process refinement, and perhaps significant future evolution for improved cost and reliability.

BASIC UNDERSTANDING ABOUT NB ELECTROPOLISHING

Understanding Potentials in Nb Electro-polishing

During Nb cavity EP process, the applied voltage is the function of anode (Nb) and cathode (Al) potentials, the voltage drops in the electrolyte and voltage drops in the connects and conductors[8]. The cavity process practice uses the power supply only to provide the applied potential, which corresponds to the potential drop between the Nb cavity and the coaxial Al rod cathode. By using a standard reference electrode, such as a saturated Hg/Hg_2SO_4 or Ag/AgCl, the individual potentials could be measured with respect to the reference electrode. We learned that under typical Nb electropolishing conditions, the majority of the applied voltage drops at the surface of the anode (niobium). The cathode exhibits well-behaved polarization behavior, and it accounts for a significant fraction of the applied potential mainly due to the hydrolysis reaction. The potential drop across the electrolyte is purely resistive. These values are strongly

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CENTRIFUGAL BARREL POLISHING OF CAVITIES WORLDWIDE

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Abstract

Much interest was generated in the mid to late 1990s in an alternative cavity surface processing technique called centrifugal barrel polishing, that mechanically polishes the inside of superconducting RF (SRF) cavities by rotating them at high speeds while filled with abrasive media. This work, which was originally done at the KEK High Energy Accelerator Research Organization (KEK) by Kenji Saito & Tamawo Higuchi, has received renewed interest recently because of work done at the Fermi National Accelerator Lab (Fermilab) which has produced mirror like finishes on the 1.3 GHz Tesla-type cavity SRF surface. In addition to Fermilab & KEK, the Cornell University SRF Group (Cornell), the Thomas Jefferson National Accelerator Facility (JLab) and the Raja Ramanna Centre for Advanced Technology (RRCAT) are all exploring CBP as a cavity processing technique. CBP is interesting as a cavity processing technique because it removes defects associated with the manufacturing process, it can yield surface finishes (Ra) on the order of 10s of nanometers, it is a simple technology that could transfer easily to industry, it could help increase cavity yields and it requires less acid than other techniques. Recent progress and the current status of CBP as a baseline and repair technique will be discussed.

INTRODUCTION

After niobium superconducting radio frequency (SRF) cavities are made there is a 80-120 micron damage layer on the inside of the cavities which must be removed [1]. This material has typically been removed in the past by buffered chemical polishing (BCP) or electropolishing (EP), if higher accelerating gradients are required [2,3]. Much interest was generated in the mid to late 1990s in an alternative cavity surface processing technique called centrifugal barrel polishing (CBP), that mechanically polishes the inside of SRF cavities by rotating them at high speeds while filled with abrasive media[4-6]. Part of the original motivating factor of this work was to remove the hazards associated with the toxic hydrofluoric acid used in electropolishing (EP) and buffered chemical polishing [2,3].

In addition to the early work in CBP, some work was done at Cornell on the tumbling of re-entrant cavities to repair them [7,8].

There has been renewed interest in CBP recently because of new results coming out of Fermilab [9,10]. New media types and a new basic approach were used in the CBP process that allowed for mirror like finishes with average surface roughness (RA) values in the order of 10 nm [10]. This is better than any other processing technique for polycrystalline cavities, including EP which can yield RA values in the order of 100 nm [11].

The current state of and possible future work on CBP programs at Fermilab, KEK, Cornell JLab and RRCAT will be discussed.

CENTRIFUGAL BARREL POLISHING PROCESS

CBP is an alternative processing technique that polishes the inside of superconducting rf cavities by rotating the cavities at high speeds while filled with an abrasive media. A schematic is shown in Figure 1 below.

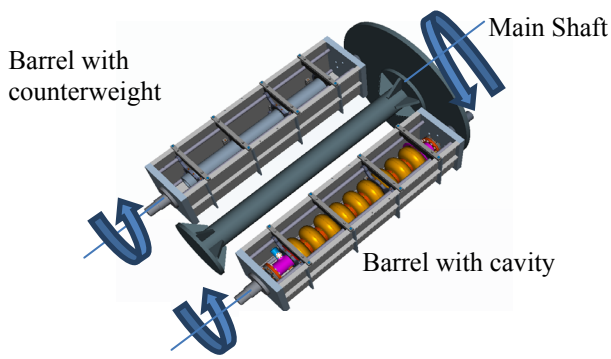


Figure 1: Schematic of main shaft and 2 barrels of a centrifugal barrel polishing machine denoting the directions of rotation. This is a model of the Fermilab machine with a 9-cell Tesla – type cavity and counterweight shown in the barrels.

In the CBP process the cavity is filled approximately 50% by volume with a mixture of different media. The media is typically used with water and a surfactant to cool the cavity and remove material from the surface to allow for further polishing.

In the CBP process two or 4 barrels spin around a central shaft. Each barrel spins around its own axis at the

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A NEW ELECTROPOLISHING SYSTEM FOR LOW-β SC CAVITIES*

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Abstract

A new electropolishing system designed for a completed low-beta niobium superconducting cavity with integral helium vessel was installed and operated at Argonne National Laboratory (ANL). The design was based on that used for the electropolishing of 1.3 GHz 9-cell elliptical cavities for the global ILC development effort at ANL, with the addition of direct water cooling to the cavity surface. This design also allows for repeated chemistry on the cavity, if needed, without producing the rougher surface associated with buffered chemical polishing.

INTRODUCTION

An upgrade at the Argonne Tandem Linac Accelerator System (ATLAS) uses a new cryomodule of seven superconducting (SC) 72.75 MHz quarter-wave resonators (QWR) to increase the intensities for both stable and exotic beams [1,2]. These seven new QWR's will provide an accelerating voltage of 2.5 MV per cavity, for a total of 17.5 MV. The electropolishing (EP) of each QWR is performed on a complete, fully jacketed cavity, and includes direct water cooling through the helium jacket to control the cavity temperature during the procedure. This differs from the previous generation of QWR's installed for the ATLAS Energy Upgrade where EP was performed as two subassemblies, followed by a final electron beam weld of the cavity, installation of the helium jacket, and a light buffered chemical polish (BCP) [3]. Using this method of EP, chemistry is decreased to two man-days per cavity, with EP being the final step before high pressure rinse (HPR) and clean assembly.

NEW EP SYSTEM FOR LOW-β SC CAVITIES

A new low-β EP tool for superconducting cavities was designed and built in the Physics Division of ANL. This tool was built to EP the QWR's required for the ATLAS Intensity Upgrade. The single most important technical improvement for these new cavities is that the EP is performed after all cavity fabrication is completed. This new EP tool is located in the chemistry room next door to the existing elliptical cell EP tool at ANL. The low-β EP tool closely resembles the elliptical cell EP tool currently in use at ANL (see Figure 1), and was designed and built over 8 months for ~$95k and with 4 man-months of effort.

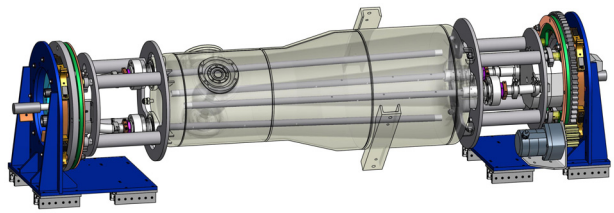


Figure 1: 3-D model of new low-β EP tool.

Design Goals

In order to maximize the accelerating gradient per cavity for the ATLAS Intensity Upgrade, many design changes were put into place for cavity EP. Some of the major design goals for the new EP tool were:

- ability to EP a complete, fully jacketed cavity
- two electrical slip ring assemblies to allow rotation of both anode and cathodes during EP
- direct water cooling through cavity liquid helium (LHe) jacket (while the cavity is rotating)
- enough cathodes to provide adequate polishing
- cathode loading system to ensure correct cathode alignment inside the cavity rf space
- ability to circulate acid during EP
- nitrogen gas purge to evacuate hydrogen gas

The end result was a new horizontal EP system (see Figure 2) modeled after the ANL elliptical cell EP tool with the addition of direct water cooling to the cavity surface through the helium jacket. Four cathodes are used to flow both the acid as well as the N_2 to evacuate the H_2, and also includes an integrated cathode loading system. The time required to load and unload the cavity into the EP tool is ~1 hour.

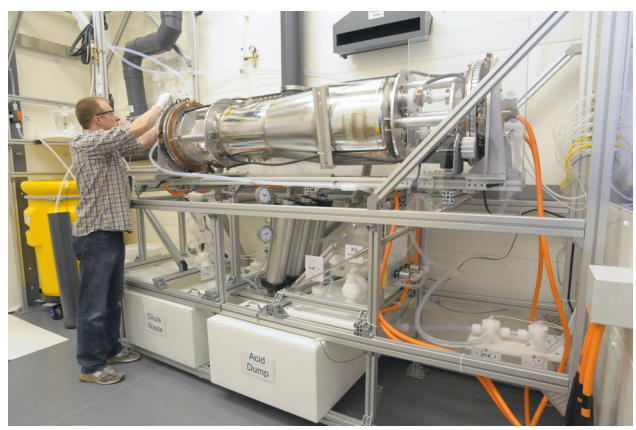


Figure 2: Prototype QWR installed in the new EP tool.

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REVIEW OF RF-SAMPLE TEST EQUIPMENT AND RESULTS *

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Abstract

A calorimetric technique enables precise measurements of the surface resistance R_S of superconducting samples. One of the devices exploiting this technique at multiple frequencies is the Quadrupole Resonator. Its measurement capabilities and limitations are discussed and compared with similar devices. Results on bulk niobium and niobium film on copper samples are presented. It is shown how different contributions to the surface resistance depend on temperature, applied RF magnetic field and frequency. Furthermore measurements of the maximum RF magnetic field as a function of temperature and frequency in pulsed and CW operation are presented.

INTRODUCTION

The surface resistance R_S of superconducting cavities can be obtained by measuring the unloaded quality factor Q_0,

$$R_S = \frac{G}{Q_0}, \quad (1)$$

where G is the geometry factor of the cavity, dependent only on the cavity shape and not on its size or material. G can therefore be accurately obtained by a numerical simulation. R_S may vary strongly over the cavity surface and the value obtained is an average over the whole surface [1].

A more convenient way consists of investigating small samples. They can be manufactured and duplicated at low cost. RF cavities excited in the TE_{011} mode with a sample attached as the cover plate are often used for material characterization. The TE_{011} mode is chosen, due to its convenient field configuration, i.e. no magnetic field and therefore no RF currents across the joint, where the demountable end plate sample is attached to the cavity and a vanishing electrical field over the whole cavity surface, helping to avoid multipacting, see Figure 1.

There are two techniques to derive the surface resistance of the attached sample. The first one is the end-plate replacement technique. It requires a reference sample of known surface resistance R_S. After the quality factor of the cavity with the reference sample attached has been measured the reference sample can be exchanged by another sample of unknown surface resistance. From the change in Q-value the surface resistance of the sample can be derived. For systems relying on the end-plate replacement technique sample, cavity and bath temperature are always identical. Therefore for these systems cavity design aims for a high magnetic field level on the sample compared to the cavity. An overview of different cavity geometries can be found in [2].

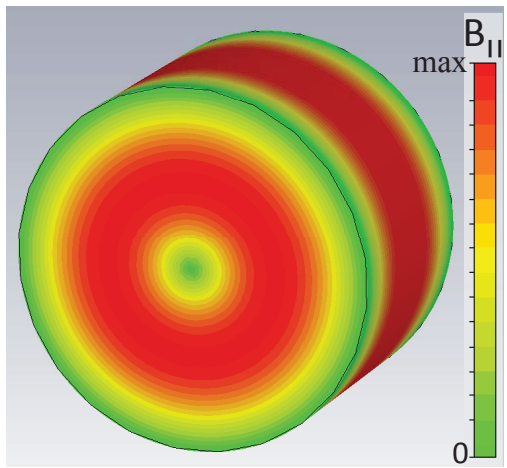


Figure 1: False color plot of the surface magnetic field $B_{\parallel}$ in a cylindrical pillbox cavity excited in the TE_{011} mode.

In a calorimetric system the sample and host cavity temperature are controlled independently. A DC heater (resistor) and at least one temperature sensor are attached to the backside of the sample, allowing to control its temperature.

Currently there are three calorimetric systems for the RF characterization of superconducting samples in use.

- A cylindrical TE_{011}/TE_{012} cavity enabling measurements at 4 and 5.6 GHz has been developed in collaboration between CEA Saclay and IPN Orsay [3, 4]. Recently a modified version has been constructed and commissioned [5].
- At Jefferson Laboratory (JLAB) a sapphire loaded TE_{011} cavity for measurements at 7.5 GHz has been recently commissioned [6].
- The Quadrupole Resonator at CERN is the only system running at frequencies of interest concerning accelerator applications. It has been used since more than ten years [7, 8, 9] and has been recently refurbished for measurements at 400, 800 and 1200 MHz [2].

The calorimetric technique applied by these three systems is explained in the following section. Afterwards a

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X-RAY TOMOGRAPHY INSPECTION OF SRF CAVITIES*

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Abstract

Performance issues with superconducting cavities and a desire for an enhanced non-invasive view of the interior of a cavity compared to that provided by optical means has led us to inspection using 3-dimensional X-ray tomography. This technique has provided the necessary view of suspected faults in Higher Order Mode couplers. This success naturally leads to determining if x-ray inspection of welds and other potential cavity defects might prove to be helpful during cavity fabrication. Results of x-ray scans from commercial vendors and potential for this technique will be presented.

INTRODUCTION

It can be difficult to determine the root cause of poorly performing SRF cavities owing to the difficulty in performing non-invasive visual inspections. Welds, in particular, and hard to reach areas such as Higher Order Mode couplers are nearly impossible to inspect without slicing or cutting open these areas. Such was the case of two poorly performing 3.9 GHz cavities at Fermilab. After a series of successful ones, repeated tests indicated multipacting of the 'Formteils', the 2-post antennae which couple the higher order mode power out of a cavity, but it was impossible to conclusively inspect these pieces for possible failure. Only by means of 3-D X-ray computed tomography (CT) was it possible to positively identify fractured 'Formteils' as the root cause.

Additional internal issues, namely questionable welds and pits/imperfections, have been targeted as other candidates for this technique.

3-D COMPUTED TOMOGRAPHY OVERVIEW

Fundamentally, 3-D Tomography requires a large number of two-dimensional images about a given axis followed by the application of mathematical techniques to create three-dimensional images.

As seen in figure 1, the X-ray tube (open or sealed) produces a conic beam of electrons that penetrates the object to be analyzed, and a digital signal is interpreted by the two-dimensional (2D) detector as a Digital Radiograph image.

The object is positioned on a precision rotational stage and an image is acquired during the rotation at a constant step. The step is usually 0.25 degree to 1 degree (1440 to 360 images). The scan usually covers a rotation of 360 degrees, but for specific applications a limited angle scan can be performed.

*Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy. #Harms@fnal.gov

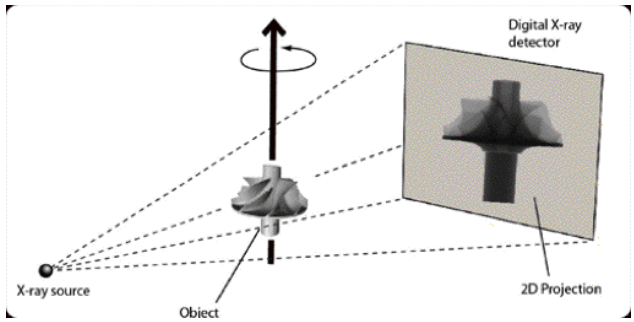


Figure 1: Overview of 2-dimensional imaging technique. Courtesy of *North Star Imaging, Inc.*

From a series of 2D Radiographs and after calibration, the CT reconstruction software provides 3D volume results using a 'Filtered Back-Projection' algorithm (Feldkamp). 3D CT data are rendered as 'voxels' (volume element) with three-dimensional resolution from a few micrometers (microCT) to hundreds of micrometers depending on the X-ray detector pixel size as shown in figure 2 [1].

What we have found particularly useful in this imaging process is the resulting 2-D slice views which are produced simultaneously in the x, y, and z planes from the series of original 2-D radiographs. Also key to quality imaging is uniform density of the object to be inspected.

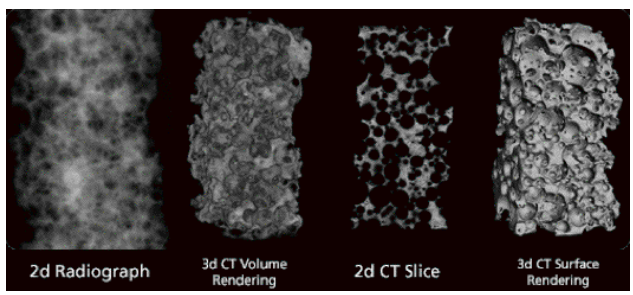


Figure 2: Steps taken in producing three-dimensional computed tomography images. Courtesy of *North Star Imaging, Inc.*

Typical parameters used for imaging cavities are:

- X-ray Energy = 225 kV
- Beam current = 350 μA
- Gun to Detector distance - 1 meter or less; gun closer to object
- Detector pixel size - 127 microns
- Resolution depends on factors above plus material (density) to be sampled
- Number of scans - variable, scans typically taken every ½ to 3 degrees over 360° of rotation
- Set-up + calibration + Scanning time - 4-6 hours
- Results available ~1hour after scans are completed.

EFFECT OF HEAT TREATMENT TEMPERATURE ON THE THERMAL CONDUCTIVITY OF LARGE GRAIN SUPERCONDCUTNG NIOBIUM*

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Abstract

The phonon peak in the thermal conductivity k_{pp} of high purity niobium is an unknown function of heat treatment temperature T_{h} and RRR, amongst other variables. The relationship between T_{h} and k_{pp} of large grain niobium is investigated using two sets of four specimens each. The specimens of Set 1 were randomly cut from four ingot discs with different RRR. These specimens were subjected to different heat treatments, ranging from 140 °C for 48 hours to 1100 °C for 4 hours. Specimens of Set 2 were cut from the same grain of an ingot disc, with the heat flow direction of each specimen along the same crystal orientation. Each of these specimens was subjected to one heat treatment, at a temperature ranging between 600 °C and 1200 °C, while maintaining a constant temperature for an interval of 2 hours for each specimen. Results from the specimens of Set 1 show that there is no change in k_{pp} after heating at 140 °C for 48 hours. Set 1 specimens also show that for a given heat treatment protocol, the maximum in k_{pp} shows a monotonic dependence on RRR. Results from the specimens of Set 2 suggest that the phonon conduction response to heat treatments for 2 hours shows no increase for $T_{\mathrm{h}} \lesssim 600$ °C and plateaus at $T_{\mathrm{h}} \gtrsim 1000$ °C.

INTRODUCTION

The thermal conductivity k of superconducting metals is a sum of its electron and phonon components. At temperatures cooler than the superconducting critical temperature of niobium (T_c = 9.25 K), the contribution from electrons decreases, due to their condensation into Cooper pairs. The purity of niobium strongly influences electron conduction, and can be correlated at 4.2 K to the residual resistivity ratio (RRR), where RRR is the ratio of the electrical resistivity at 295 K to that at 4.2 K. For $T \gtrsim 3$ K, phonon conduction is relatively minor due to electron-phonon scattering. For $T \lesssim 3$ K, electron-phonon scattering is diminished due to the fewer normally conducting electrons, and phonon conduction becomes the dominant mode of heat conduction. At about 2 K, a local maximum occurs in k, referred to as the phonon peak. Material processing influences the existence and magnitude of this phonon peak, largely through changes in the crystal structure and imperfection density. Heat treatments reduce imperfection density, and hence alter the crystal structure. There is a need for improved understanding of the relationship between thermal conductivity and heat treatment history in niobium to improve the performance of SRF cavities.

Previous studies [1, 2] on the effect of heat treatment temperature on the thermal conductivity at the phonon peak of large grain niobium involved specimens from several ingot discs, with varying RRR, tantalum content, and crystal orientation along the heat flow direction. To reduce the influence of these extraneous factors on the phonon conductivity response, a portion of this study uses single crystal niobium specimens cut from a single grain on an ingot disc with the same crystal orientation in the heat flow direction. Another portion of this study uses partial results from [1, 2] along with results from two new specimens to draw more conclusions.

METHODS

Four large grain niobium specimens (Set 1) were cut from four ingot discs with varying RRR, tantalum content, and crystal orientation along the heat flow direction. These specimens were subjected to different heat-treating protocols ranging from 140 °C for 48 hours to 1100 °C for 4 hours. Also, four single crystal niobium specimens (Set 2) were cut from one grain of an ingot niobium disc manufactured by CBMM, and the heat flow direction was aligned along the same crystal orientation. These specimens reduce the influence of extraneous factors (*e.g.,* RRR, crystal orientation, tantalum content) on the thermal conductivity response of ingot niobium to heat treatments. Each specimen was subjected to a unique heat treatment temperature T_h, while the duration of the constant T_h was maintained at 2 hours for each specimen. Thermal measurements were performed on all of these specimens before and after heat treatments. The thermal conductivity was estimated using temperature and heat flux measurements and a theoretically based model for thermal conductivity.

Experiments

A steady-state experimental system [3] was used to measure the temperature and heat flux on the eight specimens. Up to four specimens were placed in an evacuated chamber

* Work supported by U.S. Department of Energy, Office of High Energy Physics through Grant No. DE-S0004222
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GUIDED CAVITY REPAIR WITH LASER, E - BEAM AND GRINDING

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Abstract

Recent cavity processing statistics indicate that the development of RF superconductivity has reached a stage where more and more cavities were limited by quench and not by field emissions. The combination of high resolution optical inspection, cavity quench detection and surface replica revealed more than half of the cavity quenches were limited by identifiable surface features, namely pits or bumps. The quench field ranged from 12.7 MV/m up to 42 MV/m. Several methods have been explored in various laboratories to remove the surface features. Those included the laser re-melting, Electron beam re-melting and local mechanical grinding. This paper reports the latest development of those guided repair technologies and their benefits to improve cavity performances.

CONTRIBUTION NOT RECEIVED

CAVITY INSPECTION AND REPAIR TECHNIQUES

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Abstract

To develop cavity inspection and repair techniques is important for quality control of the superconducting rf cavity to get more better yield for high accelerating gradient. A high-resolution camera system was developed as a tool of optical inspection in 2008. It enables 2-D surface analysis on a defect of cavity inner surface by using striped illumination and image processing. For more detailed surface analysis, a replica technique was applied to cavity surface. By connecting defect information with quench location information, the cause of the performance limitation can be categorized by a geometrical defect or by issue of surface treatment and assembly work. By applying optical inspection at each step of the treatment, we can also obtain an information of defect appearance and development. The cavities that quenched at low field by one or few geometrical defects can be improved by removing a geometrical defect at quench location. A local grinding machine was developed for this purpose. This repair method was applied on the 9-cell cavities, and we succeeded to improve the cavity performance by the combination of local grinding and light electro-polish (EP). The method and results of the cavity inspection including the replica techniques and local grinding repair are presented in this paper.

INTRODUCTION

The inspection and repair techniques have been developed to understand the cause of performance limitation of the cavity in detail at labs around world for 1.3 GHz L-band 9-cell SC cavities [1][2][3][4][5]. Since the quality of the surface treatment and assembly work are greatly improved in these days, the cavity performance tends to be determined by the surface quality of the cavity. A major consensus is that quench limit at low gradient of 9-cell cavities is caused by highly localized defect at or near the EBW seam of equator, iris and cell-end. The size of there geometrical defects is around sub-mm (pit or bump). If there is a defect on near the equator, then quench occurs at low field by magnetic field enhancement or contamination in defect. In case of defect on iris or cell-end, the heavy field emission turns on at low field without recovery during test, once the quench happen at rather high field. These events were observed in some cavities which have a geometrical defect in them. Of cause, it depends on the size and shape of the defect whether these events occur or not. Nevertheless, the development of the geometrical defect removing method is important in order to raise the cavity performance yield better.

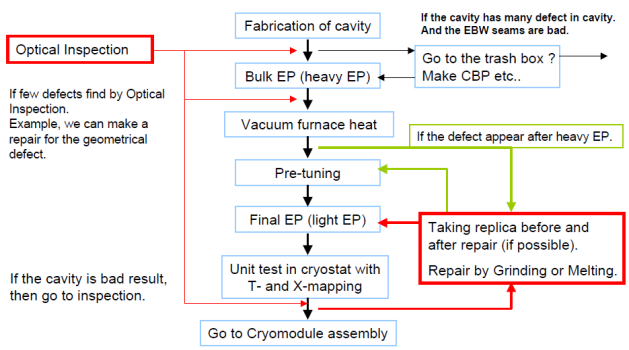


Figure 1: Repair process inclusion for the cavity treatment flow.

Figure 1 shows the example of inclusion of the defect repair process into the cavity treatment flow. We use the repair with combination of local grinding and light EP, in order to avoid the heavy EP, the vacuum furnace heating and the pre-tuning. The repair methods are under development at labs around the world. They are the local grinding, local re-melting by electron beam or laser and the tumbling. We can choose a method from them according to the type and the number of defects. It should be noted that the electro-polishing also change defect shapes.

TOOLS FOR INSPECTION AND REPAIR

Optical Inspection

Two types of CMOS cameras are used for optical inspection. For normal inspection, Toshiba Teli (CSF5M7C3L18NR. CMOS) camera is used, because this camera has quick response at maximum resolution (1400 x 1000, resolution is 10μm per pixel). Another camera is ARTCAM-900SS-OP (Artray co.). It can take higher-resolution image (3488 x 2618, resolution is 4μm per pixel), while, the response is slow due to the big amount of data to be transmitted though the limited speed of the computer interface. The 2D analysis can be made to measure the wall gradient of inner surface of the cavity by the special striped illumination and the image processing. The measurable wall gradient is ±20 deg at the equator [6].

Replica Method

In case of deeper or higher defect, the 2D profile can not be applied because of the limited measurable gradient range. The replica technique is a useful method to extend the range and to get 3D profile with high precision. The 3D information is important to calculate the magnetic field enhancement [7][8].

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IMPROVEMENT IN CAVITY FABRICATION TECHNOLOGY AND COST REDUCTION METHODS

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Abstract

Cavity fabrication method with new forming and laser welding technology are reported. 1.3 GHz 9-cell cavity with laser welding for stiffener and flange joint was achieved 29.5 MV/m at vertical test by KEK. 1.3 GHz 2-cell seamless dumbbell cavity is fabricated at MHI to verify the new fabrication method. These improvements are reported in detail. Some fabrication methods for cost reduction and stable quality are introduced.

INTRODUCTION

MHI has supplied 1.3 GHz superconducting RF cavity for STF project (STF is a project at KEK to build and operate a test linac with high-gradient superconducting cavities, as a prototype of the main linac systems for ILC.) and ERL project (Energy Recovery Linac) in several years [1][2]. To improve cavity performance, we have done several activities as shown Table 1 on STF cavity fabrication. Clean area was not used in cavity assembling at phase 1.0, but air top gun in clean area are used in cavity assembling at phase 2.0. The EBW conditions were always improved.

In recent vertical test at KEK, some STF cavities reached Eacc= 31.5 MV/m which is specification of ILC as shown figure.1. MHI-#12 cavity reached also over 40 MV/m. All these cavities (as shown figure.2) are governing high pressure gas safety law in Japan.

Table 1: Activities for improvement of cavity performance

Phase	1.0	1.5		2.0
Cavity No.	#1-4	#5-6 #7-9	#10-11	#12-22
Thickness of thinning	2.5 mm	2.0 mm	>	>
Bead condition	Bumpy	Smoother	Flatter	More stable
Shape of groove	Butt	>	Step	>
Frequency of *CP	Only after thinning	Each step (Just before EBW)	>	>
Management Of cleanness	Air duster	>	>	Air top gun
		Clean area	>	>

*CP: Chemical polishing

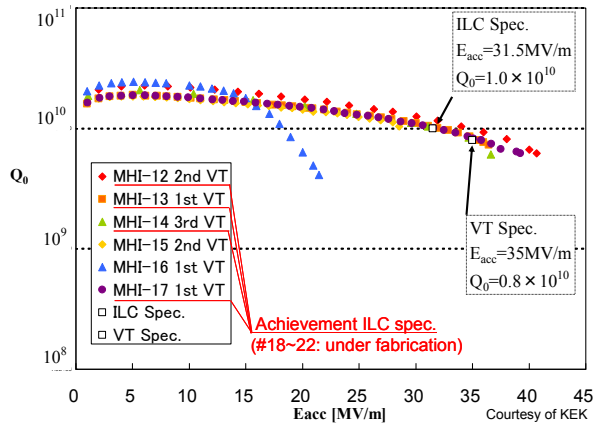


Figure 1: Q-E curve of recent vertical test for STF cavities.

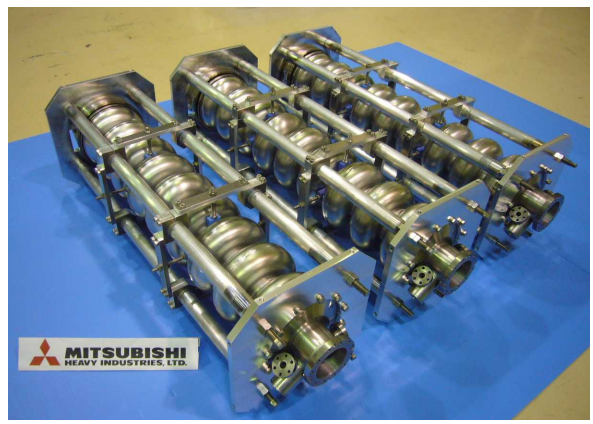


Figure 2: STF cavities governing high pressure gas safety law in Japan.

IMPROVEMENT FOR CAVITY FABRICATION METHOD

The principles for cost reduction in mass-production are reducing number of parts, automation or outsourcing, batch process and reducing process time (ex. Change of fabrication procedure, using special jig and machine or optimization of machine time and layout).

Since STF project was started, MHI has proposed some new fabricating methods based on these principles as shown below [3][4][5][6]. Some of them were applied to production or R&D cavities. Some of them are proposal for cost reduction. Improvements in R&D cavities for cost reduction are shown in detail.

XFEL CAVITY PROCUREMENT AS AN EXAMPLE OF TECHNOLOGY TRANSFER

W. Singer [DESY, Hamburg, Germany]

Abstract

Procurement of superconducting RF cavities for the European XFEL consists of two phases. The preparation phase for the European XFEL cavity production includes: qualification of high purity niobium vendors and potential cavity producers; accommodation of the TESLA cavity design to the XFEL demands; establishing the XFEL treatment process, work out and check the strategy of preparation for the vertical acceptance test; define the documentation and prompt data transfer, qualification of created infrastructure, cavity acceptance criteria and tests. A detailed specification has been worked out on the basis of ca. 50 prototype cavities. Production of 600 cavities is currently contracted on the principle "build to print"; the cavity material will be provided by DESY. DESY will supply vendors with machine for cavity tuning at room temperature and equipment for RF measurement of dumb bells and end groups. The cavity with helium tank has to be built as a component according Pressure Equipment Directive (PED) 97/23/EC. The contracted "notified body" will supervise the material qualification and procurement. Monitoring of the vendor's work will be executed by DESY and INFN (Milano) team.

CONTRIBUTION NOT RECEIVED

LARGE GRAIN CAVITIES: FABRICATION, RF RESULTS AND OPTICAL INSPECTION

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Abstract

SRF cavities produced from large grain niobium material have been investigated as an alternative to the standard fine grain material in the past years. While many single cell cavities have been prepared and successfully tested, the number of large grain (LG) 9-cell cavities available at the laboratories worldwide is still small. The worldwide experience and results with fabrication, treatment and testing will be compared.

At DESY, a batch of eight LG 9-cell cavities has been processed and tested recently, in addition to three cavities that had been processed and tested earlier.

The surface preparation process has been closely followed by optical inspection in-between all treatment steps that include surface removal. Several of the vertical RF tests have been done with T-mapping and/or second sound measurements for determination of the quench location.

The results after a first treatment cycle with buffered chemical polishing (BCP) and a second treatment cycle with electropolishing (EP) will be presented.

INTRODUCTION

Cavities from LG material in combination with BCP treatment promise good performance in a cost-effective production and treatment cycle. Direct cutting of discs from LG ingots is cheaper than the fabrication of sheets of fine-grain material including steps like forging, annealing and rolling. Because of the initially smoother surface within the grains, overall smoother surfaces can be reached with BCP without the need for the more expensive EP treatment.

The lower residual resistance of the material results in higher values for Q0 and therefore reduced cryogenic losses. That is especially needed in the prospect of CW operation of accelerators at medium gradient or operation at high gradient of pulsed machines.

RESULTS

KEK

Three 9-cell ICHIRO-shape cavities (I9#9, I9#10 and I9#11) from LG material have been built at KEK [1]. I9#9 and I9#10 are bare cavities without end-groups, I9#11 has been produced with full end-groups. I9#9 was tested two times already, I9#10 and I9#11 are under preparation [2].

Initial surface removal of I9#9 was done by Centrifugal Barrel Polishing (CBP) and vertical BCP. The average material removal was found to be 96 ± 28 µm at the equators with material removal in the centre cell twice as large as in the end cells due to the vertical BCP setup. The vertical test result was quench at 27 MV/m with Q_0=1.1E10. A horizontal BCP setup has been developed for more uniform material removal and I9#9 has been processed again. This time the material removal was 64 ± 13 µm with a more uniform distribution. The test result was the same as in the first test.

In order to improve the reliability and stability of the EBW seams, welding of all seams from the inside of the cavity has been established. All iris and equator welds of I9#10 and I9#11 have been done by inner EBW. The smoothness was improved and the number of visible defects on the equator seam after welding has been reduced by a factor of 5 from I9#9 to I9#10 [2].

IHEP

At IHEP two 9-cell LG cavities of low-loss shape [3] (IHEP-1 and IHEP-2) are under preparation [4]. IHEP-1 has been built from Ningxia material without higher order mode (HOM) couplers. The initial treatment was 190 µm CBP, 110 µm BCP, 3 h firing at 750°C and another 20 µm BCP. The first vertical test was done in July 2010 at the STF at KEK. The cavity was limited at 20 MV/m by quench with field emission. A second test at Jefferson Lab is under preparation.

IHEP-2 will be built with complete end groups; the electron beam welding is to be finished in November 2011.

PKU

At Peking University the cavity PKU2 (see Figure 1) was fabricated from Ningxia LG material in 2009 [5]. Processing and testing of the cavity has been done at Jefferson Lab [6]. In the first vertical test after 100 µm BCP, 10 hrs firing at 600 °C and additional 80 µm BCP the cavity was limited at 19.5 MV/m by quench. The second vertical test showed an improved performance, quenching at 22.4 MV/m after the Jefferson Lab standard ILC recipe including outgassing at 800 °C, 30 µm EP and baking at 120 °C. As reported in [7], there are a lot of pits visible next to the equator welding seam.



Figure 1: Picture of 9-cell LG cavity PKU2 [5].

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IHEP 1.3 GHz LOW-LOSS LARGE GRAIN 9-CELL CAVITY R&D*

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Abstract

The combination of the low-loss shape and large grain niobium material is expected to be the possible way to achieve higher gradient and lower cost for ILC 9-cell cavities, and will be essential for the ILC 1 TeV upgrade. As the key component of the "IHEP 1.3 GHz SRF Accelerating Unit Project", a low-loss shape 9-cell cavity using Ningxia large grain niobium (IHEP-01) was fabricated and surface treated (CBP, BCP, annealing, pre-tuning, HPR) at IHEP. The cavity reached 20 MV/m in the first vertical test at KEK STF on July 2010. Second vertical test on this cavity was done at JLAB recently after 2nd pass processing at IHEP. This paper reports the latest result of the vertical tests and surface diagnostics.

INTRODUCTION

The combination of the 1.3 GHz low-loss shape [1, 2] and large grain niobium material is expected to be the possible way to achieve higher gradient and lower cost for ILC 9-cell cavities, and will be essential for the ILC 1 TeV upgrade.

Large grain niobium has several benefits: low surface resistance and high thermal conductivity around 2 K, thus higher Q and potentially higher gradient of the cavity. For example, recently the electro-polished (EP) DESY large grain TELSA cavity AC155 achieved 45 MV/m at Q_0 = 1.3×10^{10}, which has the highest gradient and surface fields and the corresponding Q value ever measured in a multi-cell cavity [4]; material production cost reduction, especially by ingot slicing technique; high Q (> 2E10) in medium field level even by buffered chemical polishing (BCP), which is very promising for CW application for XFEL, ERL and ADS.

From the excellent single-cell results (50 MV/m with very small scattering) by K. Saito and F. Furuta of KEK, there is clear physical reason and enough data to support low-loss shape for higher gradient since 2005. In 2010, the KEK low-loss shape 9-cell cavity (fine grain, electro-polished) with end groups (ICHIRO#7) reached 40 MV/m at $Q_0 = 8\times10^9$ [3].

Thus, 50 MV/m or higher gradient demonstration of the low loss shape 9-cell cavity is foreseen in the next few years, especially using large grain material.

IHEP has started R&D on the 1.3 GHz large grain cavity since 2006. Three electro-polished ICHIRO single-cell cavities were fabricated and processed in KEK with Ningxia large grain niobium material provided by IHEP. The maximum gradient achieved was 48 MV/m at Q_0 = 1×10^{10} [5-7].

Then two low-loss shape single-cell cavities using Ningxia large grain niobium were fabricated and surface treated by IHEP and tested at KEK in early 2008. We made the CBP (centrifugal barrel polishing, tumbling) machine and applied for the single cell cavity in 2007. One of the CBP + BCP treated cavities (without EP) reached the high gradient of 40 MV/m at Q_0 = 1.6×10^{10} without Q-slope [8-10]. These results showed apparent advantages of large grain over fine grain material.

As the key R&D component of the "IHEP 1.3 GHz SRF Accelerating Unit and Horizontal Test Stand Project" [11-14], a low-loss shape 9-cell cavity without HOM couplers (IHEP-01, Figure 1) using Ningxia large grain niobium was fabricated and processed at IHEP. At the same time, The CBP machine, the BCP facility, the pre-tuning machine, the large ultrasonic cleaner, the high pressure water rinsing facility (HPR) and the high resolution cavity inner surface inspection system etc. for the 9-cell cavity were constructed, commissioned and successfully operated at IHEP [11-18].

The cavity reached 20 MV/m in the first vertical test at KEK STF on July 1st 2010. After the diagnostics and 2nd pass processing, the cavity was tested in JLAB. The fabrication procedure, surface treatment recipes and the test results are summarized in this paper.



Figure 1: IHEP-01 large grain 9-cell cavity.

CAVITY FABRICATION

The large grain niobium disks were provided by OTIC, Ningxia, China. The measured RRR value was 430. Ultrasonic and eddy current scanning were performed on some of the disks.

Due to the special properties of the large grain material, several mechanical and RF problems were found and successfully solved during the fabrication and EBW of half cells and dumbbells. Earrings and steps were found in the equator area. Large cracks and unsmoothness were found between adjacent grains in the iris area. Iris wall thickness was not uniform after trimming [15].

The dumbbell equators were reshaped and trimmed to have the right length and frequency [15]. We inspected

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TEST RESULTS OF THE INTERNATIONAL S1-GLOBAL CRYOMODULE

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Abstract

The S1-Global experiment is a collaborative project [1, 2] by INFN, DESY, FNAL, SLAC and KEK as part of the Global Design Effort (GDE) for the ILC. Eight superconducting RF cavities (two from DESY, two from FNAL and four from KEK) were installed into a cryostat. Three different types of frequency tuning systems (Blade tuner from INFN/FNAL, Saclay tuner from DESY/CEA-Saclay and Slide-Jack tuner from KEK) and two types of input couplers (TTF-III from DESY and STF-II from KEK) were implemented. In 2010-2011, operational tests were performed three times in the 2K environment, and many aspects of high-power pulsed operation of the cavities and associated hardware elements were studied, including: high power, cavity performance, Lorentz force detuning (LDF) and its compensation by Piezo actuators, simultaneous operation of cavities, static and dynamic heating loss, an RF system based on the Distributed RF Scheme (DRFS) [3] with LLRF (Low Level RF) feedback system. In this talk, results of the S1-Global cryomodule test are reported, discussed and summarized.

INTRODUCTION

The main motivation for the S1-Global project is to demonstrate an average accelerating gradient of 31.5 MV/m in a string of superconducting cavities in a common cryostat, as envisaged for the ILC whose design is under development by the GDE (Global Design Effort) [4], and the project was launched at the ILC GDE meeting in Mar/2008 [2]. For this work, eight cavities were contributed from DESY, FNAL and KEK, and installed into two 'half cryomodules', each 6-m long. One module (Cryomodule-C) is designed and newly built by INFN [5]. The other (Cryomodule-A) is a modification of an existing 6-m STF cryomodule [6], which was used in 2008 at the STF Phase-1 of KEK. Contributions of collaborating institutes are:

- DESY: Two TESLA type cavities [7] with Saclay-type tuners, and TTF-III power couplers.
- FNAL: Two TESLA type cavities, TTF-III power couplers, and integration of the INFN Blade tuners in the cavity packages.
- INFN: Design and construction of Cryomodule-C, and production and setting of the Blade tuners for the FNAL cavities.
- KEK: Four TESLA-like cavities including STF-II power couplers and Slide-jack tuners with two different set positions (centre or end) [8], modification of Cryomodule-A, power distribution, and infrastructure for the cryomodule tests including the software development.
- SLAC: Two sets of VTO power distribution for Cryomodule-C, and conditioning of FNAL power couplers at the test bench.

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S1-GLOBAL CRYOMODULE

The S1-Global project aims to operate 8 cavities with the average accelerating gradient of 31.5 MV/m in a way similar to what the ILC design envisages. It also serves an excellent platform for comparing the performance of the cavities, power couplers, tuners built by collaborating institutions in the world. Studies on the effect of the LFD and the compensation by piezo actuator in the high power operational conditions are particularly useful. Table 1 summarizes the hardware components that are implemented in Cryomodule-A and -C.

Table 1: Comparison of S1-Global cryomodules.

	Cryomodule-A	**Cryomodule-C**
Cavity type	TELSA-like	TESLA-type
Power coupler	Disk window	Cylindrical window
Coupling	Variable	Variable
Tuner type	Slide-jack	Blade/Saclay
Cavity package	KEK-a/KEK-b	DESY/FNAL
Magnetic shield	Inside jacket	Outside jacket
Package length	1247.6 mm	1247.4/1283.4 mm

GRADIENT R&D IN THE U.S. – OVERVIEW AND SUMMARY*

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Abstract

Over the past few years, significant effort has been made to systematically improve multi-cell cavity accelerating gradients, driven in large part by the requirements of the ILC, for which the reproducible achievement of high gradients is a prerequisite. Substantial progress has been made by teams at Cornell University, Fermilab, and Jefferson Lab, in pushing gradients to higher values and in achieving this performance on a more regular basis. Development of improved diagnostic and inspection techniques along with the utilization of both localized and global repair tools have helped enable this improvement. Likewise, processing and assembly procedures that led to a lower incidence of field emission have facilitated this progress. The present status of cavity performance will be presented along with its evolution, and examples of the role the aforementioned techniques and tools have played in achieving this performance.

INTRODUCTION

In recent years, significant effort and progress has been made in improving the achieved gradients and gradient yield in multi-cell 1.3GHz cavities, motivated by the requirements of the proposed International Linear Collider (ILC), which requires that gradients of 35MV/m and $Q_0 \geq 8 \times 10^9$ be achieved in vertical test. These efforts have proceeded along several fronts :

- Optimization of electropolshing (EP) processing
- Control of field emission
- Detection of quench origins
- Repair techniques
- New processing methods
- Alternate shapes

These efforts, over time, have improved cavity performance. In Fig. 1, the maximum achieved gradient of all 9-cell cavities processed and tested by Cornell University, Fermilab/Argonne (FNAL/ANL) and Jefferson Lab (JLab) over the past ~4 years are shown. Steady improvement is noted. The dotted lines represent a 5-period moving average of the data, and while there is certainly scatter in the data, a general trend of improvement is clear.

CAVITY GRADIENT YIELD

The cavity gradient yield is defined as the fraction of cavities in a sample that achieve a particular gradient value[1]. This yield has been calculated for cavities that undergo a single process/test cycle (so-called "first-pass yield") and also for cavities that initially do not meet the ILC performance and subsequently receive an additional round of processing/test (so-called "second–pass yield"). The yield of cavities processed and tested by the collaborating institutions of JLab, DESY, and KEK, that exceed 30MV/m after their first process/test cycle, has improved over time to 50%, while 30% of cavities reach the ILC specification of 35MV/m. Figure. 2 shows the yield of achieved cavity gradients over time, for this scenario.

When one considers the effect of an additional process/test cycle applied to cavities that do not initially reach the ILC performance specification, the yield improves substantially. Under this scenario, fully 70% of cavities reach or exceed 30 MV/m, while over 50% reach the ILC performance goal (Fig. 3).

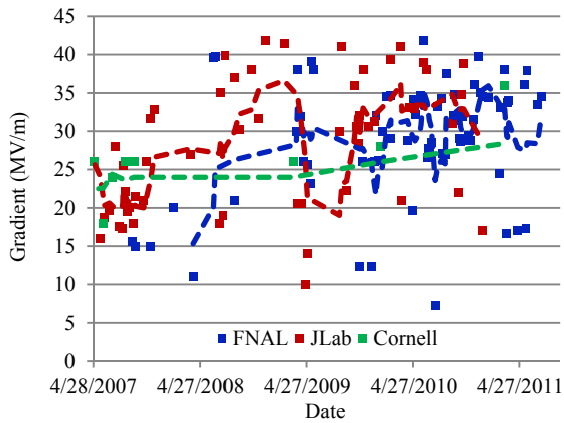


Figure 1: Cavity gradients as a function of time for cavities processed and tested at Cornell, JLab, and FNAL. The dotted lines, representing a 5-point moving average, show general improvement.

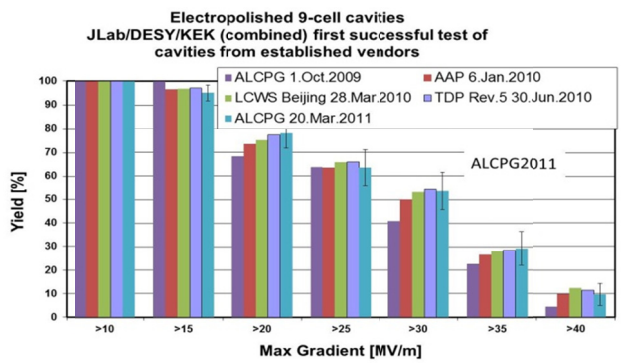


Figure 2: Cavity gradient yield after first process and test cycle. The individual vertical bars represent the yield achieved as development has progressed over time.

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COMPACT SUPERCONDUCTING CAVITIES FOR DEFLECTING AND CRABBING APPLICATIONS*

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Abstract

There is increasing interest in using superconducting cavities as rf separators (e.g. Jefferson Lab 12 GeV upgrade and Fermilab Project X) or as crabbing systems to increase the luminosity in colliders (e.g. LHC upgrade and electron-ion colliders). Several of these applications have severe dimensional constraints that would prevent the use of cavities operating in the TM_{110} mode. A number of compact designs for deflecting/crabbing cavities have been designed and are under development; their properties are presented.

INTRODUCTION

While most superconducting cavities for use in accelerators are for accelerating particles, they can also be used for deflecting beams or crabbing bunches. Accelerating cavities provide a longitudinal voltage in order to increase the forward momentum of the particles while deflecting/crabbing cavities apply a transverse voltage. Deflecting and crabbing cavities are identical, the only difference being in the phase between the rf transverse fields and the bunches. Deflecting cavities operate at maximum –or close to maximum– phase so the whole bunch acquires a transverse momentum. Crabbing cavities operate at zero phase so there is no net deflection of the center of the bunch but the front and back of the bunch are deflected in opposite direction.

Deflecting systems were one of the first applications of superconducting rf to particle accelerators. In the early 1970's an rf separator, shown in Fig.1, was designed and fabricated at KfK Karlsruhe [1]. It was comprised of 104 cells and the frequency of the deflecting mode was 2.865 GHz. The separator was operated at CERN between 1977 and 1981 and is now being resurrected at IHEP.

The first superconducting crabbing system was developed, implemented, and operated at KEK [2]. The crabbing system consisted of two cavities, shown in Fig. 2, one for each of the two rings. The cavities operated at 508 MHz in the TM110 mode. In order to remove the degeneracy between the two polarizations of the TM110 mode, the cavity was designed with a race-track shape cross-section. The cavities were installed in the rings in 2007 and were operated until recently. Although there were some difficulties associated with amplitude instabilities and mechanical tuner resolution, luminosity increase using a crabbing scheme was clearly demonstrated.

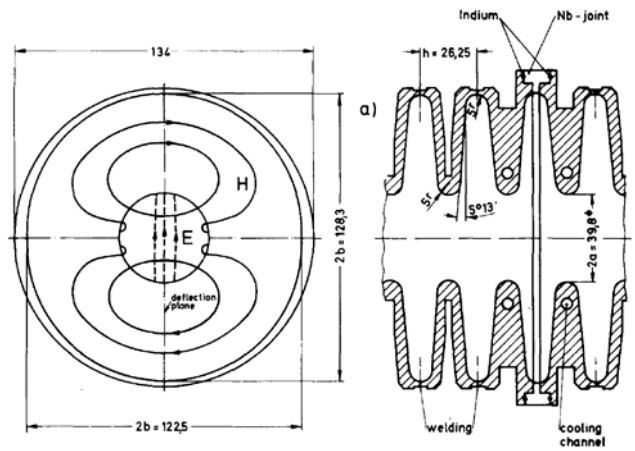


Figure 1: Karlsruhe/CERN superconducting rf separator.

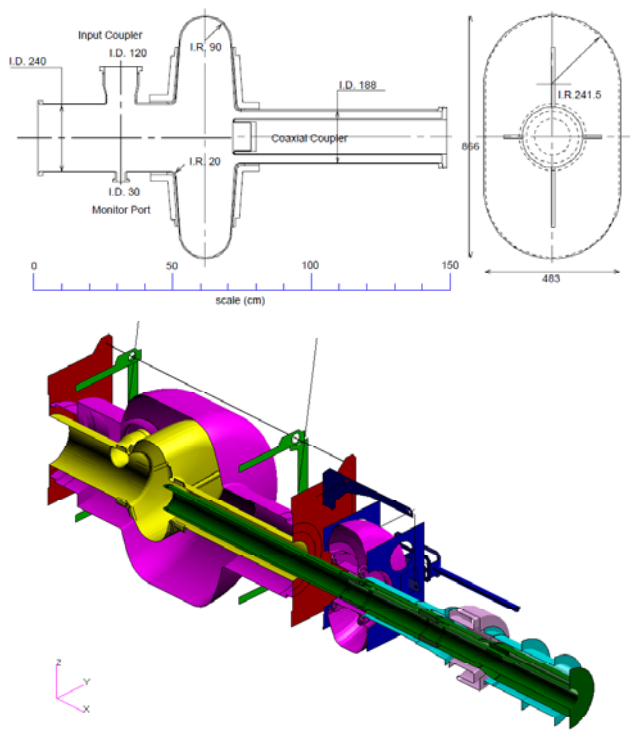


Figure 2: 508 MHz crab cavity used at KEKB

Those cavities operate in the TM110 mode, where the deflection results from the interaction with the transverse magnetic field. Because of the mode used these cavities are larger (by about 30%) than accelerating cavities of the

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QUARTER WAVE RESONATORS FOR BETA~1 ACCELERATORS *

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Abstract

The Superconducting Quarter Wave Resonator (QWR) was developed first for heavy ion acceleration in 1981 and became highly successful and widespread in low β linacs. Recently the QWR has been adapted for a variety of applications for high particle velocity, near β=1. The applications are varied, from the use in a relativistic hadron storage ring, to photocathode electron guns and crab cavities. In this work I will describe these applications, and how they benefit from the rather unique properties of this resonator, such as the Higher Order Mode spectrum, the electro-mechanical stability and the compact size.

INTRODUCTION

The Quarter Wave Resonator (QWR) is a very basic resonant structure, comprising of the coaxial transmission line shorted at one end, and "open" at the other end, a quarter of the fundamental wavelength from the shorted end. Thus the high impedance at the open end can be used for accelerating particles. The superconducting QWR was developed first for heavy ion acceleration in 1981 [1] and became highly successful and widespread in low β linacs [2].

The QWR has some limitations and some advantages. In applications where the beam travels along the axis of symmetry of the coax line, the resonator is inefficient in using space along the beam line, resulting a low "real-estate" gradient, thus suitable for small number of resonators in situations where space is not of great concern. In applications where the beam travels perpendicular to the axis of symmetry, the real-estate gradient can be quite high. The advantages of the QWR are compactness, extremely high mechanical stability and wide separation of the lowest High Order Mode (HOM) from the fundamental mode.

The most common use of the QWR by far is in the acceleration of low velocity ions, where the QWR has been made in many varieties of materials (lead-plated copper, niobium explosively bonded to copper, pure niobium metal and niobium sputtered on copper), a number of accelerating gaps per cavity and a broad range of particle velocities.

This paper is focused on the use of the QWR in less common applications where the particle velocity is high. In particular I will discuss QWR in use of relativistic heavy ions and electrons and the fast growing application of photocathode RF guns.

RELEVANT PROPERTIES OF THE QWR

The basic QWR is composed of two coaxial conductors, shorted electrically at one end, as shown in Figure 1. Usually, the outer conductor is extended in length beyond the inner conductor, as shown by the dashed

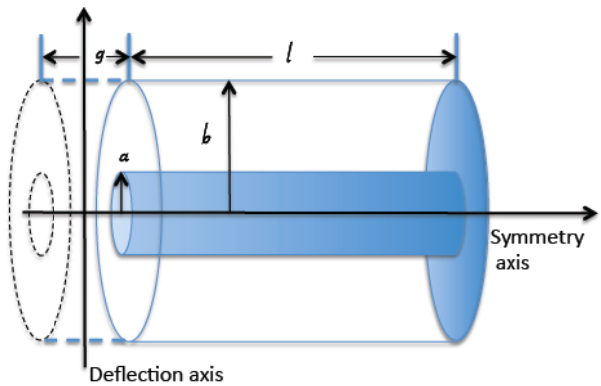


Figure 1: A schematic diagram of a Quarter Wave Resonator, defining its dimensions. The electrically shorted end is to the right.

Electrical Properties

The QWR of length l, radii of the inner and outer conductors a and b, respectively, can be described simply and quite well [1] as a transmission line of characteristic impedance Z_0 terminated by a capacitance C at a length $l=\lambda/4$ where λ is the wavelength for the resonant frequency. At resonance, a voltage V is developed between the conductors across the "open" end.

Directing particle beams along a few possible axes can apply this voltage for various purposes. One possibility is along the axis of symmetry, and a few examples will be given for this mode. Another possibility is shown in Figure 1 as the deflection axis, to be used by deflection cavities or crab cavities. The well known axis for low β linacs is paralel to the deflection axis but shifted towards the shorted end, to pass through the inner conductor.

The standing wave causes the voltage to reduce as a cosine function along the conductors, vanishing at the "shorted" end. The magnetic field is described by a sine function, with maximum at the shorted end. Let the surface resistance of the conductor be R_s. The general equation for the impedance of a transmission line is given by

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THE SC CW-LINAC-DEMONSTRATOR – SRF TECHNOLOGY FINDS THE WAY TO GSI

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Abstract

A new superconducting (sc) continous wave (cw) LINAC at GSI is desired by a broad community of future users. Especially the Super Heavy Elements (SHE) program at GSI and at the Helmholtz Institute Mainz (HIM) benefits highly from such a dedicated machine [1]. A conceptual layout of an sc cw-LINAC was worked out at the Institute for Applied Physics (IAP) at Frankfurt University [2]. Here the key component, an sc Crossbar-H (CH) cavity, was developed recently [3]. The multi-gap cavity is operated at 217 MHz and provides gradients of 5.1 MV/m at a total length of 0.69 m [4]. The first section of the proposed cw-LINAC comprising a sc CH-cavity embedded by two sc solenoids is financed by HIM as a demonstrator. One important milestone of the project is a full performance test with beam of the demonstrator in 2013/14 at the GSI High Charge Injector (HLI). With the demonstrator the srf-technology finds the way to GSI. The tests would be the first of an sc multi-gap structure with heavy ions being an important milestone towards the proposed cw-LINAC.

MOTIVATION

Since 1981 six new elements, from element 107 to element 112, were discovered at GSI. An important milestone for the successful SHE program at GSI was the commissioning of the High Charge Injector (HLI) in the early nineties. Nevertheless the HLI in combination with the Universal Linear Accelerator (UNILAC) is not a dedicated machine to the SHE-research. In future the UNILAC is designated as an injector for FAIR (Facility for Antiproton and Ion Research). Beam time availability for SHE-research will be decreased due to the limitation of the UNILAC in providing a proper beam for SHE and in fulfilling the requirements for FAIR simultaneously. To keep the SHE program at GSI competitive on a high level, an upgrade program of the HLI was initialized comprising a new 28 GHz ECR source and a new cw capable RFQ [5, 6].

As a result of a long term cost-benefit analysis a standalone sc cw-LINAC in combination with the upgraded HLI is assumed to fit the requirements of SHE at best [1]. Significant higher beam intensities will be provided and lead to an increase of the SHE production rate: The production cross section of element 120 is assumed to be smaller than 0.1 pbarn for instance. With the existing UNILAC a beam time on target of ten weeks for one event is estimated at minimum by experience [7]. The proposed sc cw-LINAC is expected to reduce the beam time by a factor of 20 to 4 days.

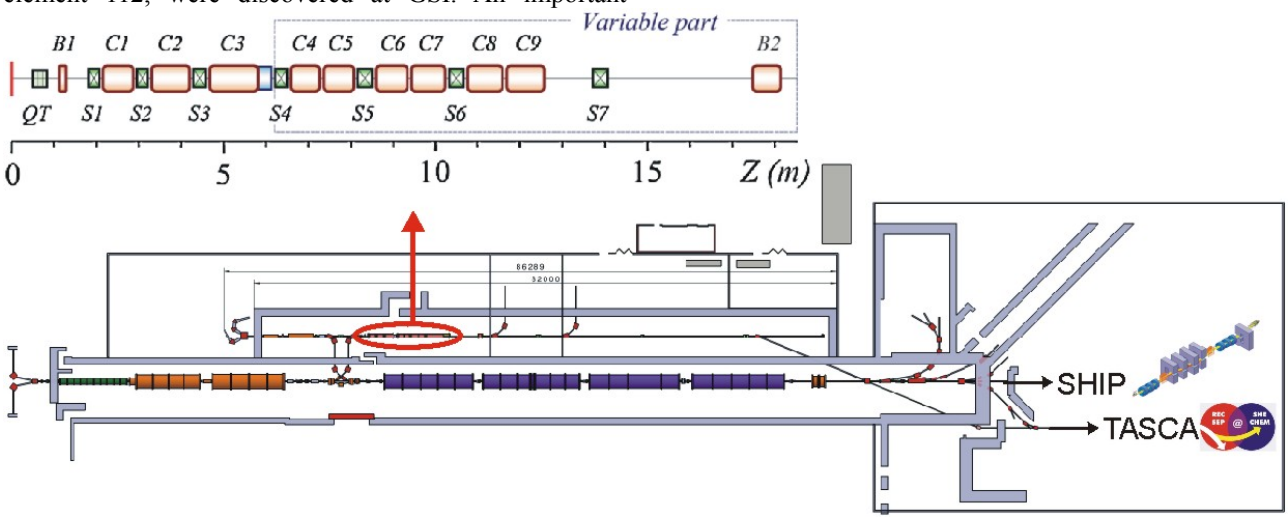


Figure 1: Draft layout of the future GSI accelerator facility with the integrated cw-LINAC in parallel to the existing UNILAC (Ci = Cavity, Bi = (Re-)Buncher, Si = Solenoid, QT = Quadrupole-Triplet). The cw-LINAC should provide SHE-experiments like SHIP (Separator for Heavy Ion reaction Products) and TASCA (TransActinide Separator and Chemistry Apparatus) with beam.

MECHANICAL DESIGN CONSIDERATIONS FOR BETA=1 CAVITIES

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Abstract

The Superconducting Proton Linac (SPL) is an R&D effort coordinated by CERN in partnership with other international laboratories, aimed at developing key technologies for the construction of a multi-megawatt proton linac based on state-of-the-art RF superconducting technology, which would serve as a driver for new physics facilities such as neutrinos and Radioactive Ion Beam (RIB).

Amongst the main objectives of this R&D effort, is the development of 704 MHz bulk niobium beta=1 elliptical cavities, operating at 2 K with a maximum accelerating field of 25 MV/m, and the testing of a string of cavities integrated in a machine-type cryomodule.

The R&D program concerning the elliptical beta=1 cavities fabricated from niobium sheets explores new mechanical design and new fabrication methods. The paper presents several opportunities for design optimization that were identified.

A comparison between stainless steel helium vessel and titanium helium vessel including Nb to Ti transitions is addressed. Different mechanical design aspects, including cryogenic considerations, and fabrication aspects were analyzed and the results are discussed.

INTRODUCTION

A first proposal for building a superconducting proton linac (SPL) at CERN to replace some of the existing accelerators was reported about 14 years ago [1], with the potential for evolving towards very high beam power, which would support new physics facilities for neutrinos and/or radioactive ion beams [2]. Later, the design of the SPL evolved towards a low-power 4 GeV version (LP-SPL), with potential use as a new injector chain for the LHC, with the Linac4, presently under construction, as a low energy front-end linac, and having the potential to be up-graded to a multi-MW proton injector [3]. Following recent changes in the mid-term plan strategy at CERN, the construction of the LP-SPL has been stopped, but the continuation of the R&D effort towards a high-power version of the SPL has been endorsed. As one of the priorities of this program, 704 MHz bulk niobium β=0.65 and β=1 elliptical cavities are to be developed and tested at IPN Orsay [4], CEA Saclay and CERN.

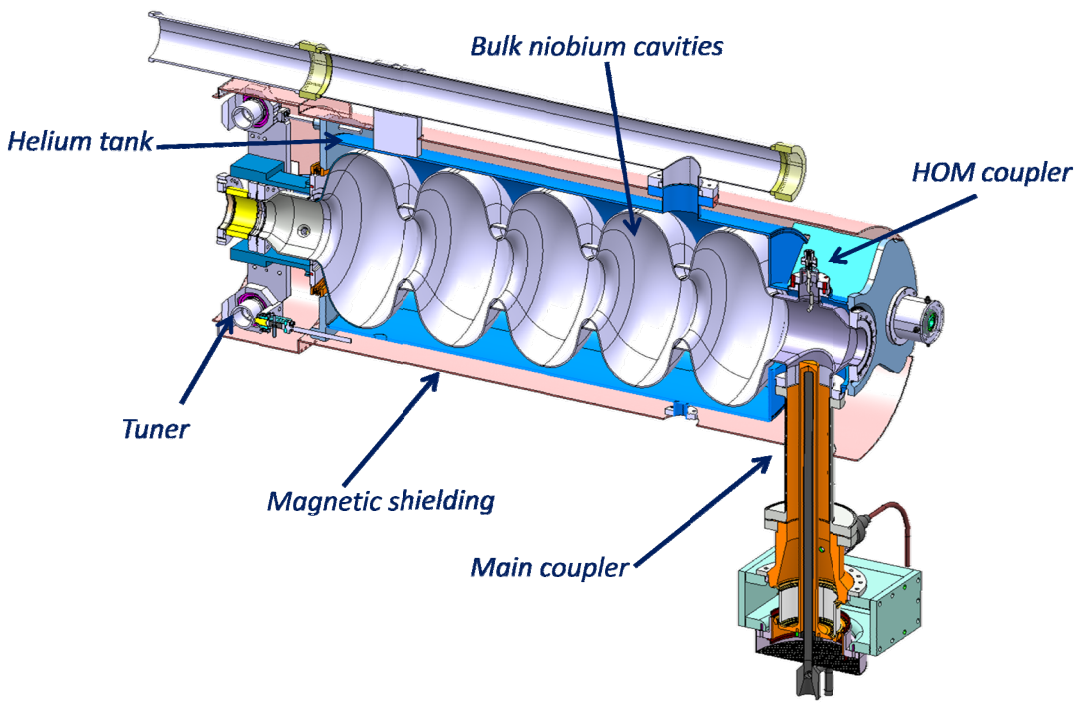


Figure 1: SPL β=1 cavity with helium tank, tuner, main coupler, HOM coupler to be tested at CERN in cryo-module.

SINGLE CELL SCRF CAVITY DEVELOPMENT IN INDIA

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Abstract

Under Indian Institutions and Fermilab Collaboration (IIFC), Raja Ramanna Centre for Advanced Technology (RRCAT) Indore, India has initiated the development of SCRF cavity technology. The R&D efforts are focused on the proposed Project-X accelerator complex at FNAL and High Intensity Proton Accelerator activities in India. As an initial effort, two prototype 1.3 GHz single cell bulk niobium cavities have been developed in collaboration with the Inter University Accelerator Centre (IUAC), New Delhi. Learning from the experience gained and the initial results of these prototypes (achieving E_{acc} ~23 MV/m), two more improved 1.3 GHz single cell cavities are being developed. These two improved single cell cavities will also be processed and tested at FNAL. Development of a single cell 650 MHz (β=0.9) prototype cavity is being undertaken as the next stage in these efforts. This paper will present the development activities and test results on the 1.3 GHz single cell cavities and status of the ongoing work.

INTRODUCTION

Superconducting radio frequency (SCRF) technology is playing a major role in many ongoing and upcoming accelerator projects all over the world. RRCAT has also initiated research program to develop the necessary infrastructure & technology for design, manufacturing and testing of SCRF cavities. Under IIFC, RRCAT together with IUAC have initially developed two 1.3 GHz (β=1) bulk niobium single cell SCRF cavities during 2009. They were processed & tested jointly by FNAL & ANL during early 2010. Based on the feedback from the test results, two more single cell cavities have been fabricated during late 2010-early 2011. Further, to align with Project-X, activities have been initiated for the development of 650 MHz (β=0.9) SCRF cavities also.

CAVITY DEVELOPMENT

Design, fabrication & testing of 'Single Cell Cavity' is a standard practice for development of various crucial elements of the cavity development cycle. Work on the 1.3 GHz single cell cavity started with the development of aluminum [1] and copper [2] cavities. This was followed by development of two bulk niobium cavities.

Forming Tool Development & Cell Forming

The first step was design and development of the half cell forming tools made of aluminum alloy (AA7075-T6). RRCAT has developed two sets of forming tools suitable for 1.3GHz structure. One set was delivered to FNAL. The second set was used for all forming work performed at RRCAT. The experience gained during aluminium and copper half cell forming were used to improve the die shape, strategy for handling, control in thickness variation & orthogonal error, before forming niobium half cells. Four precisely shaped parts viz. male forming die, female forming die, hold down plate and coining ring (Fig. 1a) constitute the forming die. A 200 ton hydraulic press with a die pillar set was used to form the half cells. Fig. 1b shows half cell forming.



Figure 1: a) Forming tool and 1b) Forming of the half cell.

CAVITY DESIGN & FABRICATION

Under the framework of Tesla Technology Collaboration (TTC), the basic DESY design was adopted for development of initial prototype of 1.3 GHz single cell cavity. As part of design validation effort, HF Emag eigen mode analysis was done using ANSYS to estimate the RF frequency for change in frequency with temperature and extra lengths at equator (Table-1). The equator frequency sensitivity coefficient K_{eq} is estimated to be -5.1 MHz/mm. This was verified during equator trimming of prototype cavity fabrication. Standard DESY recipe [3] with added FNAL experience of 3.9 GHz cavity fabrication became the basis of cavity fabrication activities. Design for manufacturing was done that included square butt joint type weld edge design, welding lip at the backside of flange joint and no recess in the flange bore.

Table 1: Estimated frequency at different temperatures

Temperature	300 K	77K	2K
Frequency MHz	1297.2872	1299.8814	1300.00

The beam tubes were rolled using dedicated precision rolling machine and were seam welded. Design and fabrication of the machining fixture, parts machining as well as inspection of various tooling and components were done at RRCAT. Detailed manufacturing plan was

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PROJECT X CAVITY AND CRYOMODULE DEVELOPMENT*

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Abstract

Project X is a proposed multi-MW proton accelerator facility based on an H- linear accelerator using superconducting RF technology at Fermilab. The Project X 3 GeV continuous wave linac requires the development of two families of superconducting RF cavities at 325 and 650 MHz, to accelerate 1 mA of average H- beam current in the energy range 2.5-160 MeV, and 160-3000 MeV, respectively. These cavities must support possible acceleration of up to 4 mA beam current. The baseline design calls for three types of superconducting single-spoke resonators at 325 MHz having geometric phase velocities, β_G, of 0.11, 0.22, and 0.42, and two types of superconducting five-cell elliptical cavities having β_G= 0.61 and β_G= 0.9. The electromagnetic and mechanical designs of the cavities are well underway and prototype tests for some cavity designs have started. Because of the CW operation, the heat load on the cryogenic system is substantial; and for purposes of cryogenic system design, the dynamic heat load is limited to 250 W at 2K per cryomodule. The anticipated heat loads for the 650 MHz section lead to stringent requirements on cavity unloaded quality factor Q_0, and on cryogenic aspects of the cryomodule design. Status and plans for the Project X cavity and cryomodule development will be described.

INTRODUCTION

Project X is a proposed multi-MW proton accelerator facility at Fermilab based on an H- linear accelerator using superconducting RF technology; the schematic layout of the complex is shown in Fig. 1. The 3 GeV Project X linear accelerator (linac) provides a continuous-wave (CW) 3 GeV 1 mA H- beam to an experimental area, and is injected into a pulsed linac for further acceleration to 8 GeV and injection into the Main Injector. These beams will support a variety of experiments in kaon, muon, nuclear, and neutrino physics [1-3]. The 3 GeV linac will use superconducting 325 MHz single-spoke cavities, and 650 MHz elliptical cavities. The 3-to-8 GeV linac will use 1300 MHz Tesla-type elliptical cavities. Six distinct cavity designs are planned spanning the geometric phase velocity range from β_G=0.11 to β_G=1. These cavities will be assembled into three different types of cryomodules. All cavities will operate at a temperature, still under consideration, between 1.8 and 2.1 K. The designs of the cavities and cryomodules for the 3 GeV linac are in progress. The 3-8 GeV pulsed linac will take advantage of the well-developed 1300 MHz Tesla-type cavities in ILC-like cryomodules. The remainder of this paper will focus on the development of the new cavities and cryomodules for the CW 3 GeV linac; the main parameters of the linac sections are listed in Table 1.

*Work supported by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

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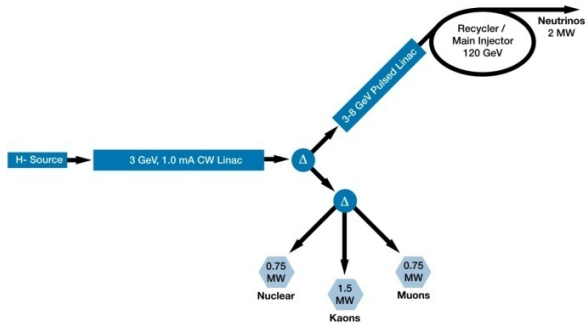


Figure 1: Schematic layout of the Project X accelerator complex.

Table 1: Parameters of the 3 GeV CW linac sections

Section	Freq (MHz)	Energy (MeV)	#cavities/ focusing elements/ cryomodules	Component Type
SSR0 β=0.11	325	2.5-11.4	18/18/1	single-spoke cavity, solenoid
SSR1 β=0.22	325	11.4-43	20/20/2	single-spoke cavity, solenoid
SSR2 β=0.4	325	43-179	44/24/4	single-spoke cavity, solenoid
LB 650 β=0.61	650	179-559	42/28/7	5-cell cavity, doublet
HB 650 β=0.9	650	559-3000	152/38/19	5-cell cavity, doublet

CAVITY DESIGN AND PERFORMANCE

The 3 GeV linac includes five distinct cavity types, spanning the geometric velocity factor range β_G = 0.11 to β_G = 0.9, with approximately 80 single-spoke cavities at 325 MHz and 200 elliptical cavities at 650 MHz.

325 MHz Single-Spoke Cavities

The three single-spoke cavities: SSR0, SSR1 and SSR2, have geometric velocity factors β_G = 0.11, 0.22, and 0.4, respectively. The cavity designs are described in detail in [4].

The SSR0 cavity design is challenging because it has very tight lattice requirements and a strong sensitivity to microphonics due to its small accelerating gap length. The design of the SSR0 cavity is complete, and initiation of procurements of two prototype SSR0's is planned for this year.

The SSR1 cavity was designed and prototyped in the context of the High Intensity Neutrino Source (HINS) program at Fermilab. Two prototypes have already been built and tested with encouraging results. Examples of cavity performance are shown in Fig. 2. The two

PRELIMINARY RESULTS OF THE IFMIF CAVITY PROTOTYPES TESTS IN VERTICAL CRYOSTAT AND CRYOMODULE DEVELOPMENT

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Abstract

In the framework of the International Fusion Materials Irradiation Facility (IFMIF), which consists of two high power CW accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV [1], a Linear IFMIF Prototype Accelerator (LIPAc) is presently under design for the first phase of the project. A superconducting option has been chosen for the 5 MeV RF Linac, based on a cryomodule composed of 8 low-beta Half Wave Resonators, 8 Solenoid Packages and 8 RF couplers. This paper will mainly focus on recent tests in laboratory of the main components of this cryomodule: HWR, RF coupler mock up, and solenoid prototypes. A section is dedicated to the HWR activities: realization and preliminary vertical tests of the two HWR prototypes. One prototype was equipped with the innovating cold tuning system, located in the central region of the cavity. Another section gives results on RF coupler'mock-up and solenoids prototypes. Finally, the LIPAc cryomodule current design is also presented.

INTRODUCTION

The main purpose of the LIPAc project [2] is to validate all the technical options for the construction and commissioning of this accelerator prototype, with a full scale of one of the future IFMIF accelerator, from the injector to the first cryomodule of the SRF Linac. The main requirements for the LIPAc project are as follow:

- Energy of D+ beam on beam dump: 9 MeV
- RF Frequency: 175 MHz
- Beam intensity: 125 mA
- Output rms long. emittance: < 0.55 π.mm.mrad, and < 0.35 π.mm.mrad in transverse.

The general layout of the LIPAc is illustrated in Figure **1**. The LIPAc cryomodule is the most difficult one, essentially due to the short drift lengths between components and small interfaces between sub-systems, in order to design a cryomodule as compact as possible to fulfil the beam dynamics requirements in the case of intense beam [3].

The goals of the cryomodule are to transport and accelerate the deuteron beam of nominal intensity, in continuous wave (CW), with energy from 5 MeV up to 9 MeV at the output of the linac. Good performances in terms of transverse and longitudinal emittances are necessary to fit with the 300 mm diameter aperture at the Beam Dump entrance, and the future footprint for IFMIF: 200 mm × 50 mm, without beam loss (< 1 W/m).

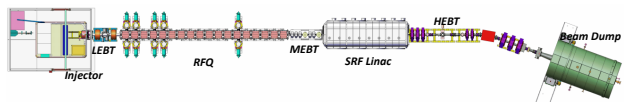


Figure 1: General layout of the accelerator prototype in the vault at the Rokkasho site.

GENERAL DESCRIPTION

The cryomodule is a complex system, due to the huge number of components sharing cryogenics circuits. The cryomodule consists of a horizontal vacuum tank of around 5 m long, ~2.8 m high and ~2.0 m wide, which includes the following elements:

- 8 low-β HWRs with a frequency tuning system,
- 8 RF power couplers,
- 8 Solenoid Packages (including solenoids, H&V steerers and cryo-Beam Position Monitors),
- A cryostat (vacuum tank) with access traps,
- Supports and alignment system,
- Cryogenic, vacuum and electrical systems,
- Magnetic shielding and thermal screen.

The cryomodule under development is illustrated in Figure 2. Main parameters of this cryomodule are summarized in the following Table 1.

Table 1: Summary of cryomodule parameters.

Parameters	Target Value	Units
β value of the HWR	0.094	
Accelerating field E_{acc}	4.5	MV/m
Unloaded Quality factor Q_0 for R_s=20 nΩ	1.4×10^9	
Beam aperture HWR / Solenoid Package	40 / 50	mm
Freq. range of HWR tuning syst	± 50	kHz
Max. transmitted RF power by coupler (CW)	200	kW
External quality factor Q_{ex}	6.3×10^4	
Transmission Lines for HWR	coax 6" 1/8	
Magnetic field B_z on axis max.	6	T
∫ B.dl on axis	≥ 1	T.m
Field at cavity flange	≤ 20	mT
BPM position accuracy	0.25	mm

STATUS OF THE REACCELERATOR FACILITY REA FOR RARE ISOTOPES BEAM RESEARCH*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is currently in the preliminary design phase. FRIB consists of a heavy ion driver LINAC, followed by a fragmentation target station, a fragment separator, a fast beam experimental area, a gas stopping area, a stopped beam experimental area and a ReAccelerator facility (RεA). In its final configuration, RεA will provide heavy ion beams from 0.3 MeV/u to 12 MeV/u for heaviest ions and up to 20 MeV/u for light ions. While FRIB plans to start conventional construction in 2012, the first stage of RεA is already under commissioning and will be connected to the Coupled Cyclotron Facility at MSU end of 2012. The front end of the accelerator consists of a gas stopper, an Electron Beam Ion Trap (EBIT) charge state booster, a room temperature RFQ, followed by a short SRF LINAC, which contains seven β=0.041, eight β=0.085 QWR cavities, and eight 9T focusing solenoids. RεA serves as prototyping test bed for the FRIB cryomodule development since FRIB utilizes similar cavities as installed on RεA. An overview and status of the RεA facility will be presented. The paper will focus on the testing, beam commissioning, and operational experience of the first β=0.041 cryomodules.

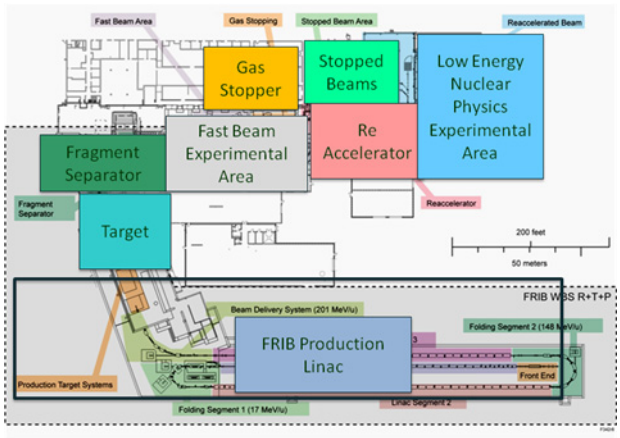


Figure 1: Concept of the facility for Rare Isotope Research (FRIB) at MSU.

INTRODUCTION

Nuclear science research requires reaccelerated radioactive isotope ion beams in a range of kinetic energies from thermal to near 20 MeV/u. The combination of a gas stopper with a re-accelerator is of particular importance, since it provides high quality beams of rare isotopes for nuclear research.

The proposed Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is designed to provide these nuclear physics research tools (see figure 1). FRIB consists of a heavy ion driver LINAC, followed by a fragmentation target station, a fragment separator, a fast beam experimental area, a gas stopping area, a stopped beam experimental area and a ReAccelerator facility (RεA).

While FRIB plans to start conventional construction in 2012, the first stage of RεA (ReA3) is already under commissioning. Therefore, one important role of ReA is to serve as a prototype for the FRIB linac to develop hardware, controls, and gaining commissioning and technical experience in operating a superconducting linac facility. However, the main mission for ReA3 [5,6] in the next few years is to connect to the Coupled Cyclotron Facility (CCF) at MSU to provide reaccelerated rare isotope beams produced by the CCF. Figure 2 shows an overview of the ReA3 facility. ReA3 will be capable of accelerating ions with a charge-to-mass ratio Q/A=0.25 from 300 keV/u to 3 MeV/u and for Q/A=0.5 from 300 keV/u to 6 MeV/u. The accelerator consists of an Electron Beam Ion Trap (EBIT) charge breeder, an off-line stable ion beam injector, a multi harmonic buncher, a room temperature RFQ and a buncher cryomodule (CM) and two low beta cryomodules with a total of fifteen superconducting cavities. The last of the three cryomodules with a beta equal to 0.085 is still under development and is expected to be installed in July of 2012, after which the installation will be completed.

In its final configuration RεA will consist of three buncher cryomodules, one β_o=0.041cryomodule and four β_o=0.085 cryomodules with a total of 41 superconducting quarter wave cavities (funding proposal submitted). In this configuration, RεA will provide heavy ion beams from 0.3 MeV/u to 12 MeV/u for heaviest ions and from 0.3 MeV/u up to 20 MeV/u for light ions.

This paper focuses on the commissioning and first beam experiments with the superconducting LINAC.

REA INJECTOR AND FRONT END

The front end system consists of two injectors. A compact vertical off line pilot beam injector (currently a small external filament ion source) provides singly charged He^+ and H_2^+ ions for commissioning and pre-tuning of the LINAC.

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Project funded by Michigan State University

SRF ADVANCES FOR ATLAS AND OTHER β<1 APPLICATIONS

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Abstract

The primary goal for seven new 72 MHz quarter wave SC cavities at Argonne is to provide the maximum accelerating gradient along the linac with large acceptance and minimal beam losses for the acceleration of high intensity beams. Cavities will be installed into ATLAS in 2012 as part of this intensity upgrade. However, ANL also intends to demonstrate the techniques required for future ion linacs for basic and applied science and technology. These accelerators would be cost prohibitive with older technology. New cavity electromagnetic design optimizations and improved electropolishing techniques developed at ANL have been applied to the construction of the first prototype. Initial tests show the highest performance achieved to date for this class of cavity designed to cover the velocity range 0.06<β<0.15. The cavity has very low RF losses and the highest useful accelerating gradients ever achieved for a quarter-wave structure. Indeed, the accelerating voltage of 4.3 MV is twice that for cavities installed and operating in ATLAS since 2009, with RF surface fields comparable to those being achieved for the ILC effort.

INTRODUCTION

The ATLAS Efficiency and Intensity Upgrade [1] includes a new high-efficiency CW radio frequency quadrupole injector [2] and one new cryomodule of 7 SC cavities to replace three existing cryomodules of split-ring resonators in the middle portion of the ATLAS SC ion linac. The cryomodule will provide 17.5 MV of accelerating potential over 5 meters and dramatically increase beam transport efficiency for both stable and radioactive ion beams by increasing overall acceptance and reducing emittance growth inherent in the earlier cavity designs.



Figure 1: Prototype 72 MHz quarter-wave cavity with 4 kW power coupler and fast and slow tuners.

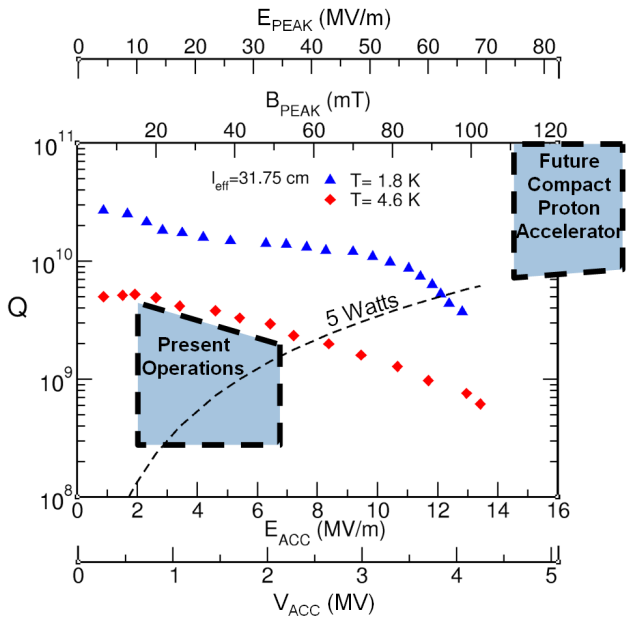


Figure 2: Quality factor versus accelerating gradient, voltage and surface fields at 2 and 4 Kelvin.

The cavity operating voltage will be V_{ACC}=2.5 MV/cavity at β=0.077, roughly two times higher than for the present state-of-the-art at this beta [3]. To achieve this, a combination of improved rf design [4] and improved cavity processing techniques have been developed.

CAVITY PERFORMANCE

Initial cold test results at both 2 and 4 Kelvin for the prototype 72 MHz cavity are complete. Processing included heavy, 150 μm, electropolishing on the complete cavity (see Figure 1). Work is ongoing, including baking and re-rinsing, however, early results shown in Figure 2. already show the highest accelerating gradients and voltages for any cavity in the region of β~0.1.

4 Kelvin Performance

In ATLAS cavities are operated at 4.5 Kelvin using the ATLAS liquid helium refrigerator. The planned accelerating gradient is 7.9 MV/m (l_{eff}=βλ=31.75 cm)

SPL CAVITY DEVELOPMENT

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Abstract

The Superconducting Proton Linac (SPL) is planned as a 4MW machine in pulsed operation at CERN. Two families (beat = 0.65 and β = 1.0) of 5 cell superconducting elliptical cavities, operating at 704.4 MHz, will be used to accelerate H– beam from 160 MeV up to 5 GeV. One of the main challenge is the nominal gradient required for both cavities type: 19 MV/m for the β=0.65 and 25 MV/m for the β=1. Several prototypes of elliptical cavities have been studied by different laboratories (CERN, CEA/Saclay, BNL, IPN Orsay) through a large collaboration (EuCARD program, French and US in-kind contribution...) and are now ready for fabrication. First of all, we will present the work done on RF and mechanical optimizations as well as the studies on HOMs. Then, we will give an overview of the short-cryomodule design, housing four β=1.0 cavities, which should be tested at CERN.

CONTRIBUTION NOT RECEIVED

RECENTS DEVELOPMENTS IN SRF AT TRIUMF

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Abstract

The TRIUMF SRF program follows three basic paths: the support of the existing installed superconducting heavy ion linac with forty quarter wave cavities, the development of infrastructure and cavities for the new e-Linac project at 1.3GHz and fundamental studies to support student projects. Work on the quarter waves primarily involves determining optimum processing steps to improve cavity performance. The e-Linac cavity is a variant of the Tesla nine cell cavity modified to allow the acceleration of 10mA in cw mode. Fundamental studies on RRR niobium have been done at the Muon Spin Resonance facility at TRIUMF to characterize the flux of first entry for different processing of the niobium. THe program will be summarized.

CONTRIBUTION NOT RECEIVED

HIE-ISOLDE QUARTER WAVE NB/CU CAVITY

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Abstract

The HIE-ISOLDE project aims at the energy boost of the radio active beams produced in the ISOLDE facility from 3 MeV/u up to 5.5 MeV/u in a first stage and 10 MeV/u as ultimate installation. The beam acceleration is mainly achieved by employing 20 Nb sputtered Quarter Wave Resonator at β = 0.1 for which an R&D program has started. RF and mechanical design as well as the latest results of the sputtering process are reported in this paper.

CONTRIBUTION NOT RECEIVED

HOT TOPICS: RECIPES FOR 9-CELL CAVITY FABRICATION AND PREPARATION

T. Saeki [KEK, Ibaraki, Japan]

Abstract

In the mass production of International Linear Collider (ILC), about 16,000 9-cell SRF cavities must be produced for the linac. The current recipe of 9-cell cavity production is not enough for the required cost reduction for ILC. Various ideas for the cost reduction of 9-cell cavity fabrication would be duscussed in this presentation. As the final surface treatment of 9-cell cavity, the Electro-Polishing (EP) is the best candidate to realize high yield rate for high-gradient performance. However, the laboratories in the world are still using different EP parameter-sets for various reasons. In this presentation, the comparison of EP parameters among laboratories would be done and how we can reach to the best parameter sets would be discussed.

CONTRIBUTION NOT RECEIVED

QUENCH SIMULATION USING A RING-TYPE DEFECT MODEL*

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Abstract

A 2-dimensional ring-type defect thermal feedback model has been improved by including magnetic field enhancement at the pit edge. Latest simulation results show that there is a thermally stable state below the quench field with part of the edge becoming normal conducting, which can explain the preheating observed in thermometry measurements at fields below quench. 3D magnetic field enhancement calculations of pit structures where done using the Omega3P code to obtain realistic values for the magnetic field enhancement at typical pit dimensions.

INTRODUCTION

Pit-like structures on the niobium surface of superconducting RF cavities have been shown to cause thermal breakdown under certain conditions. However, the field at which quench is caused by a pit defect varies significantly from pit to pit, and frequently, pits do not cause quench up to the maximum field obtained. Previous thermal feedback models treat pits as normal conducting disk-type or ring-type defects and aim to predict quench fields according to pit size [1],[2].

An interesting feature observed by temperature mapping at pit locations is that increased heating is found, starting well below the quench field [4]. Fig.1 shows a pit-like defect found in a single cell 1.5 GHz cavity which showed about 200mK pre-heating at the quench site just below the breakdown field of 120 mT. Since the thermometer efficiency is 20∼25% [3], the actual outer wall temperature rise is 800∼1000mK. Only part of this heating can be attributed to the typical high field Q-drop in BCP cavities without low temperature bake. Figure 2 shows two individual thermometer responses, one at the pit location, and one at a defect free area in the high magnetic field region. It shows that the defect heating has surpassed high-field Q slope above 80 mT. By subtracting the estimated Q slope heating, the pre-heating by the pit defect alone can be estimated. From this it is found that the temperature increase scale as H^2_{peak} and is thus ohmic in nature [3].

In this paper we present an improved version of our ring defect model [2], which is not only able to predict the quench field caused by the pit, but also explains the presence of the pre-heating observed at fields below quench.

The key idea of this new pit model is that it includes the magnetic field enhancement at the pit edge.

* Work supported by NSF CAREER award PHY-0841213 and Alfred P. Sloan Foundation

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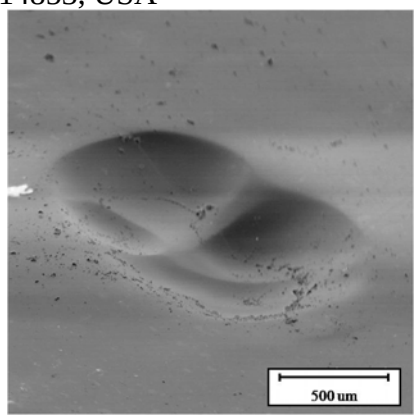


Figure 1: The SEM image of a pit causing quench at 120 mT in cavity LE1-HOR.

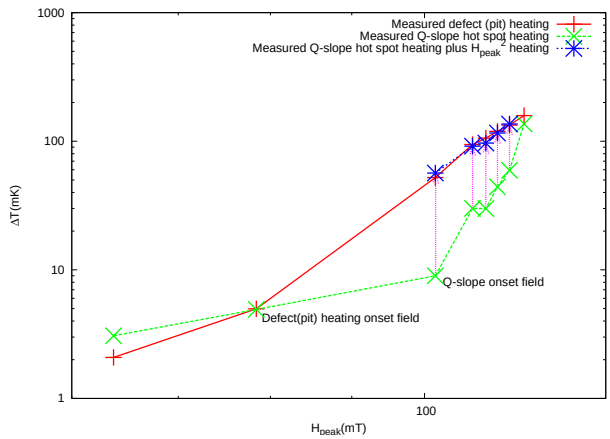


Figure 2: Individual thermometer response during test of cavity LE1-HOR. The blue symbols show the heating measured at the pit location, while the green symbols are from a location in the high magnetic field region showing the typical high field Q-drop in a BCP treated cavity.

IMPROVED RING-TYPE DEFECT MODEL

The phenomena of thermal magnetic breakdown has been numerically simulated over the years and is based on a thermal feedback process. Past models treated the defect as an axial-symmetric disk with its entire area becoming normal conducting when thermal breakdown happens. However, as observed in many cases, quench causing defects are correlated with pits on the surface with a sharp edge, and not disk like objects. Therefore, based on the assumption that only the edge of the pit becomes normal conducting, a 2-dimensional ring-type defect thermal program was

MULTIPACTING IN HOM COUPLERS AT THE 1.3GHz 9-CELL TESLA TYPE SRF CAVITY

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Abstract

During the XFEL [1] prototype module tests on the module test stand at DESY [2], [3], [4] RF power measurement anomaly on the higher order mode (HOM) couplers at the cavity operating frequency was detected and investigated. HOM coupler multipacting, predicted by the analytical simulations [5], was found to be the source of the anomalous signal peak. TESLA type SRF cavity HOM coupler multipacting simulations and observations are presented, compared and discussed.

INTRODUCTION

During the module tests of PXFEL1, 2 and 3 on CMTB [4] some RF power measurement heads, used for the accelerating cavities HOM couplers (see Fig. 1) RF power measurement at main operating frequency were damaged. The damaged RF power measurement heads have approximately -3 dB measurement error. The HOM coupler signal anomaly was investigated in search for the damage reason.

Cavities RF test data show the HOM couplers RF power anomalous jumps for some cavities during the measurements.

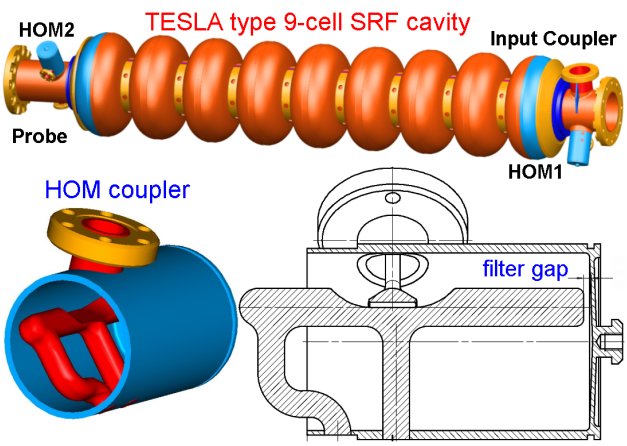


Figure 1: TESLA type SRF accelerating cavity.

XFEL PROTOTYPE MODULE MEASUREMENTS

During the module PXFEL3 test on CMTB a spectrum analyzer showed besides a stable base pulse signal sharp irregular peaks on 1.3 GHz frequency (on the base peak top), the peaks reaching +15 dB over the base signal. This effect appears after reaching certain RF power level of about 100 kW (17 MV/m) at 500 + 800 µs flat-top pulse.

Digital scope measurement with an RF diode revealed the anomalous signal structure – a very short peak about 10 µs appears about 20 µs after RF input power pulse start (see Fig. 2). It was found at both HOM couplers in cavities 1,2,3 and 7 depending on RF power level. Anomalous peak amplitude exceeds the normal HOM coupler coupled 1.3 GHz signal amplitude, but it is comparable to cavity probe signal amplitude.

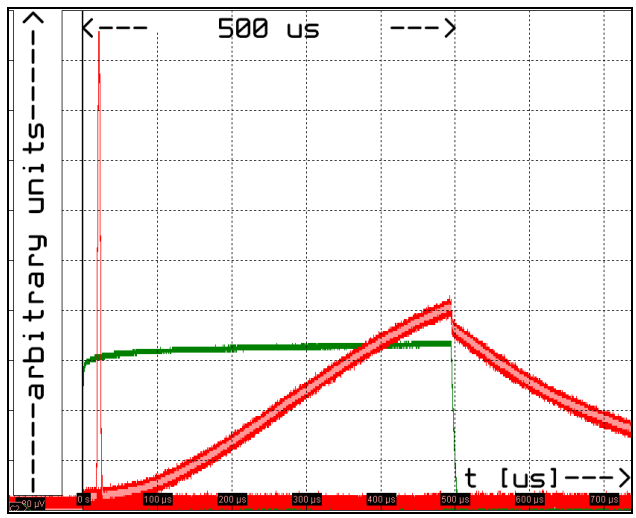


Figure 2: Anomalous peak with 500µs / 170kW RF pulse - green (21 MV/m). PXFEL3.C2.HOM1 pulse – red, measured with an RF diode.

The anomalous peak does not depend on the RF pulse length as soon as pulse is long enough for the peak to appear, about 20..30 µs.

Anomalous Peak has a definite RF power onset level, different for different cavities and HOM couplers. Increasing the RF amplitude shifts the anomalous peak in the pulse start direction (see Fig. 3). The anomalous signal is not stable, it changes its shape. It does not appear at each RF pulse, more frequent by higher RF power level, differently with different cavities HOM couplers.

Direct scope measurement without the RF diode also shows the signal with the same timing, highly modulated. RF low pass / 1.3 GHz notch filter cancels the signal.

Detuning the cavity first cancels the peak on HOM2 coupler. Partially detuned cavity (by 1 kHz, gradient decreased by 5%) has this peak on HOM2 coupler signal. Completely detuned cavity does not have the effect – anomalous peak needs the cavity field and depends on it strongly. Strong field configuration dependence is seen, partially detuned cavity field has multiple zero crossings (it oscillates) and there are multiple anomalous peaks (see Fig. 4). Detuning the neighbor cavities does not change the signal.

ELECTRO- AND CHEMICAL- POLISHING NB CAVITIES

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Abstract

Standard treatments to achieve excellent high rf power Nb accelerator cavities include electro polishing (EP), buffered chemical polishing (BCP), and ~120°C UHV baking (LTB). Those treatments change for RRR>100 Nb: rf residual losses R_{res}, BCS rf losses $R_{BCS}(T)$, low field Q- (LFQ), medium field- (MFQ) or high field- (HFQ) Q slope. Those differences between BCP, EP and LTB are related to differences in oxidation where Nb_2O_5 grows on Nb, O^{2-} is drawn through the double layer and through Nb_2O_5 injecting O into the open Nb lattice nucleating Nb_2O_5 crystallites straining the NbO_x/Nb interface heavily worked out below which gives the first consistent explanation for the superiority of EP over BCP and the reasoning for the advantage of LTB. For example by EP and LTB strong O built up and O precipitation at Nb surfaces is found being demonstrated by H_{c3} increases and by HFQ reductions. By BCP the repeated Nb_2O_5 crystallite growth creates dislocations and injects O into larger Nb depth enforcing weak link (WL) growth, i.e. R_{res}, MFQ and HFQ are enforced.

INTRODUCTION

Standard treatments to achieve excellent high rf power Nb accelerator cavities are: high pressure water rinsing (HPR), electro polishing (EP) more than 50µm Nb, buffered chemical polishing (BCP) more than 100µm Nb, and ~120°C UHV baking (LTB) [1-5], which change the rf residual losses R_{res}, the BCS rf losses R_{BCS}, the low field Q-drop (LFQ), the medium field Q-drop (MFQ), the high field Q-drop (HFQ), the impedances $Z(T>T_c,\omega<$MHz, $B_{dc})$ up to depth of 50µm and the ratio $H_{c3}/H_{c2}=r_{32}>1.69$. BCP, EP and LTB mainly differ in details of the oxide removal and the oxidation process, especially in strain relaxation and O precipitation, being summarized below.

The quality factor $Q_0=G/R$ is given by G^H containing the current distribution and R^H containing material properties

$$R^H(T,\omega,H)=R^H_{res}(\omega,H)+R_{BCS}((T\le T_c/2,\hbar\omega\le\Delta/30)= R^H_{res}(\omega,H)+r_0\omega^\beta\exp(-\Delta/kT)/kT; \quad (1a)$$

This ansatz and the BCS theory for oxidized Nb fits excellently the T- and ω- dependencies of $R^H(T,\omega)$ of oxidized Nb cavities with averaged values r_0, β, and Δ/kT_c for a λ_{BCS}~100nm penetration layer changing with oxidation for RRR>100 Nb in characteristic ways [1-8]. By the weak interaction with phonons locally confined quasiparticles $|\varepsilon|\le\Delta_{ave}$ are easily driven out of thermal equilibrium yielding a saturating loss component named low field Q-slope (LFQ) [2b,5]

$$R_s(T,B>10\text{ mT}) = a(T)/B^2 + R_{BCS}(T,\sim 20\text{mT}) + R_{res} \quad (1b)$$

whereas extended $|\varepsilon|\ge\Delta_{ave}$ rf quasiparticles have long mean free path $l_{in}=v_F\tau_{in}(T,<10\text{GHz})>6\cdot10^{-3}(T_c/T)^3$cm and so R_{BCS} does not heat its surface. At Nb_2O_5/Nb interfaces via localized states $n_L\le10^{21}/\text{cm}^3$ rf shielding current momenta are transferred to the lattice coherently

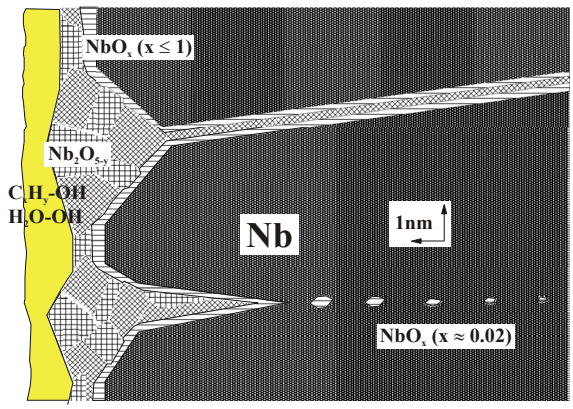


Figure 1: Nb surface with crack corrosion by wet oxidation by Nb_2O_5 volume expansion (factor 3). Nb_2O_{5-y}-NbO_x weak links/segregates (y,x<1) extend up to depths between 0.1– 1/1-100 µm for good/bad Nb quality and weak/strong oxidation [8-11]. The double layer $(OH)_yH_2O$ being chemisorbed by hydrogen bonds to NbO_x may be covered by ($C_xH_yOHOH_yH_2O$ ≥3nm) and dust.

$$R^{PH}_{res}(T,\omega)=\{e\mu_0\omega\lambda_{BCS}(T)\min[l,\lambda_{BCS}(T)]n^2_L/v_F\}^2/\rho v_T \quad (2a)$$

with ρ as density, with v_T as transversal sound velocity and with l_s~3nm as surface mean free path of Nb causing *$R^{PH}_{res}\le10^{-9}\Omega(f/GHz)^2$ by phonon generation*. At *Nb_2O_5 serrations in Fig.1* n_L cause weak links (WL) losses

$$R^{WL}_{res}(T,\omega)\ge1n\Omega(f/\text{GHz})^2 \quad (2b)$$

being obvious in cold worked or thin film Nb cavities [4a,8]. Field dependent losses $R^H(T,H)$ can be written as Taylor series with the *first two terms named MFQ*

$$\delta R^B= R^1_{hys}(T,\omega)H/H_c + R^H(T_0,\omega,H)\gamma(T)(H/H_c)^2+ \quad (3a)$$

by Josephson fluxons penetrating fast above H_{c1J} into WLs yielding the *fluxoid hysteric losses* $R^1_{hys}(T,\omega)$ $H/H_c=4/3\pi\omega|H-H_{c1J}|/2j_{cJ}(T)2\lambda(T)$ [2b,3,5,8]. As consequence R^{WL}_{res} and R_{hys} *heat the surface* enhancing γ

$$R_{BCS}(T+\Delta T)=R^HH^2/2\{1+\gamma^*(T)(B/0.2T)^2+\cdots\} \quad (3b)$$

According to [5] HFQ is based on pair breaking caused by Ecosωt with E>MV/m acting at localized states n_L in Nb_2O_5 with an energy gain 2zE>1meV above the energy gap $2\Delta^*$ being described quantitatively by

$$R^E(E)=b_sB^2/E^2s(-c/E,-c/E^0)\sim b^*(\exp(-c/E)-\exp(-c/E^0)) \quad (4)$$

being dominated by crystallographic shear planes (CS) bordering crystallographic blocks (CB) with their low Φ_S=0.1eV, i.e. κ_S = 1.6/nm, yielding $c_S = 2\kappa\Delta\varepsilon_r/e\beta^*$= 130 - 400 MV/m by Δ ~ 1.5 meV and by ε_{rS} = 20 [5,10a]. In contrast to the qualitative model in [2b] the pair breaking ezE≥Δ is treated in [5] yielding the *HFQ source term $b_ss(E)$,* feeding the *HFQ valve* and *HFQ-BCS loss terms* the latter defines Q_0. In Figs.2 Q_0 drops by more than a factor 10 without rf break down by l_{in}>mm of BCS

EXPLORATION OF VERY HIGH GRADIENT CAVITIES *

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Abstract

Several of the 9-cell ILC cavities processed at Jefferson Lab within ongoing ILC R&D program have shown interesting behavior at high fields, such as mode mixing and sudden field emission turn-on during quench. Equipped with thermometry and oscillating superleak transducers (OSTs) system for quench detection, we couple our RF measurements with local dissipation measurements. In this contribution we report on our findings with high gradient SRF cavities.

INTRODUCTION

Within ILC R&D yield study five 9-cell cavities produced by Research Instruments have been processed and tested at Jefferson Lab. All cavities passed ILC specification for vertical acceptance test after the second pass. In Fig. 1 we plot Q_0 vs $E_{\rm acc}$ for all five cavities at $T_{\rm LHe\ bath}$ = 2.0 K. The highest gradient was reached in TB9RI027, which was limited at $E_{\rm acc}$ = 43 MV/m at 1.8 K with quality factor above 10^{10}(not shown in the figure).

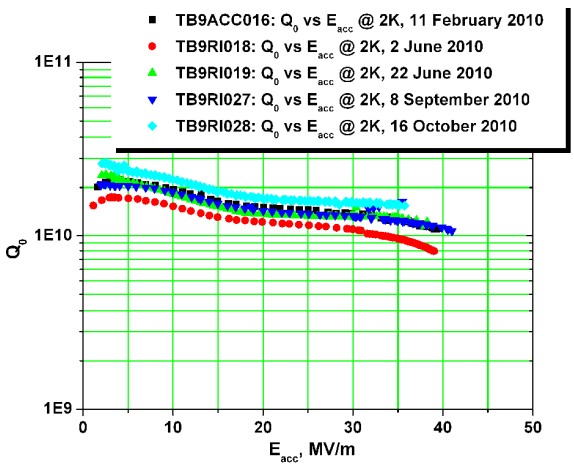


Figure 1: Q_0 vs $E_{\rm acc}$ for five RI cavities tested at Jefferson Lab in 2010 are plotted in this picture. All cavities met ILC vertical acceptance test specification.

All cavities have shown field emission, which rose above background noise of $1{\cdot}10^{-2}$ mR/h at $E_{\rm acc} \cong 25$ MV/m. In Fig. 2 we plotted radiation vs accelerating gradient measurement results.

Several interesting phenomena were recorded during these acceptance tests. In TB9RI019 and TB9RI027 we observed spontaneous pass-band mode excitation during π-mode measurements at high fields.

We also observed a sudden field emission turn-on in TB9RI027 at high fields, which degraded performance of the cavity. This event was recorded with our 2-cell thermometry cell. In this contribution we summarize our observations of these high field phenomena in SRF cavities.

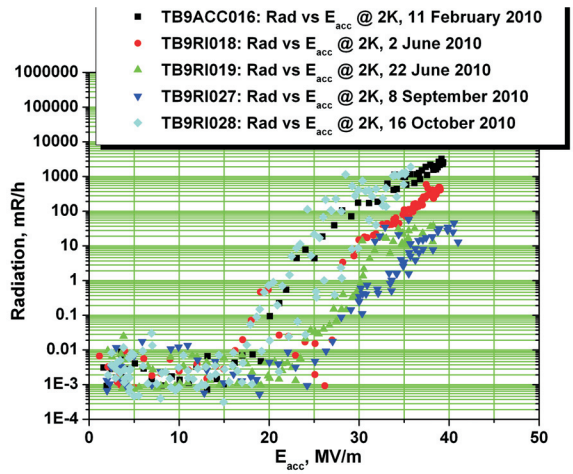


Figure 2: Radiation as function of field for five RI cavities tested at Jefferson Lab in 2010 is plotted in this figure. All cavities have shown field emission above $1{\cdot}10^{-2}$ mR/h noise floor at accelerating gradients above 25 MV/m.

SPONTANEOUS MODE-MIXING

Sponteneous mode excitation has been observed in 9-cell ILC cavities in many labs [1], [2], [3]. We observed mode mixing during RF tests of TB9RI019 and TB9RI027. Both cavities had field emission above 1 mR/h, when mode-mixing was observed.

During TB9RI019 π mode measurement we observed appearance of the $7\pi/9$ mode on the spectrum analyzer screen above $E_{\rm acc}$ = 31 MV/m. Below $E_{\rm acc}$ = 31.5 MV/m an equilibrium with both modes present could be achieved and the cavity was not quenching with both modes present. Above $E_{\rm acc}$ = 31.5 MV/m the growing $7\pi/9$ pass-band mode will eventually cause cavity to quench. We recorded the time it took for the second mode to appear on spectrum analyzer screen above noise floor of -80 dBm. In Fig. 3 we plotted this time as well as the time it took the cavity to quench due to mode-mixing above 31 MV/m.

During TB9RI019 testing, mode mixing was also observed for $4\pi/9$ and $2\pi/9$ modes measurements. During $4\pi/9$ mode measurement, spontaneous excitation of $3\pi/9$, $5\pi/9$, and π was observed. During $2\pi/9$ mode measure-

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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STUDY OF TRAPPED MAGNETIC FLUX IN SUPERCONDUCTING NIOBIUM SAMPLES

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Abstract

Trapped magnetic flux is known to be one cause of residual losses in bulk niobium SRF cavities. In the Meissner state an ambient magnetic field should be expelled from the material. Disturbances such as lattice defects or impurities have the ability to inhibit the expulsion of an external field during the superconducting transition so that the field is trapped.

We measured the fraction of trapped magnetic flux in niobium samples with different treatment histories, such as BCP and tempering. The differences between single crystal and polycrystalline material as well as the influence of spatial temperature gradients and different cooling rates were investigated. In addition, the progression of the release of a trapped field during warm up was studied.

INTRODUCTION

The surface resistance defines the dissipated power in an SRF cavity. It consists basically of two contributions. The BCS contribution described by the BCS theory decreases exponentially with temperature and depends additionally on the operating frequency.

In addition to the BCS contribution there is a residual resistance which is temperature independent. At a typical operating temperature of 2 K, the residual resistance accounts for 10 to 30 % of the total surface resistance [1].

SRF cavities are operated in the Meissner state so an external magnetic field should be expelled from the material. Imperfections of the crystal lattice like impurities, dislocations and grain boundaries have the ability to suppress the expulsion of magnetic field during the superconducting transition. The field remains in the material even after switching off the source of the external magnetic field.

This trapped field penetrates the material in the form of flux tubes which have a normal conducting core. The unpaired electrons in this normal conducting areas cause an ohmic resistance and therefore account for the (residual) surface resistance.

The residual resistance increases linearly with the trapped field and depends on the operating frequency:

$$R_{\mathrm{res}} = \alpha H_{\mathrm{trap}} \sqrt{f/\mathrm{GHz}} \qquad (1)$$

α describes the sensitivity of the surface resistance on the trapped field. It has to be determined experimentally, e.g. reference [2] found $\alpha = 2.2 \frac{\mathrm{n\Omega}}{\mu\mathrm{T}}$.

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At 1.3 GHz the additional surface resistance due to trapped flux would be 125 nΩ if no magnetic shielding is provided and the earth magnetic field of about 50 µT is trapped completely. In the early 90's, Vallet et al. already measured 100 % flux trapping when exposing niobium to external fields up to 300 µT [3].

At 2 K and 1.3 GHz, the surface resistance can be as high as 15 nΩ [4]. If a magnetic shield with 95 % efficiciency is used, then the earth's field would account for nearly half of this residual resistance (6.3 nΩ).

The flux trapping mechanisms are predominantly studied in the Shubnikov phase of type II superconductors where it is energetically favorable when an ambient magnetic field penetrates the material. In the Shubnikov phase the magnetic field forms a hexagonal lattice of quantized flux tubes. A lot of calculations where done, estimating the interaction between the flux tube lattice and the variation in the lattice defects distribution. Pinning forces of different kinds of pinning centers, the interaction between the flux tubes themselves as well as the coexistence of normal conducting and superconducting areas (*intermediate state*) are subjects of the recent studies. An overview on these topics can be found in reference [5].

The goal of these experiments was to study the flux trapping (in the Meissner phase) in representative niobium samples to better understand the impact of treatment history and operating conditions on flux trapping.

Moreover, past measurements suggest that thermal gradients will generate currents by the Seebeck effect whose magnetic field can be trapped during the superconducting transition [6]. A further goal of these measurements was to study this effect in more detail.

EXPERIMENT

Set-up

We constructed a scanning device capable of generating trapped flux in niobium discs and scanning the field with the niobium in the superconducting state. The setup was installed in the HoBiCaT facility [7].

Figure 1 shows the top view onto the sample holder made from copper. The niobium samples are located under the rectangular copper covers. It provides four sample positions and is cooled to 6 – 8 K.

Two heater foils serve as heat sources in order to quickly cycle the samples between normal and superconducting state without warming up the whole cryostat.

NOVEL DEFLECTING CAVITY DESIGN FOR eRHIC*

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Abstract

To prevent significant loss of the luminosity due to large crossing angle in the future ERL based Electron Ion Collider at BNL (eRHIC), there is a demand for crab cavities. In this article, we will present a novel design of the deflecting/crabbing 181 MHz superconducting RF cavity that will fulfil the requirements of eRHIC. The quarter-wave resonator structure of the new cavity possesses many advantages, such as compact size, high R_t/Q, the absence of the same order mode and lower order mode, and easy higher order mode damping. We will present the properties and characteristics of the new cavity in detail.

INTRODUCTION

In the past few years, the application of deflecting cavities has extended to a wide range of projects and facilities [1, 2, 3]. As the accelerator systems grow in complexity, developing compact and efficient deflecting cavities is of great interest [4]. Such cavities will benefit situations where the beam line space is limited.

The future linac-ring type electron-ion collider requires implementation of a crab-crossing scheme for both beams at the interaction region. The ion beam has a long bunches and high rigidity. Therefore, it requires a low frequency, large kicking angle deflector. The frequency of the deflecting mode for the current collider design is 181 MHz, and the deflecting angle is ~5 mrad for each beam.

At such low frequency, the previous designs of the crab cavities will have very large dimensions, and also will be confronted by typical problems of damping the Lower Order Mode (LOM), the Same Order Mode (SOM), and as usual, the Higher Order Modes (HOM).

In this paper we describe how one can use the concept of a quarter-wave (QW) resonator for a deflecting/ crabbing cavity, and use its fundamental mode to deflect the beam. The simplicity of the cavity geometry and the large separation between its fundamental mode and the first HOM make it very attractive.

CRAB CAVITY CONCEPT

The QW crab cavity concept is shown in Figure 1. As the major drawback of a simple QW crab cavity is residual acceleration, the idea in the proposed design is to add a coaxial stub opposite to the main coaxial line to symmetrize the longitudinal field on beam axis and thus eliminate acceleration.

*Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE.
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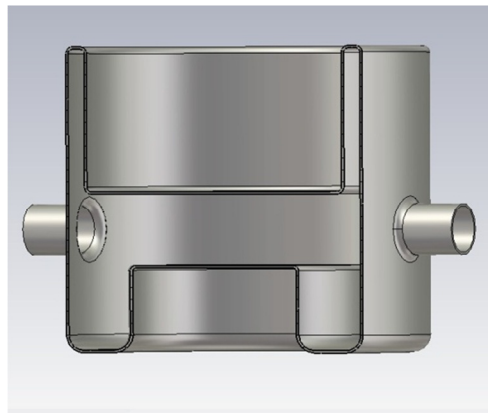


Figure 1: Concept model of QW crab cavity.

Figure 2 shows the electric field of the fundamental (deflecting) mode in the cavity symmetry plane. As the beam passes the cavity, the deflecting field in the gap interacts with the particles as a pair of parallel plates. The longitudinal electric field have large non-zero components near the beam pipes while the center of the cavity is dominated by transverse electric field.

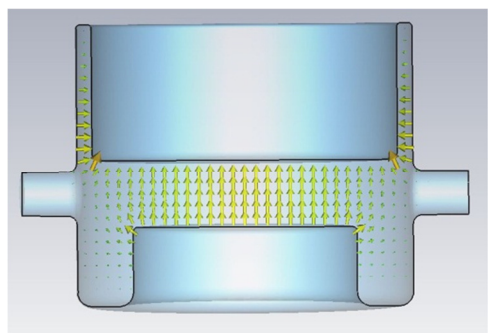


Figure 2: Electric field of the fundamental mode in the symmetric plane.

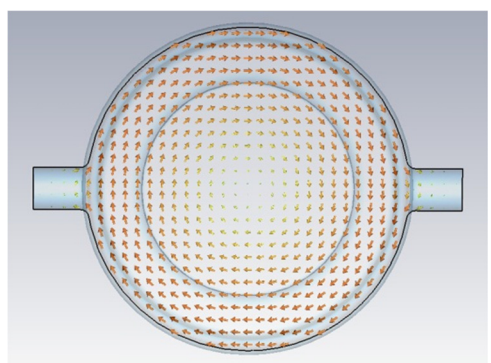


Figure 3: Magnetic field of the fundamental mode in the top view.

POST-BAKING LOSSES IN ELECTROPOLISHED NIOBIUM CAVITIES: CUTOUT STUDIES

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Abstract

Recent technological advances in superconducting RF (SRF) niobium cavities allowed reaching highest gradients by mitigating the high field Q-slope (HFQS) using the combination of electropolishing (EP) and a 120°C vacuum baking for 24-48 hours. When the high field Q-slope is removed, the hard limit to the achievable accelerating gradients in state of the art cavities is set by the localized quench at surface magnetic fields of 120-200 mT. Nevertheless, localized anomalous losses of different character do still show up in cavity walls, and may lead to the quench at surface fields lower than theoretically possible to sustain. In this contribution we present the first direct study of cavity cutouts representing these lossy areas as well as the quench location in the EP-treated niobium cavity with no HFQS limited by localized quench. Surface studies of cutouts allowed to correlate the post-baking losses with dendritic surface features on the inner cavity surface. The nature and possible origins of these objects is discussed in the context of cavity surface treatments. Possible sources of the high field quench at the corresponding cutout are investigated as well.

INTRODUCTION

Superconducting radio frequency (SRF) cavities serve as primary particle accelerating structures in many modern accelerators as well as are a technology of choice for several future accelerators. Intense research in recent years has been focused on understanding and overcoming limitations on the way to achieve higher accelerating gradients such as the high field Q-slope and quench. Among different experimental techniques a very powerful approach is provided by using temperature mapping of outside cavity walls during RF tests. Temperature maps allow identifying areas of different dissipation as well as localizing the quench site. Subsequent cutting out areas of interest and subjecting them to extensive surface analytical and superconducting measurements makes possible identifying the differences in near-surface properties leading to different RF dissipation. Such studies have been performed on the high field Q-slope cutouts [1, 2, 3, 5, 6] and low field quench sites [7]. Yet none of the cutout studies have been reported so far on the high field quench and post-baking dissipation, which is currently the practical limit in SRF cavity performance.

We pursued the cutout approach on the mild baked EP niobium cavity free of the high field Q-slope and limited by the localized quench at the peak surface magnetic field of 160 mT.

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EXPERIMENTAL

RF Test and Cutout Procedure

An elliptical single cell TESLA shape 1.3 GHz niobium cavity of 2.8 mm wall thickness and 50 μm grain size manufactured by AES was subjected to 105 μm buffered chemical polishing (BCP) followed by 65 μm electropolishing (EP), 120°C vacuum baking for 48 hours and high pressure water rinsing (HPR) before RF tests. The final RF test of the cavity was performed at Jefferson Lab with the temperature mapping system of 576 thermometers attached to the outside cavity walls registering local temperature increase with respect to the bath temperature sensor. The detailed design of the system is described in [8]. The measured quality factor dependence on the peak surface magnetic field at $T = 2\ K$ is shown in Fig. 1. The maximum

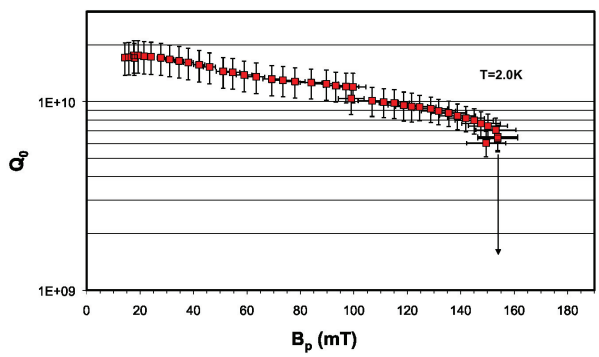


Figure 1: The quality factor Q_0 of the cavity plotted against the peak surface magnetic field H_{peak} as measured during the RF test.

surface magnetic field was limited by the localized quench at about 160 mT. Temperature maps obtained just before and right after quench are showed in Fig. 2.

Based on these temperature maps three different kinds of locations were identified: (i) exhibiting strong RF losses (black circles in Fig. 2a), (ii) exhibiting weak losses (blue circles), and (iii) the quench site (black circle in Fig. 2b).

Circular samples of about 1 cm in diameter were extracted from the selected locations using the automated milling machine with no lubricant to prevent possible contamination. The rotation speed of the milling tool was kept

QUENCH STUDIES IN LARGE AND FINE GRAIN Nb CAVITIES*

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Abstract

Quenches without radiation are sometimes observed at accelerating fields between 25 and 40 MV/m in niobium SRF cavities. The cause for this limitation is not well understood. This work presents results from vertical tests of seven 1.3 GHz single-cell cavities performing above 25 MV/m. Studies were carried out on both fine grain and large grain cavities in ILC and Cornell Reentrant shape geometries. The quenches were located by triangulation using Cornell oscillating superleak transducers and then cavities were optically inspected to determine the surface conditions of the cavity at the quench location. Optical inspection images are presented as well as 3D recreations of quench spots generated using a surface mold and a confocal microscope.

INTRODUCTION

Over the years of SRF development, several different limitations of accelerating gradient in niobium cavities have been encountered, studied, explained, and mitigated. However, the cause of quenches without radiation at fields between 25 and 40 MV/m is not known, and finding a way to avoid such quenches would be highly beneficial to routinely achieving high gradients. This paper presents preliminary results of an investigation into these types of quenches.

CAVITY TESTS

Vertical tests were performed on seven different 1.3 GHz single-cell cavities. The properties of the cavities, their preparation, and their test results are summarized in Table 1.

The Q vs E curves of the cavity tests are shown in Figure 1 for the tests at 1.4 K and in Figure 2 for the test at 1.6 and 1.8 K. NR1-3 experienced some conditioning at low and mid fields. It still showed radiation above background near the quench field, but the quality factor remained above 1×10^{10} without strong Q-drop, indicating that the quench was likely not caused by field emission.

OPTICAL INSPECTION PHOTOS

Optical inspections were performed over the entire heat affected zones of the cavities, not just the quench spots. Any defects—especially near the equator—were noted.

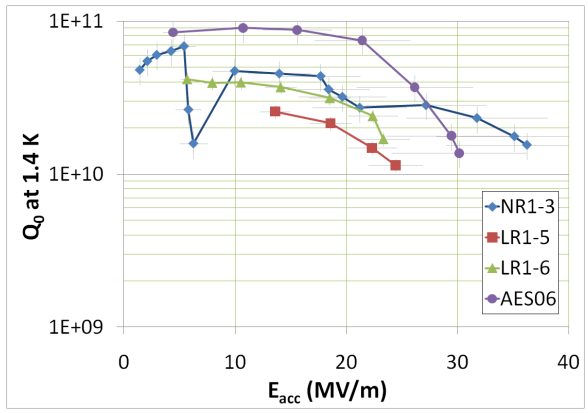


Figure 1: Q vs E curves of cavities tested at 1.4 K.

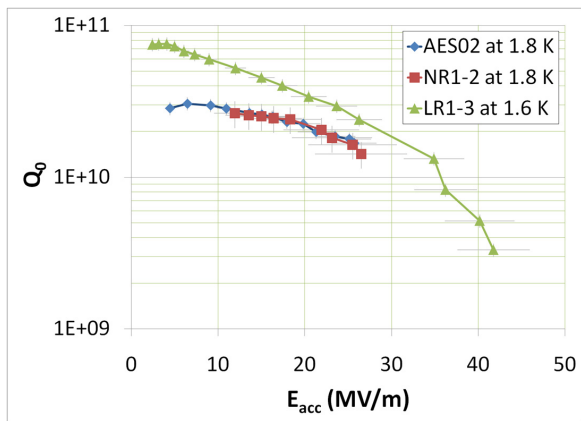


Figure 2: Q vs E curves of cavities tested at 1.6 and 1.8 K.

The optical inspection system consists of a camera connected to a telescope, which is focused on a mirror with LED lights around it, tilted at 45 to the vertical, suspended inside the cavity. The cavity is rotated and translated by hand, and pictures are taken using a computer remotely controlling the camera. The setup is shown in Figure 3.

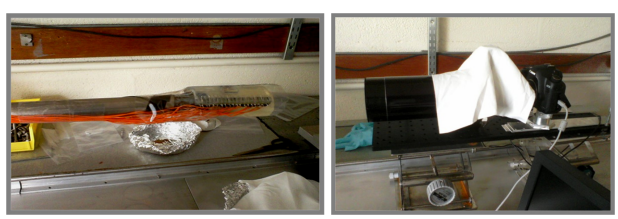


Figure 3: Optical inspection system light and mirror (left) and camera and telescope (right).

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MULTIPACTOR STUDIES FOR DIAMOND STORAGE RING CAVITIES

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Abstract

The Diamond storage ring is presently operating with two CESR type Superconducting (SC) RF cavities operating at 499.654 MHz. The cavities are suffering from a significant number of trips due to a sudden loss of accelerating field believed to be caused by multipacting. It is observed that operating the cavities at lower voltages reduces the trip frequency significantly. In order to estimate the multipacting thresholds and to determine safe (multipactor free) parameter zones, we have initiated a detailed simulation study of multipacting in the cavities and the coupling waveguide. The cavities have fixed coupling, and therefore the match of the cavities varies with beam current, radiation loss and cavity voltage. A change in any of these parameters leads to a different standing wave in the waveguide. This requires the simulations to account for the different operating conditions. In addition to the waveguide and the cavity cell, the simulations also indicate the possibility of multipactor in the connecting beam tubes. In this paper, we summarise the results of our simulations obtained using CST Studio PIC and Tracking solvers.

INTRODUCTION

Diamond has suffered with frequent trips interrupting beam operation. The trips result in a sudden loss of accelerating field followed by a large pressure spike observed on the gauges placed on the beam pipes and in the vicinity of the RF window (PO Box). Despite regular cavity conditioning [1], the trip rate remained unacceptably high, so we initiated a detailed multipactor simulation study of the cavity and the waveguide.

The Diamond cavities are single cell elliptical cavities with relatively large diameter beam tubes to facilitate the propagation of the HOMs to loads mounted outside the cryostat. The RF power is transmitted through rectangular waveguide WR1800. Inside the cryostat, the height of the waveguide is reduced. The reduced height waveguide on the cavity end opens up in the RBT and couples RF power into the cavity through a specially shaped iris (with a protrusion from the broad wall known as the 'coupling tongue') as shown later in Fig. 9. Figure 1 shows the RF cavity and its different parts as modelled in CST Studio [2]. The niobium parts are shown in a bluish colour. The stainless steel thermal transitions and the reduced height waveguide is copper plated to reduce the RF losses. These parts are shown in a reddish colour. The RF window and the rest of the waveguide are shown in grey.

Like other SC cavities, the Diamond/CESR cavities are elliptically shaped to reduce the possibility of one point or single surface multipacting in the main cavity body. Secondary electrons, generated at the high E field locations, drift towards the equator of the cavity due to the varying magnetic field along the cell wall losing energy on successive impacts. The E field vanishes at the equator, reducing the energy gain by the secondary electrons to a minimum and thus arresting one point multipactor [3]. However, there is still a significant possibility of two point multipacting in elliptic cavities near the equator [4]. Though the electric field vanishes at the equator, the strong magnetic field near the equator bends the path of the electrons causing them to strike the cavity surface on either side of the equator, where the surface electric field is non-zero and its amplitude is in the range favourable for MP to take place.

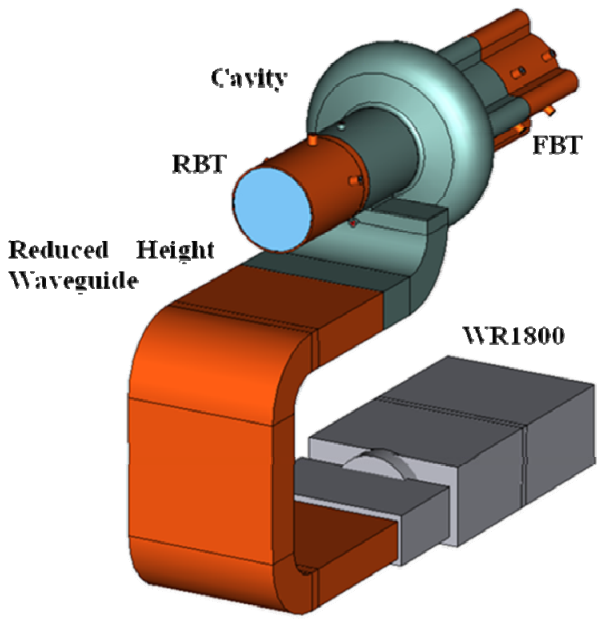


Figure 1: The Diamond storage ring cavity and the coupling waveguide as modelled in CST Studio.

In addition to the main cavity body, the other regions, where multipacting can be suspected to occur, are the reduced height waveguide, the region around the coupling tongue and the beam tubes. Multipacting in the reduced height waveguide has been studied at Cornell and at Daresbury Laboratory [5,6]. As a result of these studies, certain remedies were suggested to reduce the multipactor in the waveguide [7]. These include coating the waveguide with TiN, longitudinal grooves and ridges in the centre of the waveguide broad wall and the use of a longitudinal DC bias magnetic field, to distort the path of the multipacting electrons. Waveguides with single and multiple grooves were investigated and it was found that these can reduce the multipactor saturation current and decrease the growth rate but they cannot prevent it.

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IMPROVING THE INTRINSIC QUALITY FACTOR OF SRF CAVITIES BY THERMAL CYCLING

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Abstract

We investigated the influence of the cooling gradients near the critical temperature T_c on the obtained intrinsic quality factor Q_0 of a TESLA cavity. Measurements were performed in the HoBiCaT test stand by briefly warming the cavity above T_c via He depletion inside the cryovessel and subsequent cooling. The temperature was measured at different points at the cavity and the cryo-tank. It turned out that there is a correlation between obtained Q_0 and the time lag between the first and the last transition of any sensor through T_c. This is interpreted as a spatial gradient. We have observed no correlation to the cooling speed, i.e. different temperature gradients in time. The findings could help explain the large fluctuations in measured Q_0 values in different test-stands. They could open up pathways to devising a cooling scheme to consistently obtain high residual Q_0 values.

INTRODUCTION

The RF-surface resistance of niobium is determined by two contributions: The BCS-resistance R_{BCS} [1] and the residual resistance R_{res}. The intrinsic quality factor Q_0 of a resonator made from this material is given by $Q_0 = G/(R_{\mathrm{BCS}} + R_{\mathrm{res}})$, with a material-independent geometry-factor G. While the BCS-resistance is pure physics, well defined and unavoidable, the residual resistance R_{res} is a matter of materials science and influenced by various material and operational parameters, like the RRR-value of the material, crystallinity and mosaicity, grain boundaries, lattice mismatch, inclusion of foreign atoms, like oxygen or hydrogen, surface smoothness, etc.

As a second effect, an ambient magnetic field that is present during the superconducting transition can be collimated at a region that remains normal conducting and continue to exist there at a local strength of above H_{c1}. Here, the Meissner-effect results in a remanent magnetisation by bunches of flux lines distributed over the cavity wall. Even after further cooling and reducing the external magnetic field these field lines can remain in place because the super-currents that maintain the flux cannot penetrate the normal conducting region (flux pinning). Hence, under realistic operating conditions, after cool-down vortices of flux are distributed over the cavity surface, although it would be energetically more favorable for it to be field-free. The movement of these vortices in the RF-field is a dissipative process that contributes to the residual resistance. Since the flux-pinning is assumed to be getting weaker towards higher temperatures, we have investigated if and how heating up the cavity near T_c can be utilized to get rid of frozen flux.

EXPERIMENTAL PROCEDURE

Experiments were carried out with a TESLA type cavity installed in the horizontal cavity testing facility HoBiCaT[2] at HZB. Cernox thermal resistors were placed at the Helium inlet of the titanium tank and the conical end pieces, the beampipes and the end flanges of both ends of the cavity as illustrated in Figure 1.

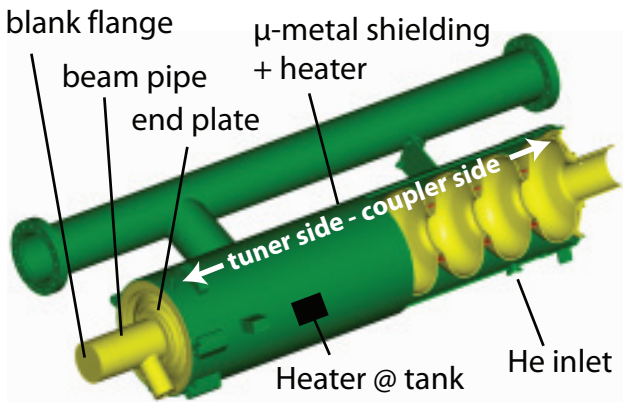


Figure 1: Placement of Cernox thermosensors and heater on the cavity tank.

All temperatures were monitored over time on a 1 second basis. Q_0 measurements were performed at critical or close-to-critical coupling.

The main objective of the measurements was to observe the influence of cool-down conditions on the achieved quality factor. For this, a thermal cycling was performed on the cavity, heating it slightly above T_c and cooling it down again in a controlled and reproducible manner. This was done by evaporating the liquid Helium from the cavity tank with a heater and closing the Joule-Thompson valve for the Helium supply. The Helium pumps were left running so Helium was slowly removed from the system. This procedure leads to a rapid temperature rise once all Helium is used up, which should be avoided, so the timing is rather critical. Depending on the duration of the cut in Helium supply and the used heater power, very different temperature profiles of the cavity could be established, some of which are exemplarily depicted in Figure 2. One entire cycle took approximately 4 hours before the cryosystem was once again stable enough to perform Q_0 measurements. Note that the cavity temperature always remained

INFLUENCE OF FOREIGN PARTICLES ON THE QUALITY FACTOR OF SUPERCONDUCTING CAVITIES*

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Abstract

The quality factor of superconducting (SC) cavities of the Cornell Energy Recovery Linac (ERL) Injector measured in its horizontal cryostat appears systematically lower than in vertical tests. Furthermore, this lower value of the Q factor is scattered in a range of about ±50%. A similar Q degradation has been observed in many accelerators. Here, an explanation of these effects is presented taking into account contamination of the cavities by microscopic particles of ferrite used in the higher order mode (HOM) loads and other particles present in the vicinity of cavities during assembly of the horizontal cryostat. The average Q degradation and the scatter of Q values are used to estimate the size and the number of contaminants per cavity. We also analyze, which materials have relevant contaminants.

INTRODUCTION

Assembly of the SC niobium injector cavities [1] of the Cornell ERL [2] proceeds in a Clean Room of class 100, i.e. the number of particles of size 0.5 μm or larger permitted per cubic foot of air is 100. One cannot avoid all foreign particles in the cavity volume and some particles will settle down on the cavity walls. However, a class 100 Clean Room seems adequate because in most of the experiments the values of the Q factor are close to theoretical values.

In the ERL Injector Cavities a degradation of Q has appeared three times after successful tests in a vertical test cryostat: once in a horizontal test cryomodule (HTC) and twice in the Injector Cryomodule (ICM) incorporating the whole injector string of 5 cavities with their couplers and 6 HOM loads. The first observation of a low Q was in the HTC [3] when the cavity intrinsic quality factor of $\approx 1.5\times10^9$ was measured at 1.8 K, about one order of magnitude below the expected value. One cavity only was tested in the HTC but this was a "fully dressed" cavity with two HOM loads and two symmetric input couplers. In this case, a contamination of the cavity occurred when two ferrite tiles fell off and broke into pieces during cool down; as revealed after opening the HTC. More attentive study of the surfaces of survived tiles detected microscopic cracks that can be a starting point for further contamination or at least of dust development.

Following the full system test of a single cavity HTC, the full ERL injector SRF cryomodule has been fabricated and assembled. The broken tiles in the damaged HOM load were replaced by tiles of the same size but made of one of two other RF absorbing materials used in the loads [4]. However, all 5 cavities also have shown intrinsic quality factors below 10^{10} at 2 K even at low fields [5]. Two measurements of the effective Q of all 5 cavities operated together, spaced in time by several months, showed a further reduction in the quality factors. After deflection of the beam showed that absorber tiles charge up at low temperatures [6], the absorbers were further altered.

The absorbing tiles in the HOM load are placed on two sides of a plate; one side is faced to the axis of the beam pipe, the other side to bellows on the outer wall, see Fig. 1 (top).

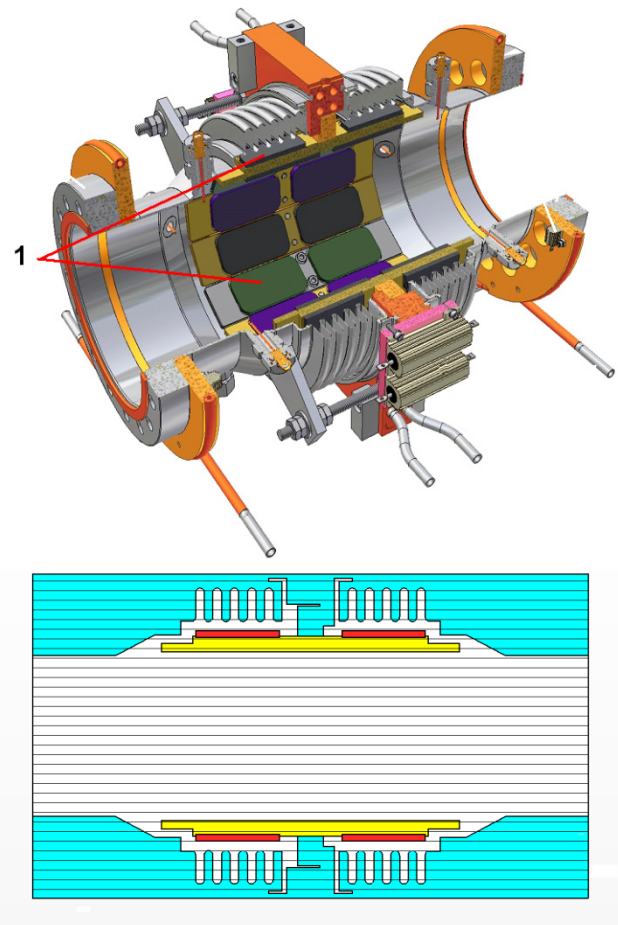


Figure 1: HOM load. Top: 1 – absorbing tiles on both sides of plate. Bottom: MWS model of the load without inner tiles.

In the latest, second cool down of the ICM [7], to prevent charging, the tiles of absorbers were left on the outer side of the plates only, see Fig. 1 (bottom). Extreme precautions were taken to clean cavities, HOM loads, and other components, more accurate measurements of Q of each cavity were done: in the vertical and horizontal (in the ICM) tests, see Table 1.

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INVESTIGATION OF 9-CELL CAVITY PERFORMANCE PROBLEM BY FACILITIES IN KEK AR EAST 2ND EXPERIMENTAL HALL

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Abstract

In this half of year, our 9-cell cavity performance often suffered from field emission. We investigated our facilities in the KEK AR East 2nd experimental hall. Particle contamination problem was found in our HPR system, cavity assembly and vacuum evacuation procedure. We took cures for these problems. Field emission problem has reduced remarkably after these cures. We will report about these problems and cured results on cavity performance in this paper.

MOTIVATION

We are developing an alternative high gradient cavity for ILC 1TeV energy upgrade, applying Ichiro shape instead of TESLA one. Currently we have achieved the ILC alternative configuration design goal: 40MV/m @ Qo=8E+9 on the Ichiro 9-cell cavity as seen in Fig.1 right bottom, which was done by KEK/Jlab collaboration. More information is in the reference [1].

However, as seen in Fig.1, since last October 2010, Ichiro 9-cell cavities tested in KEK are limited to the gradient lower than 20MV/m. I9#11 in the 2nd and 3rd tests, which is made of large grain niobium material, was limited by hard quench due to less material removal (60μm by BCP). Centrifugal barrel polishing, which is our standard procedure prior to EP or BCP, did not take place for this cavity. In the I9#11 3rd VT, rinsing was strengthened around end group by adding steam cleaning and wiping before HPR. The amount of X-ray reduced very much by these methods, that suggests the strengthened end group cleaning is effective to suppress field emission. However, other most cases were limited by field emission.

Our concern is the onset of X-ray. X-ray starts from 10 -15 MV/m at all KEK tests in Fig.1. In the single cell cavity test, we have often observed the X-ray onset around 20MV/m initiated by Multipacting (two point first order) but the 10 - 15MV/m X-ray onset is too low. The I9#7 result shown in Fig.1 right bottom, on which all preparations including EP were done in Jlab. In this case, X-ray onset is around 15MV/m. This onset is lower than that of ILC baseline cavity (TESLA shape) treated and tested in Jlab. The amount of X-ray is also more serious in I9#7 than that of ILC cavity in Jlab.

Our most concerns are 1) why the X-ray onset is so low in our recent test, 2) why the amount of X-ray is so serious in our test. We started to suspect our facility. We have investigated our facility to look for the answer from particle contamination point of view.

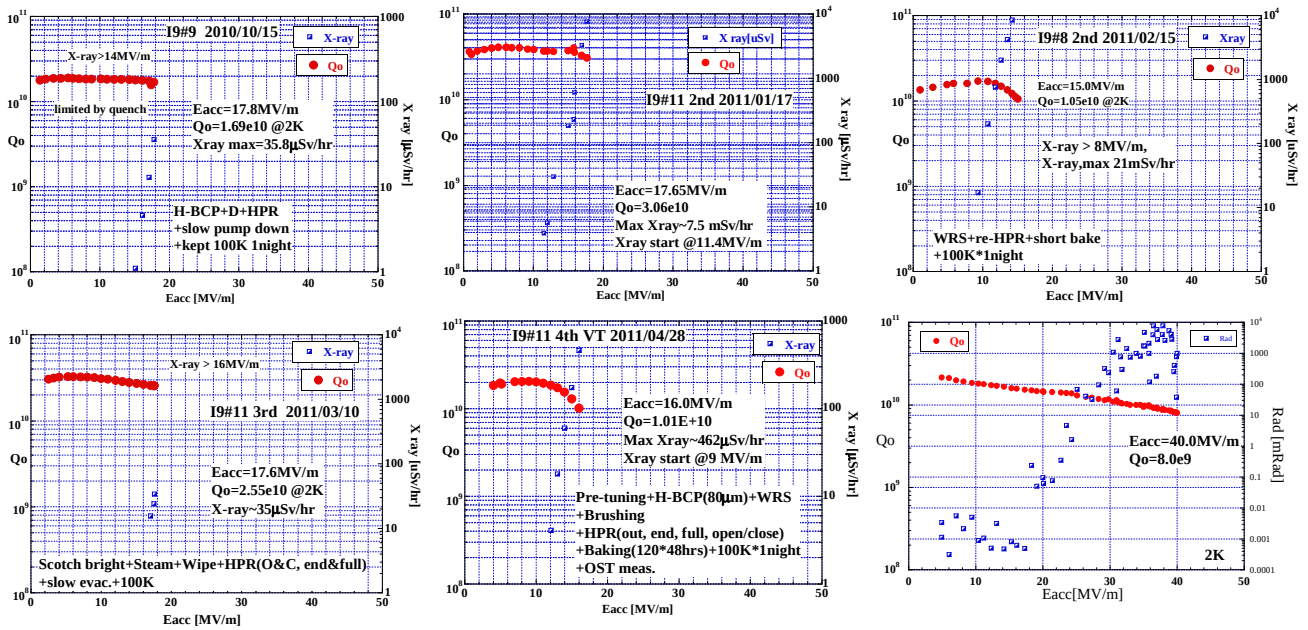


Figure 1: Vertical test results of Ichiro 9-cell cavities at AR East 2nd experimental hall (Top three and Left two) and the result of Ichiro #7 electropolished and VT tested in Jlab.

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REPAIR SRF CAVITIES BY RE-MELTING SURFACE DEFECTS VIA HIGH POWER LASER TECHNIQUE

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Abstract

As field emission is gradually under control in recent SRF activities, cavity performance is limited by hard quench in most cases. Surface defect has been identified as one of main sources caused cavity quench, scattering cavity accelerating gradient from 12MV/m to 40MV/m. Laser re-melting technique is able to re-shape sharp pit rim to be a flat and smooth surface. In Fermilab, a sophisticated laser repair system has been developed for 1.3GHz quench-limited cavities. A pit in a 1.3GHz single-cell cavity was re-melted by high power laser pulse, after the laser processing the cavity took 30μm light Electropolishing. The cavity gradient achieved 39MV/m in initial run; after another 30μm Electropolishing, it reached 40MV/m. An improved laser repair system, which is able to re-melt surface defects in one meter-long 9-cell SRF cavity, has been developed at Fermilab after the success on single-cell cavity. It successfully re-melted a pit in 9-cell SRF cavity TB9ACC017.

INTRODUCTION

Superconducting Radio Frequency (SRF) cavity is a key component in state-of-the-art accelerators. It has many orders of magnitude higher intrinsic quality factor (Q0) than copper cavity due to extremely low RF loss on cavity wall, thus save cost for RF power in accelerator operation. It reduces total cost of accelerator even accounting refrigerator power which is for liquid helium production. Moreover, the SRF cavity has large beam aperture. It imposes less beam disruption such as energy spread, beam halo, etc; and provides high quality beams for physics research. Therefore SRF technology has been widely used in large accelerator projects and huge amount of high performance SRF cavities are demanded.

Recent SRF cavity performance reports [1, 2] indicate that field emission is gradually under control; and many SRF cavities limited by hard quench. Surface defects e.g. pits, bumps, cracks, scratches, etc., have been identified as a main source quenched cavities at a board spread of accelerating gradient, which is from 12MV/m to 40MV/m. It dramatically decreases reproducibility of cavity RF performance [3], and thus increases the whole accelerator costs.

Computer simulation indicates that magnetic field is enhanced at edge of a defect, which leads to localized heating when the cavity is at high fields. The enhancement factor correlates to sharpness of the defect edge [4, 5]. When the enhanced magnetic field at the defect edge exceeds local critical magnetic field, the edge would transit from superconducting to normal conducting state. This leads to a sudden increase in surface impedance. If the increasing in surface impedance causes the cavity wall temperature to locally exceed the critical temperature, the entire cavity will quench [6, 7]. This conclusion has been experimentally confirmed by using optical inspection techniques [8, 9], replica techniques [10, 11], full t-mapping system [12, 13], and Oscillating Superleak Transducers technique [14].

Therefore, to smooth the sharp defect rim is able to effectively reduce the field enhancement fact. It would improve cavity RF performance as well as reproducibility. Based on this purpose, several cavity repair techniques have been developed by KEK, Cornell University and Thomas Jefferson Lab [15, 16, 17]. These techniques include locally mechanical grinding the defects, tumbling the cavity, re-melting the defect by electron beam.

In this work, we propose to use high power laser pulse to re-melt pits which have shape rim to flat surface. Compared to mechanical grinding and EB re-melting technique, laser technique is able to re-melt flaws within a second in the air. Hence it doesn't need a serial of mechanical heads from the coarsest to finest to grind the flaw step by step, nor is a vacuum system necessary for electron beam. Here we show after re-melting a pit by laser pulse, the cavity accelerating gradient was improved to 40MV/m which is very close to the theoretical limitation of TESLA shape cavity [18].

LASER RE-MELTING SYSTEM

The laser re-melting system developed at Fermilab is aimed to remove flaws which limit cavity below 20MV/m. The accelerating gradient would be restored upon 35MV/m, which is ILC goals representing the highest level in SRF field.

Concerns of system design are how to delivery high power laser beam to pit location through one meter-long and dark cavity. The pit dimension is typically 100-400 μm in diameter and 10-150 μm deep. Therefore a high-resolution CCD camera and a diffusing light are required for tracking pits. A huge amount of oxygen would dissolve in Nb surface if laser processing were implemented in the air without any protection. The thick oxygen layer, causing extra RF surface loss, leads cavity quench at the re-melting spot as well. Thus the molten region needs to be protected by inert gas; here we use high pure Argon gas.

Figure 1 shows the sketch of laser re-melting system. The high power collimated laser beam comes horizontally

PRELIMINARY RESULTS ON THE LASER HEATING INVESTIGATION OF HOTSPOTS IN A LARGE-GRAIN NB CAVITY

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Abstract

Magnetic vortices pinned near the inner surface of SRF Nb cavities are a possible source of RF hotspots, frequently observed by temperature mapping of the cavities outer surface at RF surface magnetic fields of about 100 mT. Theoretically, we expect that the thermal gradient provided by a 10 W green laser shining on the inner cavity surface at the RF hotspot locations can move pinned vortices to different pinning locations. The experimental apparatus to send the beam onto the inner surface of a photoinjector-type large-grain Nb cavity is described. Preliminary results on the changes in thermal maps observed after applying the laser heating are also reported.

CONTRIBUTION NOT RECEIVED

PROBING THE FUNDAMENTAL LIMIT OF NIOBIUM IN HIGH RADIOFREQUENCY FIELDS BY DUAL MODE EXCITATION IN SUPERCONDUCTING RADIOFREQUENCY CAVITIES*

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Abstract

We have studied thermal breakdown in several multi-cell superconducting radiofrequency cavity by simultaneous excitation of two TM_{010} passband modes. Unlike measurements done in the past, which indicated a clear thermal nature of the breakdown, our measurements present a more complex picture with interplay of both thermal and magnetic effects. JLab LG-1 that we studied was limited at 40.5 MV/m in $8\pi/9$ mode, corresponding to B_{peak} = 173 mT in the end cells. Dual mode measurements on this quench indicate that this quench is not purely magnetic, and so we conclude that this field is not the fundamental limit in SRF cavities.

INTRODUCTION

Multi-cell cavities have multiple pass-band modes. The surface field distribution in each cell is the same among all pass-bands, but relative field strengths between different cells vary from mode to mode. Hence, if two pass-band modes in a cell are excited at the same time their vector fields are collinear, however, the field strengths do not sum up coherently, because resonant frequencies vary among different modes.

In 1980 D. Proch exploited this fact to distinguish between thermal and magnetic breakdown in SRF cavities at that time [1]. π and $\pi/2$ modes were excited simultaneously in several 2-cell cavities. By bringing cavities into repetitive quench with varying relative field strengths between two modes, quench dependence on mode mixture was measured. The conclusion was that "The data unambiguously supports the thermal model."

Today elliptical niobium SRF cavities are reaching above bulk lower critical field of niobium, and in a few cases cavities reaching above niobium thermodynamical critical field have been reported. At this point we start asking ourselves if the niobium material finally hit the hard limit, the superconducting critical field, or if the cavities are still limited by a local imperfections on the surface. In order to address this question, we implemented dual mode excitation technique to distinguish purely magnetic quench from other quenches.

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EXPERIMENTAL SETUP

For the dual mode excitation, all the pass-band modes of a cavity are measured first and the maximum gradient for each cell is determined. During pass-band measurements quench locations are measured with OSTs [2] and the cells responsible for quench in each mode are identified. After the data is analyzed, two modes that are quenching on the same defect of interest are chosen.

Drive signals from two independent voltage-controlled oscillators (VCO), each oscillating at one of the modes of interest, with independent phase-lock loops (PPL) are combined with power combiner and fed into power amplifier. From the power amplifier through the conventional RF system, the signal is fed into the cavity via the input coupler. Phase locking is accomplished by splitting transmitted power from the pick-up probe with power dividers and feeding the transmitted signal into respective phase lock loops. Part of the transmitted signal is sampled by the spectrum analyzer.

The spectrum analyzer that we use to measure each field level is calibrated in the following way. Two markers are placed on the respective resonance frequencies and the marker measurement mode is set to band power measurement. The spectrum analyzer is connected to PC via Ethernet cable and a continuous data acquisition with DAQ time of about 5 msec is done. The data is recorded continuously to a file on the computer. One of the VCOs then locked onto resonance frequency, while PPL of the other VCO is open, and the cavity is brought into quench. From the known quench field of this mode, measured earlier during the pass-band measurement, the calibration factor from the spectrum analyzer data to the field level is calculated. The procedure is repeated for the second mode with the other VCO. After the calibration factors have been measured, the both VCOs are locked onto respective resonance frequencies and the dual mode excitation measurements is performed by varying field amplitudes of the pass-band modes.

Fig. 1 shows an example of the measurements. The stored energy rises as a function of time on about 1 sec scale determined by high intrinsic quality factor of the cavity ($\approx 10^{10}$). When the field at the quench location exceeds the critical condition the location becomes normal conducting causing rapid drop in quality factor and energy dissipation on the order of 1 msec. In quench the quality factor of the cavity drops by several orders of magnitude. The resulting mismatch at the input coupler leads to field drop in the

QUENCH STUDIES OF ILC CAVITIES *

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Abstract

Quench limits accelerating gradient in SRF cavities to a gradient lower than theoretically expected for superconducting niobium. Identification of the quenching site with thermometry and OST, optical inspection, and replica of the culprit is an ongoing effort at Jefferson Lab aimed at better understanding of this limiting phenomenon. In this contribution we summarize experiments that have been and are being developed at JLab for quench studies.

INTRODUCTION

ILC project calls for construction of thousands of 9-cell SRF cavities. To make cost of the project financially sound, yield of high performance SRF cavities was set at 90 percent. One of the goals of cavity R&D part of ILC research program is to understand and to mitigate limitations in SRF cavities that inhibit reaching 90 percent yield. ILC R&D have shown that quench is one of the main limitations, and it is especially a typical problem in cavities made by new vendors. Such cavities are limited at 15-25 MV/m and additional chemical polishing has little or no effect. Understanding and mitigation of low field quench is an important part of proving ILC project feasibility.

A number of techniques and experiments have been and are being developed at Jefferson lab for localization, characterization, understanding, and mitigation of quench in ILC cavities. RF measurements along with thermometry, OSTs, optical inspection, high resolution thermometry, and replica profilometry provide non-destructive information about the quench region, whereas experiments such as dual mode excitation, artificial defect investigation, centrifugal barrel polishing, and electron beam re-melting are aimed at understanding and mitigation of the defect. Below we summarize ongoing quench studies at JLab.

QUENCH LOCALIZATION

Quench field analysis of all TM_{010} pass-band modes is a standard procedure at JLab to reduce ambiguity in π-mode quench location to two cells out of nine in a 9-cell ILC cavity. To find the responsible cell and location, two techniques are currently in use at JLab: 2-cell ILC thermometry and second sound detection with oscillating superleak transducers (OSTs).

Thermometry

After the ambiguity of quench location was reduced to two cells via pass-band measurements, JLab 2-cell ILC thermometry [1] is attached to these two cells. Each cell's thermometry has five G-10 boards with 32 Allen-Bradley 100 Ohm thermometers each that cover equator and regions around equator. Typically, during quench event, a heating spot of 4 - 8 thermometers diameter is seen on temperature maps. Analysis of temperature maps allows to identify the location of the quench-inducing defect. In case of type-II quench, we often find no dominating thermometer in the quench region below quench field. In case of type-I quench, a single thermometer in the quench region typically dominates the temperature map below quench field. In this case a clear preheating field dependence of the quench spot is recorded. Fig. 1 illustrates pre- and in-quench temperature maps.

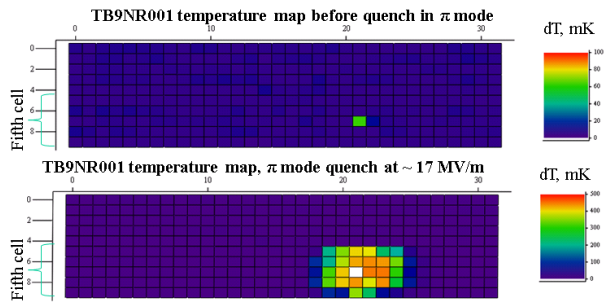


Figure 1: TB9NR001 was limited by a quench in the center cell at 17 MV/m in π mode. In the upper temperature map a single hot spot at the quench location dominates the temperature map below quench field. The lower temperature map was captured in repetitive quench at random quench development stage.

Second Sound Detection

Second sound detection with oscillation superleak transducers is another method put forward recently at Cornell University for quench localization in 9-cell ILC cavities [2]. Second sound detection offers unique advantage over thermometry for quench localization by being shape-independent. Since the technique is not limited by the cavity shape, it can be applied not only to

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DESIGN, CONSTRUCTION, AND INITIAL TEST OF HIGH SPATIAL RESOLUTION THERMOMETRY ARRAYS FOR DETECTION OF SURFACE TEMPERATURE PROFILES ON SRF CAVITIES IN SUPERFLUID HELIUM*

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Abstract

We designed and built two prototype high resolution (0.6-0.55mm spatial resolution [1.1-1.2mm separation]) thermometry arrays out of Allen Bradley 90-120 ohm 1/8 watt resisters to measure local surface temperature profiles on SRF cavities. One array was designed to be physically flexible and conform to any location on a SRF cavity; the other was modeled after the common G-10/Stycast 2850 thermometer and designed to fit on the equator of an ILC (TESLA 1.3 GHz) cavity. We will discuss the advantages and disadvantages of each array and their construction. In addition we will present a case study of the arrays performance on a real SRF cavity TB9NR001. TB9NR001 presented a unique opportunity to test the performance of each array as it contained a dual (4mm separation) defect which conventional methods such as OST (Oscillating Superleak Transducers) and full coverage thermometry mapping were unable to resolve. We will discuss the new arrays' ability to distinguish between the two defects and their preheating performance.

INTRODUCTION

Modern superconducting radio frequency (SRF) cavities for use in particle accelerators are often limited below the theoretical limit by a single defect. There are three common techniques used in the SRF to ascertain the quench location; these include pass band measurements, OST (Oscillating Superleak Transducers) [1], and thermometer mapping [2]. Modern thermometry systems are broken into two categories; fixed thermometry systems [3–6] and rotation thermometry systems [7, 8]. Each system type has its limitation: fixed thermometry for instance have a spatial resolution of about 1 in, yet very sensitive temperature resolution; rotating thermometry systems have in theory infinite latitudinal resolution but low temperature sensitivity. While all these systems can give one the approximate location of the defect, they are not designed to distinguish between closely packed defects or give understanding about the defect in terms of local heat flux and heating profile.

In an effort to gain higher spatial resolution without sacrificing the sensitivity of a fixed system, we designed and tested two prototype high spatial resolution thermometry arrays. These are the first step in moving from a thermometry mapping system to a calibrated calorimetry system which will give us the local heat flux and heating profile of a defect and its exact location. In this paper we describe the design, construction and initial test of two high resolution thermometry arrays, one flexible to fit any radius of a cavity and the second with a fixed radius matching a standard ILC cavity on the equator. Both arrays were able to identify the quench defect in TB9NR001 which had two cat-eye defects 4mm apart, the fixed array showed better thermal isolation, and therefore is a better candidate for calorimetry measurement in the future.

ARRAY DESIGN AND CONSTRUCTION

One of the initial goals of the project was to gain as high a spatial resolution as possible while keeping the (T*dR)/(R*dT)≈4 (1.4 to 4K) comparable with the current thermometry system at JLab [5, 9]. Keeping with the same resistive element, i.e., Allen Bradley 100 Ohm 1/8 watt (AB100Ω) carbon composite resisters was the logical choice.



Figure 1: Preparation of AB100Ω resisters for arrays. The top is the original and the bottom is modified for the arrays. See description in the text.

Preparation of Resisters for the Arrays

In order to archive the smallest possible resolution, the sides of the resistors needed to be ground down (to improve the packing ratio (Figure 1). The grinding was performed using a 3 axis milling machine and a dermal cut off wheel disk. The resistors were held in place with bees wax to reduce stress on the element. One side was then ground flat until the resistive element was exposed; then the wax was

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EXPLORATION OF QUENCH INITIATION DUE TO INTENTIONAL GEOMETRICAL DEFECTS IN A HIGH MAGNETIC FIELD REGION OF AN SRF CAVITY*

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Abstract

A CEBAF shape single cell cavity with four intentional geometrical defects was built at Jefferson lab to research the influence of magnetic field enhancement on the quench initiation of SRF cavity. This cavity has been RF tested with the T-mapping system at Jefferson lab. Experimental result shows that quench location appears at one of the four intentional geometrical defects and preheating phenomenon occurs at all four intentional defects. At all other areas of the cavity, except the four intentional defects, almost no preheating is found. The fabrication procedures and the surface characterization of the four defects, the preheating phenomenon and associated quench initiation analysis of this cavity are presented here.

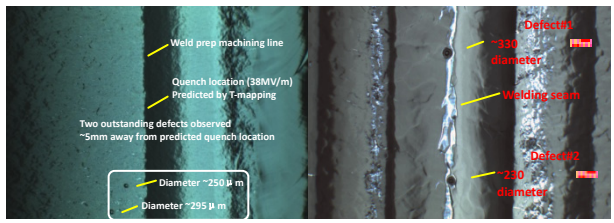
INTRODUCTION

Recent RF tests and surface morphology for a few of nine-cell SRF cavities at Jefferson lab (TB9RI019, PKU2, TB9NR001) show that there are always some geometrical defects near each quench site. The quench location and associated preheating data of these cavities were obtained by T-mapping and OST (Oscillating Superleak Transducers) technique [1-3]. Subsequently, optical inspection of these defects was performed by a high-resolution optical inspection machine ("Kyoto camera" [4]). The inspection shows that most of the defects have the same topographical structure [5]. Further analysis indicates that this kind of topographical structure has a pit-type shape. Subsequently, replica-profilometry technique [6, 7] was used to characterize the profile details of these defects; it also indicates that most of the defects are pit type shape, see the examples in Figure 1.

The quench sites in these 9-cell cavities are all at the EBW (electron beam welding) area, where the magnetic field highest. We assume the magnetic field enhancement of the pit-like defects would contribute to the quench initiation. In order to verify this assumption, one CEBAF style single cell cavity with four intentional geometrical defects was fabricated to research the influence of magnetic field enhancement on the preheating and quench phenomenon in SRF cavities. The experiment results and some preliminary analysis of preheating data are presented here.

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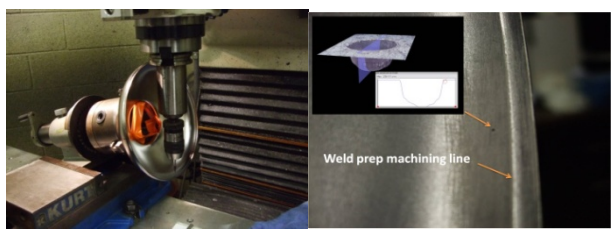
(a) (b)

Figure 1: Defect examples near quench location: (a) nine-cell cavity TB9RI019, two pit-type defects observed ~5mm away from the predicted quench location; (b) nine-cell cavity TB9NR001, two pit-type defects were found near the quench site.

DEFECT FABRICATION

The initial fabrication goal was to make four pits in the cavity without introducing any foreign material. This would ensure the geometrical shape and associated magnetic field enhancement would play the leading role to the RF performance.

The four pits were chosen to be located near the equator area where the magnetic field is highest. The pits were machined by a TRAK DPM3 CNC Mill with a 400 μm diameter diamond drill (HOO micron ball end mill), as shown in Figure 2.



(a) (b)

Figure 2: (a) The fabrication of pit-kind geometrical defect; (b) One intentional pit-kind defect on the fabricated cavity.

The cavity was mounted on a holder with rubber foot to protect cavity inner surface. The angle between the axis of cavity and the ground was 13° to allow the drill to be perpendicular to the cavity equator area. The velocity of the mill was set at 5000 RPM when the four pit-type defects were fabricated. After mechanical fabrication, some sharp bumps were found at the rim of each pit. Mechanical polishing was performed to remove this kind of sharp edge for each pit by a grind paper. Subsequently, 10 μm BCP was performed to clean the cavity for equator welding. After welding, an additional 5 μm BCP was performed for RF test preparation. The total 15 μm BCP is

EXTERNAL MAGNETIC FIELDS AND OPERATING SRF CAVITY

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Abstract

When an SRF cavity is undergoing a transition to the superconducting state in an external magnetic field it traps some of the flux which results in an increase of surface resistance. This effect was extensively studied, is well understood by now and results in stringent requirements for an ambient magnetic field on the surface of an SRF cavity. The situation is quite different when magnetic field is applied to a cavity already in the superconducting state. During normal operation the bulk of the superconducting Nb should protect the RF surface of the cavity from fields on the outside. So we expect that the requirements on an external magnetic field applied to an operating cavity could be significantly relaxed. One possible failure mode is when the cavity quenches while the external field is applied. The magnetic field would penetrate through a normal zone formed during the quench and can get trapped during the subsequent post-quench cooling. We studied the effects of an external magnetic field applied to an operating SRF cavity and report the results.

CONTRIBUTION NOT RECEIVED

QUENCH DYNAMICS IN SRF CAVITIES*

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Abstract

Quench is a fundamental process in SRF technology, limiting the maximum accelerating gradient of an SRF cavity. Better understanding of its nature provides us with time-dependent variables like temperature, normal zone radius, energy, etc. Some of them cannot be measured by existing experimental setup. Nevertheless, these physical quantities are essential for understanding of quench process and for future improvements of the cavity performance. We present here our current algorithm to solve the system of nonlinear equations describing the quench process and discuss the obtained results.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities is the leading technology for future linear accelerators[1]. A quench often is the limiting factor of a cavity performance. It is widely assumed that quench is caused by some abnormality: either a surface defect or a localized material contamination near RF surface of the cavity. To study the nature of this defect we put forward a quench process model, which can be implemented in terms of the nonlinear equations.

Quench is usually caused by some defect on the inner surface of the cavity. The surrounding area resistance is significantly higher (due to various factors) than the resistance of the superconducting niobium. As a result, this area becomes normal conductor at the temperature lower than critical temperature of niobium and starts heating while dissipating RF energy. Surrounding niobium, heated up to its critical temperature, becomes normal conductor as well. Thus normal zone continue to expand.

We need to solve the system of nonlinear equations, which describes stored energy dissipation, caused by Joule heating of normal conducting niobium, and heat transfer in both superconducting and normal conducting niobium. In this paper we discuss modeling results, problems arisen, and prospective computational techniques.

QUENCH MODEL DESCRIPTION

In our model quench is a heat propagation in niobium with a heat source is due to dissipating of electromagnetic field energy, stored in the cavity. Thermal conductivity, heat capacity, and bulk resistance of the material in this case are strongly and nonlinearly dependent on temperature [2][3][4]. Thus, this problem could be solved only by numerical methods. We assume the quench to arise from a defect, which is normal conducting at any temperature. Its bulk resistance at some temperature is supposed to be equal to normal conductor extrapolated resistance at the same temperature. Superconducting niobium residual resistance is negligibly small compared to normal conducting niobium resistance. If the temperature increases to 9.22 K, niobium surface resistance steps up from zero to several mOhm. [1] Normal conducting area absorbs the RF energy and heats up. We can use a uniform field approximation to solve our problem, provided that (a) the cavity radius of curvature is much greater than linear dimensions of the area under study and (b) the time period of RF wave is much smaller than the quench process characteristic time. Normally, a quench origin is located near the weld of the cavity, so the peak magnetic field can be used as a uniform field value.

Stored energy in the cavity

$$W = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 dv. \tag{1}$$

Using uniform field approximation

$$W = \frac{1}{2}\mu_0 \overline{|\mathbf{H}|^2} K_v, \tag{2}$$

where K_v is a volume constant. Thus, the loss power

$$P = \frac{dW}{dt} = \frac{1}{2}\mu_0 K_v \frac{d(\overline{|\mathbf{H}|^2})}{dt}. \tag{3}$$

On the other hand loss power can be defined through the average magnetic field and the urface resistance as follows:

$$P = \frac{1}{2}\overline{|\mathbf{H}|^2} \int_S R_s ds. \tag{4}$$

Thus,

$$\mu_0 K_v \frac{d(\overline{|\mathbf{H}|^2})}{dt} = \overline{|\mathbf{H}|^2} \int_S R_s ds. \tag{5}$$

Surface resistance is a function of bulk resistance and frequency and is equal to

$$R_s = \sqrt{\rho \pi f \mu_0}. \tag{6}$$

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[1] In numerical computing an instability often follows any physically incorrect discontinuity. Thus, one has to smooth over this discontinuity on a finite time interval.

SECOND SOUND MEASUREMENT FOR SPL CAVITY DIAGNOSTICS

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Abstract

Second sound is a temperature wave which travels at a speed of ≈ 20m/s in superfluid helium. The second sound detector used is a so-called oscillating superleak transducer (OST), initially provided by Cornell-CLASSE, and thereafter manufactured at CERN. It contains a flexible porous membrane for transmitting and blocking the movement of the superfluid and normal fluid components of the second sound wave. From the measured speed of this wave and by determining the travel time between the quench event and several OSTs, an alternative method is offered to localise the quench site by triangulation. Several surface mount devices (SMDs) – thick film chip resistors – are used to simulate the quench spot in a cavity. Given the heat pulse and the location of the installed OSTs, the temperature dependence of the second sound velocity is determined under different experimental conditions and compared with previous results and theoretical expectations. The second sound triangulation will eventually be used to determine quench locations on the Superconducting Proton Linac (SPL) test cavities (704MHz) at CERN.

INTRODUCTION

Second sound is a quantum mechanical phenomenon exhibited in superfluids. The name "second sound" is derived by analogy with first sound where the former propagates as an entropy wave and the latter, a density wave. The oscillating superleak transducer was developed and constructed by R. Sherlock and D. Edwards in the 1970s [1] to detect second sound in superfluid ^{4}He and in dilute ^{3}He-^{4}He mixtures at few milli-Kelvin. The OST contains a superleak membrane with micrometer size pores which allow the movement of superfluid component go through without viscosity leaving the viscous normal fluid component outside. The oscillation of the two fluids introduces the principle of operation and the name of this second sound detector – oscillating superleak transducer. This technique was first introduced by K. W. Shepard [2] for the detection of the quench location in a superconducting cavity. Since then this technique has been widely used in second sound measurement in many laboratories over the last few decades and in quench detection in cavity diagnostics [3-7]. This paper reports on second sound characteristics for quench detection being studied in a dedicated cryostat in CERN's Cryolab.

The paper is split into four parts. First, the experimental setup and procedure is introduced. Second, second sound measurement improvements and results of characteristics studies are presented. Third, the manufacturing process and membrane sputtering regarding OSTs at CERN are described (with a slight change to Cornell's design). Finally, the paper is distilled with some conclusive remarks and an outline of future plans.

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EXPERIMENTAL SETUP

Six surface mount devices (SMDs) – thick film chip resistors with various specifications – are soldered on a printed circuit board with dimensions 20 x 10 x 1.5 mm^3 (Table 1). One side of the board has printed circuitry while the other one remains insulated so to be fixed on the bottom plate of the insert (see Fig.1 (a)).

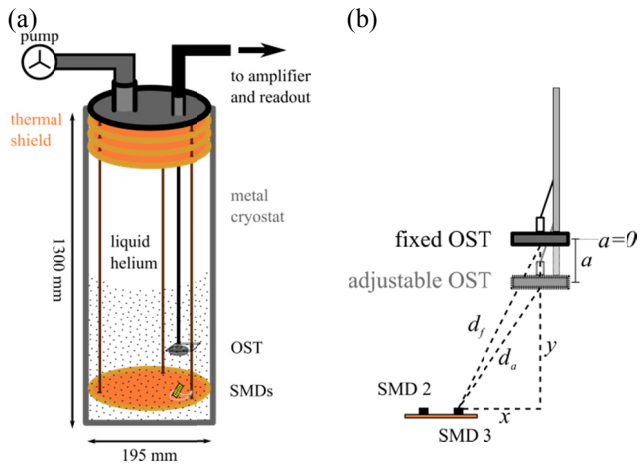


Figure 1: (a) Illustration of the experimental setup. (b) The orientation of the two OSTs. The distances between the SMDs and the OSTs are determined by the fixed x, y values and the increment *a* or decrement *-a* on the adjustable insert.

One oscillating superleak transducer (OST) was mounted at a fixed distance of d_f above the SMD board where the level is defined as $a = 0$ (see Fig.1 (b)). A second OST is mounted on a movable rod on the insert which is manually adjustable. Thus the distance between the OST and the SMD used is determined by the Pythagoras' theorem. The distance is measured by a ruler with a measurement error of ±1 mm in both the *x* and *y* direction. Temperature is monitored by one Cernox sensor (Lakeshore CX-1050-SD-1.4L) and the signal is read out via a Labview programme. The insert is to be fitted in a metal cryostat filled with liquid ^{4}He.

Measurement Procedure

The pulse technique is used to trigger the SMDs on the board in order to initiate the second sound wave (see Fig. 2). The second sound signal received from the OST is amplified by 23 times and displayed on the oscilloscope (Tektronix MSO/DPO 3000 series). The amplifier box

OPTICAL OBSERVATION OF GEOMETRICAL FEATURES AND CORRELATION WITH RF TEST RESULTS*

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Abstract:

Three kinds of geometrical feature analysis techniques were adopted in association with cavity gradient R&D at the Jefferson Lab: (1) feature shape analysis by Kyoto camera system; (2) 3D profile analysis using the KH-7700 high resolution digital-video microscopy system (HIROX); and (3) replica technique plus surface profiler for profile measurement of geometrical features. These three profile measurement methods have been applied to three nine-cell SRF cavities: PKU2, TB9RI019 and TB9NR001. The shape analysis of geometrical features and correlation with RF test results of these cavities will be presented here.

INTRODUCTION

The superconducting radio frequency (SRF) cavity has been widely used for many large accelerator projects such as international linear collider (ILC) [1] and the Relativistic Heavy Ion Collider (eRHIC) [2]. For example, 90% of the over 16000 cavities required for ILC program must achieve an accelerating gradient of 35MV/m. However, there are still some limiting factors which result in low production yield of the SRF cavity. The 4th update of the global database of ILC cavity production yield show that recent production yield of nine-cell cavities with gradient over 35MV/m is still at the range of 50~60% [3].

For SRF cavity, the limiting factors which influence the reproducibility of cavity performance mainly include quench and field emission; both of these two limiting factors have strong relationship with the condition of the cavity inner surface. Collecting and categorizing the defects on the inner surface of the cavity and establishing relationship between these defects and RF performance may help to further understand the cavity limiting mechanism and provide guidance to improve technical procedures of cavity fabrication and chemical treatment, so as to improve cavity gradient and yield. Recently, three kinds of optical inspection methods (replica-profilometer [4, 5], HIROX and Koto camera optical inspection system) have been adopted at Jefferson Lab to characterize the defects inside the cavity. Characterization of mechanical features and building correlation with the cavity RF performance using these three inspection methods are the main focus of this paper.

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DEFECT CHARACTERIZATION METHODS

The Kyoto camera (Figure 1) is the most frequently used inspection tool at Jefferson Lab because it can be put into the cavity to inspect the inner surface without cutting samples from the cavity [6]. The system consists of a high resolution CMOS camera and a lighting system which consists of 21 lights built inside a 50mm diameter cylinder. When needed, the cylinder is inserted into the cavity and images are taken of the interested area. The images can be analyzed by two kinds of software (OpenCV and ActivePerl) to generate a 3D profile of the features. The resolution of this system is estimated to 6μm.



Figure 1: Kyoto camera optical inspection system.

To obtain an accurate characterization of defect profile, replica-profilometer technology provides a good choice for measurement. The replica material used at Jefferson Lab is WACKER dental ADS 931 A & B. These two compounds are mixed in the weight ratio of 1:1. The mixture is then poured onto the interested area of the cavity to duplicate the surface details. After one hour of curing at room temperature, the mixture is drawn out of the cavity. It is important to note that this cured mixture only reflects the reverse information of the inspected area. In order to reflect the positive defect detail, two other compounds (STYCAST 2850 FT BLACK and CATALYST 9, manufactured by Henkel corporation) are mixed in the weight ration 100: (4~6) to generate a mixture which is poured onto the reverse replica to form a positive sty-cast replica for the defect. The mixture needs 20 hours at room temperature to cure the positive sty-cast replica. The KLA-Tencor Profilometer was selected to analyze the positive replica. The resolution of this replica-profilometer technology is ~ 1 μm.

SIMS AND TEM ANALYSIS OF NIOBIUM BICRYSTALS

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Abstract

Interstitial impurities such as C, N, O and H on the Nb surface play a key role in the efficiency of superconducting radio frequency (SRF) cavities for particle accelerators. Thus, it is important to understand the behaviour of these interstitial impurities with respect to grain boundaries. The large single crystal grains in large grain Nb make it possible to select bicrystal samples that have a well defined grain boundary. In this work, Dynamic SIMS was used to analyze two Nb bicrystal samples, one of them heat treated and the other chemically treated by buffered chemical polishing (control). H levels were found to be higher for the control sample and a difference in the H intensity and sputtering rate was also observed across the grain boundary for both samples. Transmission Electron Microscopy (TEM) was used to study the bicrystal interface and the surface oxide layer. The interface showed no discontinuity and the oxide layer was uniform across the grain boundary for both samples. TOF-SIMS imaging was also performed to analyze the distribution of the impurities across the grain boundary in both samples. C was observed to be segregated along the grain boundary for the heat treated sample, while H and O showed a difference in signal intensity across the grain boundary. Crystal orientation appears to have an important role in the observed sputtering rate and impurity ion signal differences, both across the grain boundary and between samples.

INTRODUCTION

Nb has become the material of choice for superconducting radio frequency (SRF) cavities due to its high critical temperature (9.2 K) , high critical magnetic field (200mT) and easy formability, that is, it can be molded to a cavity shape, which is extremely important from the manufacturing aspect. It is known that polycrystalline Nb tends to harbor interstitial impurities such as C, N, O, and H, which play an important role in the RF losses of these cavities. The presence of such impurities near the surface is particularly detrimental given that the penetration depth of the RF field is of the order of 40 nm.[1]

Initial experiments using Dynamic Secondary Ion Mass Spectrometry (SIMS) have shown that heat treated large grain Nb has lower H levels on the surface compared with non heat treated Nb, and that the cavity efficiency is seen to improve with heat treatment.[2,3]

Figure 1 shows mass spectra from two Nb samples, one with no heat treatment, just chemical etching by buffered chemical polishing (BCP), and one which was heat treated at 800°C for 3hrs and then baked at 120° C for 24hrs. The non heat treated sample mass spectrum in Fig 1(a) shows very intense peaks for the negative ions NbH^-, NbH_2^-, NbH_3^-, NbH_4^-, NbH_5^- which indicate the presence of a high level of H and an affinity of Nb for H. These peaks dramatically decrease and the higher H containing ions vanish for the heat treated sample as shown in Fig. 1(b). Thus, heat treatment plays a very important role in controlling H levels in Nb. This is a known issue related to SRF Nb cavities [4]: heat treatment is part of the standard preparation procedure but a chemical etching is typically done after the heat treatment. Hydrogen can still be absorbed during the chemical treatment and its high concentration near the surface may still impact the cavity performance. Initial experiments were confined to an analysis area within a particular grain and the effects of grain boundaries on Nb-impurity element dynamics were not taken into account. Since it is known that grain boundaries are more susceptible to diffusion of impurity elements, it is important to study them. Thus, the current work focuses on the characterization of H, C, O and N at the grain boundary and near grain boundary regions of Nb bicrystal. Crystal orientation of these bicrystals was determined using Electron Back Scattering Diffraction (EBSD). Difference in crystal orientation was observed for the two crystals of both heat treated and control bicrystal samples. Dynamic SIMS was used to analyze the near grain boundary regions and Time of Flight SIMS (ToF SIMS) imaging was used to observe the presence of C, H , O and N right at the grain boundary interface. Transmission Electron Microscopy was also used to study the grain boundary interface and the surface oxide layer of both the Nb bicrystals.

EXPERIMENTAL

Samples of 7mm x 5mm x 2mm dimensions were cut by wire electro-discharge machining from large grain polycrystalline Nb disc in such a way that the grain boundary divided the sample into two parts, with each part being a separate crystal and having a distinct crystallographic orientation. The samples were chemically etched by BCP to remove about 80 μm of material from each surface, then they were heat treated in a vacuum furnace at 600 °C for 10 h, followed by 20 μm chemical

COMMISSIONING CORNELL OSTS FOR SRF CAVITY QUENCH IDENTIFICATION AT JLAB*

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Abstract

Understanding the current quench limitations in SRF cavities is a topic essential for any SRF accelerator that requires high fields. This understanding crucially depends on quench localization. Second sound quench detection in superfluid liquid helium with oscillating superleak transducers (OSTs) is a technique recently applied at Cornell University as a fast and versatile method for quench localization in SRF cavities [1]. Having adopted Cornell design, we report in this contribution on our experience with OSTs for quench localization in different cavities at JLab.

INTRODUCTION

The International Linear Collider (ILC) reference design report specifies $Q_0 = 8 \cdot 10^9$ at $E_{acc} = 35$ MV/m as the acceptance criterion in the vertical acceptance tests of 9-cell ILC cavities. This specification is the current state of art in superconducting RF and presents a challenge to cavity vendors. Many of the produced cavities fail to meet this specification because of quenches. Understanding of the quench limitation is a scientific challenge pursued by many SRF groups, which rely heavily on thermometry for quench localization on the cavity surface and thermal characterization of lossy regions.

Recently, detection of second sound wave from quench with oscillating superleak transducers was put forward at Cornell University as another tool for quench localization. Unlike thermometry, second sound time-of-flight measurements do not provide information on heat distribution and preheating field dependence in the quench region, however, second sound detection also is not limited to a particular cavity shape and can be used for virtually any cavity testing in superfluid helium. Many SRF laboratories around the world adopted this technique. In this contribution we discuss our experience with OSTs.

EXPERIMENTAL SETUP

For the second sound detection system we have adopted Cornell design. Dr. Zachary Conway kindly provided us with 16 OSTs built at Cornell University. For standard ILC tests we attach 8 OSTs onto the standard JLab cage around the cavity, Fig. 1. The OSTs are connected with RG-174 cable to a 120 volts-biased amplifier outside the dewar. The amplified signal is then fed into TDS2024B oscilloscopes. For quench location determination after the test we use the



Figure 1: For the standard ILC RF test 8 OSTS are attached to the standard JLab cage around the cavity. Two more OSTs are behind the cavity and cannot be seen on this picture.

Cornell "wire" method: second sound time-of-flight measurement is determined for each OST trace, the distance to the quench origin is calculated from time-of-flight and second sound velocity for each OST, then wires are cut to the corresponding length and attached to respective OSTs, finally, the point where all wires converge is the quench origin [2].

RESULTS AND DISCUSSION

Second sound system was routinely used for SRF testing of 9-cell cavities since September 2010. OSTs were used at JLab to locate quenches in TB9RI019, TB9RI027,

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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MICROPHONICS COMPENSATION FOR A 325MHZ SINGLE SPOKE CAVITY AT FERMILAB

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Abstract

Fermilab is developing 325MHz CW narrow-bandwidth spoke cavities for the proposed Project X. The first results of active microphonics compensation for these cavities are presented.

CONTRIBUTION NOT RECEIVED

SECOND SOUND AS AN AUTOMATED QUENCH LOCALISATION TOOL AT DESY*

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Abstract

The understanding of the origin of local thermal breakdown („quench“) in superconducting RF cavities is still a challenge. Such heat spots can be conveniently measured using the second sound in superfluid helium. This detection technique has been examined in several institutes. At DESY there are currently two vertical bath cryostats where cold RF tests with a cavity mounted in a cryostat insert can be done. At all of the four inserts the second sound setup consisting of eight Oscillating Superleak Transducers (OSTs) is mounted. These are connected to amplifier electronics and the measured signals are fed into an ADC to be read out with MATLAB†. Within MATLAB the location is derived from the measured propagation times. The present system is already in use on a regular basis. For the efficient testing and diagnosis of a large batch of cavities such as the 1.3 GHz cavities (see Fig. 1) for the European XFEL [1] and the International Linear Collider ILC [2], fast diagnostic tools are mandatory. An automated setup which will be implemented into the routine RF measurement procedure is under development.

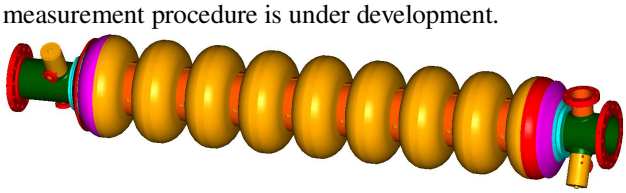


Figure 1: 1.3 GHz 9-cell superconducting RF cavity.

QUENCH LOCALISATION METHODS

A quench may arise from impurities or irregularities in the superconducting niobium, which will cause a temperature rise until the critical temperature T_C of the niobium is reached and a quench is induced. The heat deposited in the niobium and subsequently in the helium bath can be detected by thermometers attached on the outer cavity surface, the so-called temperature mapping (“T-Map”) [3]. Another possibility is the use of the second sound, a phase-transition wave induced by depositing heat into the superfluid helium bath [4]. This quench localisation method is much faster than T-Map, since it omits the mounting procedure of the sensors, and one quench is sufficient to detect the quench location.

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†MATLAB is a registered trademark of The Mathworks, Inc.

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AUTOMATION OF QUENCH LOCALISATION USING SECOND SOUND

Second Sound Detection

The second sound in liquid helium can be detected with condenser microphone-like Oscillating Superleak Transducers as shown in Fig. 2.



Figure 2: Picture of an OST in use at DESY (and in other institutes).

Liquid helium cooled below the λ-point can be described as a mixture of two fluids, He-I and He-II. As He-I cannot propagate through the thin porous membrane of the OST, it exerts pressure on the membrane which changes the capacity of the OST. This change is detected by the voltage-variation at the device. A schematic drawing about this process is shown in Fig. 3.

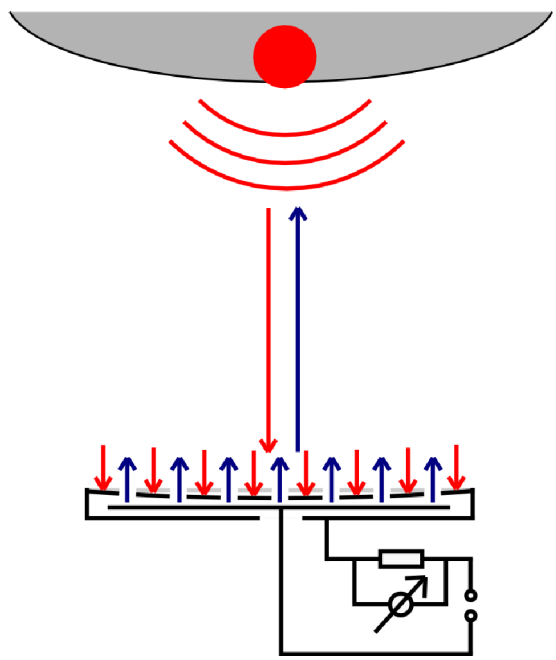


Figure 3: Schematic drawing of the second sound detection with an OST. He-I (red) is “blocked” by the porous membrane and exerts pressure, while the counterflow of He-II may pass the membrane easily.

TOF-SIMS ANALYSIS OF HYDROGEN IN NIOBIUM, FROM 160°K TO 475°K

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M. Rigsbee [Materials Science and Engineering, Raleigh, USA]

Abstract

Niobium (Nb) is the material of choice for superconducting radio frequency (SRF) cavities due to its high critical temperature and critical magnetic field. Interstitial impurity elements such as H directly influence the efficiency of these cavities. Quantification of H in Nb is difficult since H is extremely mobile in Nb with a very high diffusion coefficient even at room temperature. In the presented work, Time of Flight Secondary Ion Mass Spectrometry (TOF-SIMS) was used to characterize H in Nb over a wide temperature range (160°K to 475°K) in situ to check for changes in mobility. Multiple experiments showed that as the specimen temperature is decreased below 300 °K, the H/Nb intensity changes by first increasing and then decreasing drastically at temperatures below 200°K. As specimen temperature is increased from 300°K to 450°K, the H/Nb intensity decreases. Remarkably, the H intensity with respect to Nb increases with time at 475°K (approximately 200oC). Correlation between this data and the H-Nb phase diagram appears to account for the H behaviour.

CONTRIBUTION NOT RECEIVED

VERTICAL TEST RESULTS ON KEK-ERL 9-CELL L-BAND SUPERCONDUCTING CAVITY

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Masaru Sawamura, JAEA, Tokai, Naka, Ibaraki, Japan

Abstract

In order to develop the Energy Recovery Linac at KEK, we are studying the performance of two prototype L-band superconducting cavities by means of vertical tests. After annealing, electro polishing, high pressure rinsing and baking, several vertical tests were performed and the cavities were inspected through rotating X-ray and temperature mapping system. The performance limiting factor was found to be the field emissions. We observed X-ray emission and temperature raise along the cavity wall. The quench locations were determined with a good agreement between X-ray and temperature sensors. During vertical test we experienced some interesting phenomena such as quality factor degradation and X-ray burst. In the first case the degradation was observed even at low field, however we recovered it with a warming up to room temperature without additional surface treatment. In the latter case new emitters suddenly appeared after some quenches. They remained in the same location also after the warming up. The cavities fulfilled the requirement for the KEK-ERL main linac reaching an accelerating field of more than 20 MV/m.

INTRODUCTION

Developing and characterization of superconductive cavities is one of the most demanding aspects for the development of a new light source based on Energy Recovery Linac (ERL) concept. At KEK a compact ERL (cERL) is now under construction, to demonstrate the performance of components under CW operation at 100 mA of currents, 3GeV of energy and with ultra-short pulses of 100 fs. Figure 1 shows compact ERL conceptual design.

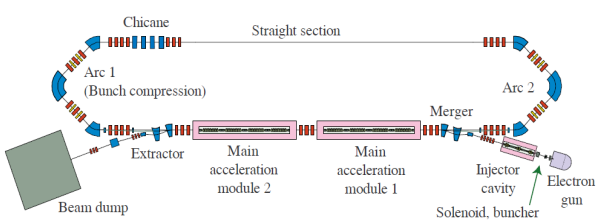


Figure 1: cERL conceptual design

Our group has developed and characterized the superconductive cavities for the main accelerator section. The performance of two L-band superconductive cavities was studied by means of vertical tests after different surface treatment. In order to obtain a precise diagnosis of the cavities during the tests we have used a rotating mapping system equipped with X-ray and temperature sensors.

CAVITIES AND EXPERIMENTAL SETUP

Two 1.3GHz superconductive cavities have been manufactured following the design for the main acceleration section of the ERL project. The main parameters for the cavity are summarized in table 1.

One of these cavities was inspected also from a manufacturing point of view. The same model will be installed in cERL so it shall fulfill the high pressure vessel Japanese law, stiffen rings are welded between the center cells while end cells are thicker (3.5mm instead 2.8mm). Moreover titanium end plates were welded between the beam pipes and the end cells, the welding process is also important. Figure 2 shows a detailed view of stiffen rings and titanium end plate.

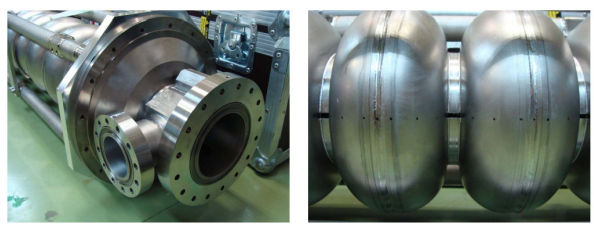


Figure 2: Detailed view of main acceleration cavities, input port and eccentric fluted beam pipe (left) stiffen rings (right).

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COMPARISON OF FIELD EMISSION AT DIFFERENT CAVITY ASSEMBLY STATES AND TEST STANDS

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Abstract

RF cavity Field Emission (FE) presents a major diagnostics instrument on the cavity performance, save the FE levels differ significantly from one cavity test setup to another, making the analysis difficult. A comparison study complimented with a direct calibration of FE in the cavities tested with different auxiliaries and test stands (vertical / horizontal / module) is presented and discussed.

INTRODUCTION

TESLA type SRF accelerating 9-cell cavities for FLASH and XFEL [1] are being tested at DESY. SRF accelerating cavities FE caused gamma radiation is being measured at different cavities test stands using the "Unidos" devices with 1 l spherical gamma sensors. The "Unidos" is set to measure with 1 kHz sampling rate and 200 ms filter (integration), so with a 1 ms / 10 Hz RF pulse 1:100 peak to average ratio is to consider for the pulse measurements. There are three different cavity test stands: vertical cryostat (CW test), horizontal cryostat (pulsed test) and module test stand (pulsed test). Gamma sensors positions for different test stands are shown in Fig.1 (Gun – upstream, Dump – downstream the module).

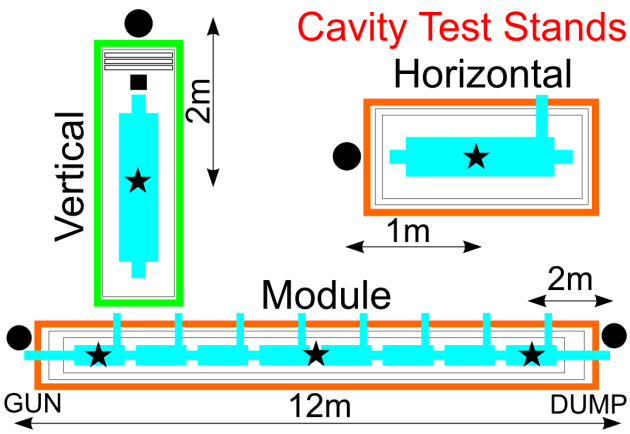


Figure 1: Cavity test stands gamma sensors (black orbs) and test Co-60 source (black stars) positions.

GAMMA RADIATION MEASUREMENTS

Gamma radiation measurements statistics for all 9-cell cavities measured so far at DESY is presented in Fig.2. The data are sorted between the three test stands and five cavity gradients values. Horizontal cryostat and module test (CMTB) [2], [3] statistics have yet a rather small data points numbers, still the comparison is possible.

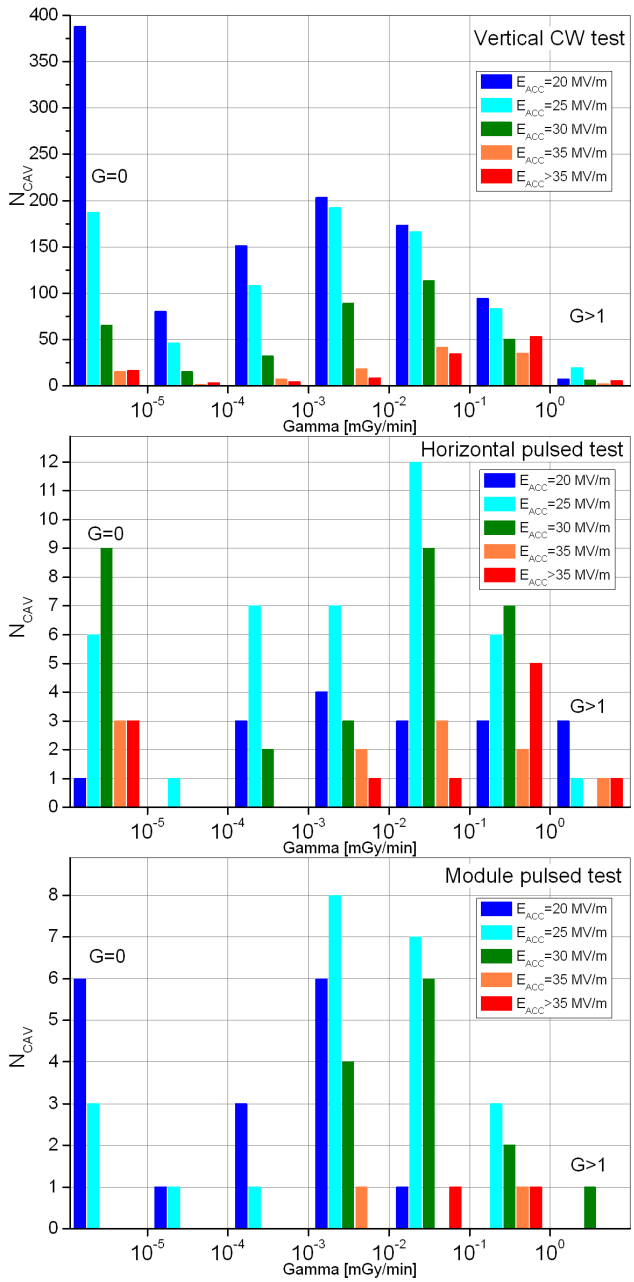


Figure 2: 9-cell SRF accelerating cavities tests at DESY: gamma radiation measurements statistics.

Module PXFEL3 was tested on the CMTB [4]. After the test module was disassembled and all cavities were tested separately on vertical and horizontal cryostat cavity test stands. Gamma radiation measurement data for module PXFEL3 cavities is shown in Fig.3.

A MACHINE FOR HIGH-RESOLUTION INSPECTION OF SRF CAVITIES AT JEFFERSON LAB*

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Abstract

A high-resolution cavity inspection machine has been built at JLab. It is based on a long-distance microscope with a spatial resolution down to 3 μm. This system has been a work horse in support of the on-going ILC cavity gradient R&D. More recently, this machine has been also used to inspect small aperture cavities including some 1497 MHz 7-cell CEBAF upgrade cavities and S-band single-cell crab cavities, demonstrating the capability and flexibility of the machine. We will describe the detailed features of the inspection machine along with some exemplary inspection results.

INTRODUCTION

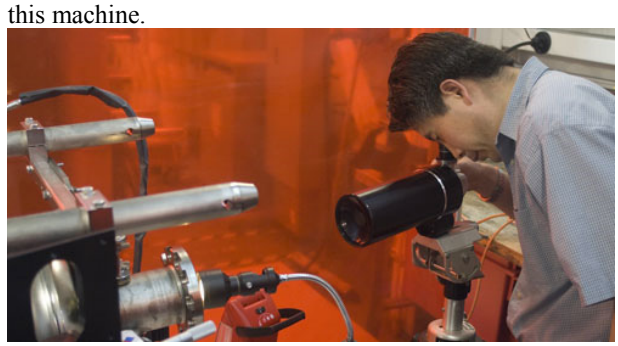
Visual inspection is an inexpensive and useful means for identification of dangerous or suspicious features on the surface of cavity components such as dumb-bells. Unaided human eyes lack the ability to inspect places such as the inner surface of the equator region of an elliptical shape cavity. Tools such as a bore scope can come handy, but its use is often rather limited due to poor quality in image contrast and poor spatial resolution. A high-resolution optical inspection machine, as it turned out, is a necessary and useful tool for high quality inspection (for discovery) and documentation (for tracking) of features in any region of real SRF cavities.

Recently, high-resolution optical inspection of SRF cavities has received lots of attention primarily due to the advanced gradient R&D of real 9-cell cavities for the International Linear Collider (ILC). One important ILC cavity gradient R&D goal is to understand the nature of the quench causing defects and help develop solutions for defect treatment and prevention. As it turns out, high-resolution optical inspection has played an important role in these studies. It is hopeful that such a machine will become part of industrial fabrication QA/QC. The well-known optical inspection machine is the "Kyoto camera", developed by a KEK/Kyoto University collaboration, which is now also used at other labs [1][2]. At Jefferson Lab, development of high-resolution optical inspection of 9-cell ILC cavities started in 2008 [3][4]. This system is based on a long-distance microscope. Pictures in Fig. 1 show the evolution of the system from the simple line-of sight style inspection in 2008 to the advanced and automatic full-inner-surface inspection at the present time.

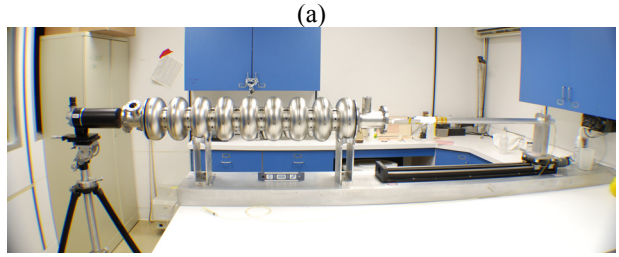
* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

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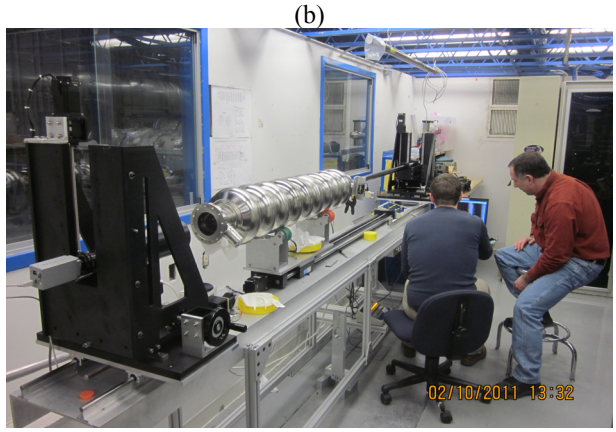
In this paper, we will describe the principle of the long-distance-microscope based optical inspection of SRF cavities as well as the detailed features of the machine components. Some exemplary inspection images will be given to show the capability of the system. It should be mentioned that this system has been a work horse in support the on-going ILC cavity gradient R&D at JLab since 2008. More recently, a variety of SRF cavities including CEBAF 12 GeV upgrade cavities and ANL crab cavities have also been successfully inspected by using this machine.



(a)



(b)



(c)

Figure 1: Development of JLab's high-resolution optical SRF cavity inspection system. (a) Direct line-of-sight inspection of end cell surface, circa April 2008. (b) Initial prototype of the full inner-surface inspection system, circa November 2008. (c) Present system with advanced automatic functions, February 2011.

LORENTZ FORCE DETUNING COMPENSATION IN FERMILAB CRYOMODULE 1

Y.M. Pischalnikov, B. Chase, E.R. Harms, W. Schappert [Fermilab, Batavia, USA]

Abstract

Cryomodule 1 of the Fermilab SRF Accelerator Test Facility has recently been commissioned. First results are presented from the simultaneous compensation of Lorentz force detuning in all eight of the 1.3 GHz Tesla style superconducting cavities.

CONTRIBUTION NOT RECEIVED

DETAILED NB SURFACE MORPHOLOGY EVOLUTION DURING ELECTROPOLISHING FOR SRF CAVITY PRODUCTION *

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Abstract

Electropolishing of niobium is currently an important part of attaining the best performance of SRF cavities. We endeavour to develop sufficient understanding of the process dynamics to gain predictive power over specific topographies subjected to controlled electropolishing conditions. This work examines the evolution of centrifugal barrel polished fine-grain Nb samples as this material is electropolished under different temperatures. The morphology evolution of Nb surface has been described using a combined approach of scaling analysis and predictions of the electropolishing theory. Our results suggest that centrifugal barrel polishing leaves highly strained topmost surface structure, the surface morphology evolution during following electropolishing could not be well described by a self-affine fractal structure until the plastic deformed layer is removed. The present analysis suggests electropolishing at low temperature helps to reduce the kinetics-controlled surface etching. A preliminary computational model has been developed that simulates the evolution of specific topography of a niobium surface under parameterized conditions. This work is expected to lead to the direct linking of starting surface morphology specification, specific processing protocol, and consistently attained finished surface condition.

INTRODUCTION

Electropolishing of niobium in the hydrofluoric and sulphuric acid mixers has been used for polishing Nb cavities for decades, and it has been develop empirically through cavity process practices. Recent R&D studies revealed that the standard electropolishing of niobium proceeds via anodization of niobium by the sulphuric acid moderated by the dissolution of the anodized layer (Nb_2O_5) via the available fluoride ions [1-2], higher temperature provokes another oxide dissolution process, which may be described more as etching rather than polishing[3]. Because electropolishing is becoming an important part of attaining the best performance of SRF cavities, the correlation between parameters of electropolishing process and the resulting surface smoothening needs to be established.

The scaling analysis has been used to describe the kinetic roughening of surface during the non-equilibrium deposition and erosion. In most of studies of surface morphology evolution, the observed systems were found to obey normal and anomalous scaling law [4-7]. To apply the scaling law to electropolishing, the surface morphology evolution could be carried out through the simulation using algorithms for diffusion limited model (DLA) [5]. It predicts that the corrugations of surface would diminish exponentially as a function of time, independent on the length scale of observation, and it is supported by the fundamental concept and mathematical description of an ideal electropolishing process [6].

The focus of this paper is to investigate the evolution of the Nb surface morphology during the electropolishing process. The data are analyzed using scope of both scaling analysis and predictions of the electropolishing theory. The approach has been successfully used to simulate Cu surface evolution during electropolishing [7]. A preliminary computational model has been developed that simulates the evolution of specific topography of a niobium surface under parameterized conditions.

EXPERIMENTAL

The starting Nb surfaces were produced by a series centrifugal barrel polishing under different durations at KEK. Previous statistical studies suggested that this fine centrifugal barrel polishing (CBP) treatment provided a highly reproducible starting surface [8]. Atomic Force Microscopy (AFM) measurements were performed using a commercial AFM (Digital Instruments: Nanoscope IV) in a tapping mode using silicon tips with a diameter of 10 nm. The samples were each scanned in more than five different positions with the scan size of 50 μm × 50 μm. The EP solution was a 1:10 mixture of HF (49%) and H_2SO_4 (96%). For electropolishing, two Nb disk samples were mounted to a customized sample holder subjected different durations EP at 10 volts simultaneously. The bulk electrolyte temperature was controlled by a circulated water bath at 20±1˚C and 34±1˚C respectively, the removal of Nb surface is kept the same for different temperatures by different durations EP.

The AFM images were analyzed using custom image processing software based on Matlab programming language platform. This characterization software is capable of processing AFM images of a given size represented as two dimensional matrix of the data containing the information of the surface topography as a normal distance (h) with respect to the average plain of the image. The size of the observation window in the software has been designed to be an input parameter with subsequent step of the observation window enlargement. The surface roughness ($w(l,t)$) defined as [9]:

$$w(l,t) = \sqrt{< \left(h(r,t) - \bar{h}(r,t)\right)^2 >},$$

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes
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A WIRE POSITION MONITOR SYSTEM FOR THE 1.3 GHZ TESLA-STYLE CRYOMODULE AT THE FERMILAB NEW-MUON-LAB ACCELERATOR*

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Abstract

The first cryomodule for the beam test facility at the Fermilab New-Muon-Lab building is currently under RF commissioning. Among other diagnostics systems, the transverse position of the helium gas return pipe with the connected 1.3 GHz SRF accelerating cavities is measured along the ~15 m long module using a stretched-wire position monitoring system.

An overview of the wire position monitor system technology is given, along with preliminary results taken at the initial module cooldown, and during further testing. As the measurement system offers a high resolution, we also discuss options for use as a vibration detector.

INTRODUCTION

An electron beam test facility, based on superconducting RF (SRF) TESLA-style cryomodules is currently under construction at the Fermilab New-Muon-Lab (NML) building [1]. The first, so-called type III+, cryomodule (CM-1), equipped with eight 1.3 GHz nine-cell accelerating cavities was recently cooled down to 2 K, and is currently under RF conditioning. The transverse alignment of the cavity string within the cryomodule is crucial for minimizing transverse kick and beam break-up effects, generated by the high-order dipole modes of misaligned accelerating structures. An optimum alignment can only be guaranteed during the assembly of the cavity string, i.e. at room temperatures. The final position of the cavities after cooldown is uncontrollable, and therefore unknown.

A wire position monitoring system (WPM) can help to understand the transverse motion of the cavities during cooldown, their final location and the long term position stability after cryo-temperatures are settled, as well as the position reproducibility for several cold-warm cycles. It also may serve as vibration sensor, as the wire acts as a high-Q resonant detector for mechanical vibrations in the low-audio frequency range [2], [3].

The WPM system consists out of a stretched-wire position detection system, provided with help of INFN-Milano [4] and DESY Hamburg, and RF generation and read-out electronics, developed at Fermilab.

THE WIRE POSITION MONITORING SYSTEM

The Cryomodule WPM Detection Assembly

Figure 1 gives an overview of the WPM system. It is based on a stretched wire in a coaxial transmission-line arrangement. A 28 mm inner diameter tube with bellows between seven (only four are shown in Fig. 1) stripline position pickup's, distributed along the module, serves as outer conductor, while the 0.5 mm diameter Cu-Be wire is the inner conductor of this coaxial line, giving a characteristic impedance of ~240 Ω. The wire is fixed at the feed- and endcap of the cryomodule, which are both room temperature parts of the cryo-vessel, thus reference the wire position. The wire is stretched applying the tension of an 18 kg weight over a wheel fixed to the endcap, and therefore its sag is independent of the elongation effects of the cryomodule. The WPM

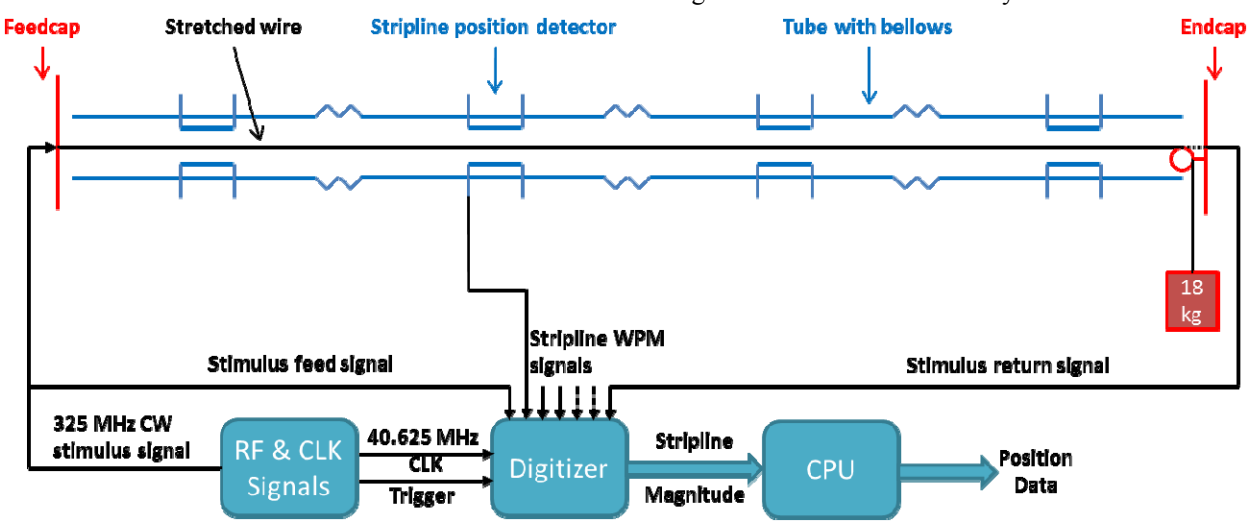


Figure 1: Schematic of the wire position monitoring system, installed at the Fermilab TESLA-style CM-1 cryomodule.

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HOM IDENTIFICATION AND BEAD PULLING IN THE BROOKHAVEN ERL *

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Abstract

Several past measurements of the Brookhaven ERL at superconducting temperature produced a long list of higher order modes (HOMs). The Niobium 5-cell cavity is terminated with HOM ferrite dampers that successfully reduce the *Q*-factors to tolerable levels. However, a number of undamped resonances with $Q \geq 10^6$ were found at 4 K and their mode identification remained as a goal for this paper. The approach taken here consists in taking different S_{21} measurements on a copper cavity replica of the ERL which can be compared with the actual data and also with Microwave Studio computer simulations. Several different S_{21} transmission measurements are used, including those taken from the fundamental input coupler to the pick-up probe across the cavity, between probes in a single cell, and between beam-position monitor probes in the beam tubes. Mode identification is supported by bead pulling with a metallic needle or a dielectric sphere that are calibrated in the fundamental mode. This paper presents results for HOMs in the first two dipole bands with the prototypical 958 MHz trapped mode, the lowest beam tube resonances, and high-Q modes in the first quadrupole band and beyond.

INTRODUCTION

Several past measurements of the Brookhaven ERL at superconducting temperature produced a long list of higher order modes (HOMs). The Niobium 5-cell cavity is terminated with HOM ferrite dampers that successfully reduce the *Q*-factors to tolerable levels. However, a number of undamped resonances with $Q \geq 10^6$ were found at 4 K and are listed in Table I. Their mode identification is essential in order to establish the R/Q for beam break up estimates and this task remained as one goal for this paper. The present study was also initiated to prepare for the field flatness measurement and the HOM identification of the BNL-3 cavity that is being constructed for the electron ion collider at Brookhaven, eRHIC. As a preparatory step in developing the best techniques, bead-pull measurements were performed on a copper cavity replica of the ERL and compared with Microwave Studio computer simulations.

This paper is organized as follows. In Section II, the bead- pull technique is described with considerable detail and theoretical sensitivity factors are collected in a table.

*Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE and by the DOE grant DE-SC0002496 to Stony Brook University.
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Table I: High-*Q* modes in the BNL ERL @ 4 K

f [GHZ]	*Q*
1.22008	920,000
2.14764	5,503,500
2.14831	1,306,900
2.32984	2,291,800
2.34421	908,180
2.45578	1,025,400
2.74324	620,040
2.90829	406,090

In Section III, bead pulling with a metallic cylinder and a dielectric sphere is applied to the fundamental TM01-π mode yielding field flatness and a calibration of the beads. Section IV discusses resonances that are located in the bam tube between cavity and ferrite damper and distort the proper cavity modes. A major concern in the cavity design stage and then during the measurements is the existence of trapped modes such as the ~ 958 MHz resonance analyzed in Section V. In the last Section VI, the attempt at identification of the very high-Q resonances using bead- pulling is presented and compared to other methods. The short conclusion summarizes the necessary steps and limitations of HOM identification in the ERL cavity.

PERTURBATION MEASUREMENTS

The availability of advanced electromagnetic computer programs has to some degree replaced perturbation measurements to obtain field configuration and the performance parameters of resonant cavities. However, they remain a valuable tool to analyze geometrically complex structures or to confirm theoretical results that are modified by construction errors. Measurements by bead pulling were performed for this paper in order to verify the field flatness and to identify higher order modes in the copper model of the five-cell ERL cavity in Fig. 1.

The frequency change produced by the insertion of an object into a resonant cavity is a topic in standard electromagnetic text books. The possibility to interpret this frequency change for the identification of the local field strength and direction as well as the cavity interaction parameters was pointed out by Müller [1] and is well known in the accelerator community as Slater perturbation method [2]. Theoretical expressions for the frequency change have been derived for simple geometries with a near complete list to be found in a technical report by L. C. Maier, Jr. [3]. The typical application of bead-bull measurements is to establish or to

CRYSTALLOGRAPHIC ORIENTATION OF EPITAXIAL TRANSITION OBSERVED FOR NB (BCC) ON CU AND MGO (FCC) SINGLE-CRYSTALS

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Abstract

Niobium thin films were grown on (001) MgO (or Cu) single-crystal using a coaxial energetic deposition. The quality of the substrate surface and epitaxial Nb layers were investigated by the XRD and pole figure measurements. Depending on growth temperature, in-plane XRD show Kurdjumov-Sachs (KS) as well as Nishiyama-Wassermann (NW) epitaxial relationships for (110) and (001) Nb on (001) MgO. Calculation of the interface energy in rigid lattice models finds one KS and two NW minima. For the NW case the optimal atomic diameter ratio dbcc/dfcc=0.866 and 1.061, whereas for the KS case it is at dbcc/dfcc=0.919. Transitions of this type are usually induced by a change in the lattice parameter ratio resulting from a relaxation process in the early stage of the growth.

CONTRIBUTION NOT RECEIVED

STRUCTURAL CHARACTERIZATION OF NIOBIUM FILMS DEPOSITED BY ECR PLASMA ENERGETIC CONDENSATION ON CRYSTALLINE INSULATORS*

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Abstract

An energetic condensation thin film coating technique with an electron cyclotron resonance (ECR) induced Niobium (Nb) plasma ion source is used to deposit Nb thin films on crystalline insulating substrates, such as a-plane and c-plane sapphire (Al_2O_3) and on magnesium oxide, MgO (100), (110), and (111).

Hetero-epitaxial Nb films were produced by ECR deposition with regulated substrate temperature. The residual resistivity ratio (RRR) of about 1 micron thick films on *a*-plane (1,1,-2,0) sapphire substrates reach values (350 - 450) comparable to high RRR bulk Nb commonly used for SRF cavities.

The epitaxial relationship of Nb/crystalline substrate is found to be strongly influenced by the substrate bias voltage (added to the initial Nb^+ kinetic energy, 64 eV), the substrate crystalline orientation, and heating conditions.

At low substrate temperature, the Nb films demonstrate crystalline textures, revealed by XRD Pole Figure technique and Electron Backscattering Diffraction (EBSD). Niobium, as most metals, is known to grow with the "Volmer-Weber" growth mode, i.e. island growth.

This study shows that the film's crystal structural character has great impact on its RRR/T_c values.

INTRODUCTION

The characterization of the microstructure of ECR Niobium (Nb) thin films on crystalline insulator materials is practical in many interdisciplinary fields. For instance, sapphire is a well-known substrate to investigate Nb epitaxial growth. For Superconducting Radio-Frequency (SRF) particle accelerators, Nb and Nb compound thin films inter-layered with a dielectric buffer layer (such as a 50 nm layer of Al_2O_3 to suppress vortex-induced breakdown) might be a promising approach to replace the state-of-the-art bulk Nb materials in order to achieve higher accelerating gradient and to reduce liquid He cryogenic expense [1].

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METHODS

In this study, an energetic condensation thin film coating technique, known as Electron Cyclotron Resonance (ECR), is applied to deposit Nb thin films on a variety of crystalline insulating substrates, such as *a*-plane (11-20) and *c*-plane (0001) sapphire (Al_2O_3) and on magnesium oxide, MgO (100). By controlling the coating time, thickness of all the films in this study is about 1 micron.

The crystal structure and texture were investigated via X-ray diffraction (XRD) $\theta/2\theta$ and pole figure scans with a four-circle PANalytical X'Pert PRO-MRD diffractometer. The diffractometer scanned over a 2θ range from 30° to 120° at step size 0.02°. The slit aperture of the X-ray source is 10×17mm. The scan has a divergence slit of 0.5°, a receiving slit of 0.1° and use a line focus Mirror primary optics with Cu $K\alpha$ source. The source with wavelength λ_{Cu}=1.54 Å was operated at 45 kV and 40 mA. XRD Pole Figures in Stereographic Projection format were used to investigate the "texture" (grains distribution in-plane) [2]. Pole figure (or texture) measurement is an efficient way to reveal polycrystalline structural character in a material.

Electron-beam backscattering diffraction (EBSD) characterization of the samples was conducted using a state-of-the-art TSL/EDAX OIM™ system. EBSD relies on rastering the e-beam of a scanning electron microscope (SEM) and/or moving the sample stage to map a large area. The uniqueness of this technique is being able to probe the crystal orientation of a small domain (tens of nanometers). The OIM™ software can automatically interpret the domain's crystal orientation by indexing the Kikuchi-bands diffraction pattern. The crystal orientations of the scanning points are rendered by a color map, called the Inverse Pole Figure (IPF).For instance, a pixel in green means the domain has a {110} orientation in-plane.

In this study, the grayscale of all the IPFs is rendered by the *Confidence Index* (C.I.). Dark and gray pixels are the points of low confidence indexes (CI < 0.05). Although there is no quantified relationship between crystalline order and CI, qualitatively, lower CI suggests lower crystallinity. The black or deep gray areas in an IPF color map might be the zones where either the grain size is <50nm or the grains might be entirely amorphous. The Kikuchi-diffraction patterns from these low CI zones were observed to be very faint or could not be indexed by the OIM™ software.

MgB_2 NONLINEAR PROPERTIES INVESTIGATED UNDER LOCALIZED HIGH RF MAGNETIC FIELD EXCITATION

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Abstract

In order to increase the accelerating gradient of Superconducting Radio Frequency (SRF) cavities, Magnesium Diboride (MgB_2) opens up hope because of its high transition temperature and potential for low surface resistance in the high RF field regime. However, due to the presence of the small superconducting gap in the π band, the nonlinear response of MgB_2 is potentially quite large compared to a single gap s-wave superconductor (SC) such as Nb. Understanding the mechanisms of nonlinearity coming from the two-band structure of MgB_2, as well as extrinsic sources, is an urgent requirement. A localized and strong RF magnetic field, created by a magnetic write head, is integrated into our nonlinear-Meissner-effect scanning microwave microscope [1]. MgB_2 films with thickness 50 nm, fabricated by a hybrid physical-chemical vapor deposition technique on dielectric substrates, are measured at a fixed location and show a strongly temperature-dependent third harmonic response. We propose that at least two mechanisms are responsible for this nonlinear response, one of which involves vortex nucleation and penetration into the film.

INTRODUCTION

The discovery of superconductivity in MgB_2 in January 2001 [2] ignited enthusiasm and interest in exploring its material properties. Several remarkable features, for example a high transition temperature ($T_c \sim 40$ K), a high critical field, and a low RF surface resistance below T_c, shows great potential in several applications such as superconducting wires and magnets. The success of making high quality epitaxial MgB_2 thin films provides another promising application as an alternative material coating on superconducting radio frequency (SRF) cavities [3]. Over the past decade, the improvement of accelerating gradient in Niobium (Nb) SRF cavities has almost reached the BCS limit, 57 MeV/m [4]. In order to go further, new high T_c materials with low RF resistance are required for interior coating of bulk Nb cavities. High quality MgB_2 thin films may satisfy the demands for SRF coating materials because these high quality films can avoid the weak link nonlinearity between grains, and lead to the possibility of making high-Q cavities [5].

However, there still exist mechanisms that produce non-ideal behavior at low temperatures under high RF magnetic fields, such as vortex nucleation and motion in the film [6]. In addition, due to the π band and σ band, the intrinsic nonlinear Meissner effect of MgB_2 is large compared to other single-gap s-wave superconductors [7]. Therefore the study of MgB_2 microwave nonlinear response in the high frequency region (usually several GHz in SRF applications) can reveal the dissipative and nondisipative nonlinear mechanisms and allow application of these high quality MgB_2 films as cavity coatings.

In our experiment the localized harmonic response of superconductors is excited by a magnetic write head probe extracted from a commercial magnetic hard drive [1]. Based on the gap geometry of the magnetic write head probe, sub micron resolution is expected. We present our observation of at least two measurable nonlinear mechanisms involved in high quality MgB_2 films below T_c. These films were grown on sapphire substrates by hybrid physical-chemical vapor deposition technique (HPCVD). A detailed description of the growth technique has been reported before [8]. Finally, experimental nonlinearity data will be interpreted as a combination of intrinsic nonlinear response [9] and vortex nonlinearity [6].

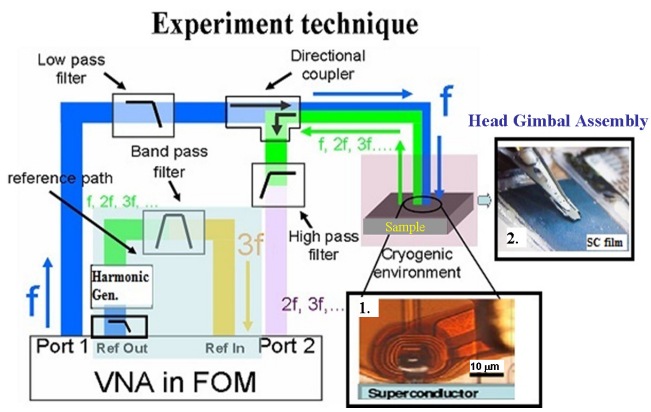


Figure 1: Set up of phase-sensitive measurement in nonlinear microwave microscopy. The frequency offset mode (FOM) of a vector network analyzer (VNA :model PNA-X N5242A) is used in this measurement. Inset 1. is a schematic picture of the probe above the sample and inset 2 shows the magnetic write head probe assembly on top of a superconducting thin film.

EXPERIMENTAL SETUP

The experimental setup for amplitude and phase measurements of the superconductor harmonic response is

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CHARACTERIZATION OF SCALE-DEPENDENT ROUGHNESS OF NIOBIUM SURFACES AS A FUNCTION OF SURFACE TREATMENT PROCESSES*

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Abstract

Microscopic topography is attributed to be a critical issue for realizing optimum performance of superconducting radio frequency (SRF) cavities. Several surface processing methods such as chemical, mechanical and plasma are used to obtain relatively smooth surfaces. Among those process methods, buffered chemical polish (BCP) and electropolishing (EP) are most commonly used in current niobium SRF cavity production. The power spectral density (PSD) of surface height data provides a thorough description to the topography measurement and reveals useful information including fractal and superstructure contributions.

Polishing duration and temperature can have predictable effects on the evolution of such features at different scale regions in PSD spectrum. In this study, one dimensional average PSD functions derived from the topography of niobium surfaces treated by BCP and EP with different controlled starting conditions and durations have been fitted with a combination of power law, K-correlation and shifted Gaussian models, to extract characteristic parameters at different spatial harmonic scales.

INTRODUCTION

Particle accelerators play a steadily increasing role in a steadily expanding range of scientific research. Their greater capabilities and superior cost for performance in many instances results in even more rapid growth for accelerators using superconducting radio frequency (SRF) cavities to power the beam. Topography of the cavity internal surface can be a major issue for cavity RF performance, thus different treatments are developed and applied to achieve high accelerating gradient.

To correlate topography and performance, a means of acquiring and analyzing topography data is needed. Data acquisition so far has been by stylus profilometer (SP) or atomic force microscopy (AFM). The data set is the vertical position of the probe at the sequence of lateral positions comprising the scan. Data analysis may be as simple as the average displacement from the mean vertical position (R_a, roughness), which has proven insufficiently incisive for SRF purposes. The next level of analysis is to condition and Fourier transform the scan data to display the contribution at each lateral dimension, the power spectral density (PSD).[1] The approach can be extended by separating the PSD into contributions related to families of surface features, as is done in the optics community.[2] These and related analyses probe the average characteristics of the surface. They are relatively insensitive to a small number of singular features, though a single major protrusion or pit may cause poor cavity performance. For these, a kind of approach that views singularities is needed.[3]

We report here two sets of experiments relevant to SRF cavity processing to show what can be revealed by the more extensive data processing approaches.

EXPERIMENT

Materials

Two fine grain samples were polished as for metallography. (nanopolished, NP), then subjected to BCP etching with very short duration to study the initial steps of BCP polishing.

Four other fine grain samples (FG) were subjected to BCP etching sufficient to remove mass equal to 100 μm thickness from the interior surface. All fine grain specimens used here were cut from untreated sheet as 10 mm × 10 mm squares. [2]

Treatments

Genesis of topography in BCP etching: Initial effect of etching

Two nanopolished NP specimens were examined as-received, after BCP with solution 1:1:2 for a time expected to remove 3 μm and the same BCP treatment applied to another two NP fine grain samples after a time expected to remove a further 3 μm.

Smoothing in EP: Initial smoothing

Four fine grain specimens, FG, subjected 100 μm BCP, were then subjected to EP treatments at 20 °C expected to remove 5 μm, 10 μm, or 15 μm one each, respectively. These conditions were chosen to explore the early short duration of EP such as is used in the latest final production etch practice of the CEBAF 12 GeV Upgrade. [3,4]

Characterization

The topography was examined by optical microscopy and atomic force microscopy (AFM) Digital Instruments

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STRAIN EFFECTS IN THE SUPERCONDUCTING PROPERTIES OF NIOBIUM THIN FILMS GROWN ON SAPPHIRE*

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Abstract

Fundamental aspects of epitaxial thin film growth such as strain due to lattice mismatch can drastically affect the superconducting properties of thin films. In our studies, we show a clear correlation between the surface morphology and microstructure with the superconducting properties of single crystal Nb(110) thin films sputter deposited on *a*-plane sapphire substrates. We found that the lattice mismatch between Nb and sapphire induces the formation of a hexagonal surface structure during the first 3 atomic layers followed by a strained *bcc* Nb(110) phase whose lattice parameter progressively relaxes reaching bulk value after 14 Nb atomic layers. The influence of the properties of such initial layers on the superconducting transition process is analyzed in detail. The results reported here indicate that interfacial strain effects must also be considered when evaluating the feasibility of multilayers for SRF cavity applications

INTRODUCTION

Superconducting thin films and multilayers have attracted the attention of the SRF scientific community in the last years due to the promise of overcoming the maximum field gradients that current bulk Nb SRF cavities can withstand, pushing them above 100 MeV/m [1]. Nevertheless, in order to achieve the desired properties, special attention needs to be devoted to the epitaxy and growth mode of such thin films. In particular, high quality films have been obtained on *a*-plane sapphire, where Nb grows (110) with the Nb[$\bar{1}$11] direction parallel to Al_2O_3[0001] leading to a lattice mismatch of 10.7% along the Nb[001] direction and of 8.3 % along the perpendicular Nb[110] direction[2, 3]. Oderno et al.[4] showed a transition from an initial hexagonal surface structure for thicknesses lower than 1.5 nm to *bcc* Nb(110) for thicker films, nevertheless they did not report on whether the *bcc* phase is already relaxed or if there exists a coherent strain relaxation. The study of the early stages of Nb thin films growth is of paramount importance since the presence of additional phases, coherent relaxation of the strain, misfit dislocations or other epitaxial growth defects can strongly affect the superconducting properties of the entire system. Nevertheless, a clear connection between interfacial growth effects and superconducting properties for Nb thin films grown on *a*-plane sapphire has not been established yet. Here, we present a complete correlation between morphology and structure of Nb thin films and their superconducting properties, emphasizing the influence of the first strained atomic layers on the global superconducting properties of the films.

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RESULTS AND DISCUSSION

Nb thin films were prepared by DC magnetron sputtering deposition in an ultra-high vacuum (UHV) system with base pressure in the low 10^{-10} Torr range on *a*-plane sapphire substrates with miscut angles lower than 0.05 degrees. The substrates were ultrasonically cleaned in baths of acetone and methanol and subsequently annealed at 600 ºC for one hour in UHV conditions prior to growth. Sputtering deposition was carried out from a high purity (99.95 %) Nb target at 1 x 10^{-3} Torr Ar pressure, resulting in a growth rate of 0.35 Å/s. Nb films of thickness up to 600 nm were deposited at a substrate temperature of 600ºC which was determined to favor crystalline ordering.

The surface morphology of superconducting thin films is of great importance for SRF applications since it can affect their surface impedance and hence their SRF performance In Figure 1, Atomic Force Microscopy (AFM) topography images clearly show the evolution of the morphology of the Nb films with thickness ranging from 30 nm to 600 nm.

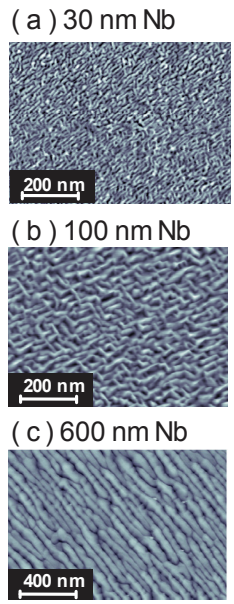


Figure 1: AFM topography images for the (a) 30 nm (b) 100 nm and (c) 600 nm Nb films grown on a-plane sapphire.

RF SURFACE IMPEDANCE OF MgB_2 THIN FILMS AT 7.5 GHz *

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Abstract

The Surface Impedance Characterization (SIC) system at Jefferson Lab [1] can presently make direct calorimetric RF surface impedance measurements on the central 80 mm^2 area of 50 mm diameter disk samples from 2 to 40 K exposed to RF magnetic fields up to 14 mT at 7.5 GHz. MgB_2 thin films from STI/LANL were deposited on 50 mm diameter Nb disks using reactive evaporation technique. We will report the results of measurement on one of these samples using the SIC system. The data is interpreted based on BCS theory as the temperature-dependant properties suggest evaluation of the T_c, energy gap, penetration depth, mean free path and coherence length.

INTRODUCTION

The accelerating gradient of superconducting radiofrequency (SRF) Nb cavities has been pushed to 52 MV/m for single-cell cavity [2] with quality factor higher than 10^{10}, approaching the theoretical limit of Nb. It is still not quite clear that whether RF critical field of SRF cavities are limited by superconductor's superheating critical field or not, the efforts on Nb cavities already showed that RF critical field could be higher than Nb's lower critical field. Thus, superconductors with surface resistance lower than, and superheating critical field higher than those of Nb are of great interest for SRF application. Magnesium diboride (MgB_2), discovered to be a superconductor by Nagamatsu et al, in 2001 [3], could potentially be one of the substitute materials for SRF applications.

MgB_2 is a simple binary compound that contains graphite-type boron (B) layers separated by hexagonal close-packed magnesium (Mg) layers, with a high critical temperature at 39~40 K [4], twice as high as the second highest T_c (Nb_3Ge at 23K) in binary superconductors. It has two energy gaps, with π-band at 2.3 meV and σ-band at 7.1 meV [5]. At temperatures much lower than its critical temperature, the BCS surface resistance $Rs \sim (A\omega^2/T)\exp(-\Delta/k_bT)$ is dominated by the π-band. Comparing with Nb's energy gap at 1.5 meV, the BCS surface resistance of MgB_2 could be much lower than that of Nb. The superheating critical field for MgB_2 can be calculated from $H_{sh} = 0.75\sqrt{H_{c1}H_{c2}}$ [6], which is about 170~1000 mT [4] depending on the field's direction. In case the RF performance is limited by its lower critical field, MgB_2 is still an attractive choice for multilayer thin film coating, which is proposed by Gurevich [7], that the structure of alternating insulating layers and thin superconducting layers of thickness smaller than the London penetration depth could be adopted to overcome the RF critical field of either superconducting layer or superconducting substrate, and at the same time to get benefit from the low surface resistance of the superconducting layer.

In this paper, we report the use of the SIC system developed at Thomas Jefferson National Accelerator Facility (JLab) to measure the surface impedance of MgB_2 under different temperatures.

DESCRIPTION OF APPARATUS

In the SIC system a sample is placed at the open end of a TE_{011} cylindrical Nb cavity with a sapphire rod inside, shown in Figure 1. The whole system works at 7.5 GHz. The sample is thermally isolated from the cavity body. Heat can be conducted from the sample only via the thermal insulator. The surface impedance of the sample can be derived by directly substituting heater heat for RF heat (heat substitution method) under controlled RF field and temperature conditions. A detailed description has been given in [1].

The calorimetry of the SIC system has been recently upgraded to accommodate different substrates such as aluminium, copper, sapphire, magnesium oxide, Nb, silicon, etc. Two versions of calorimetry system are currently using in SIC system: high precision version and high power version. The only difference between them is that the high precision version adopts stainless steel as the thermal insulator while the high power version adopts copper. Samples are clamped onto the sample holder using a stainless steel cap with 6 aluminium bolts and 15 lb-in torque on each of them. The thermal contraction $(L_{293}-L_0)/L_{239}$ of aluminium is 0.00415, larger than those of copper (0.00326) and stainless steel (0.00296), which would make the thermal contact between sample and sample holder even better while cooling down from room temperature to 2 K. G-10 washers are used to thermally separate aluminium bolts from the stainless steel cap so that thermal leak from the stainless steel cap to the bath could be minimized. Thermal radiation of the sample is in μW range; the ratio between thermal leak from electric wires for heaters/sensors and the designed thermal pass is less than 1%. Sample temperature is measured from sensor N in Figure 1, which is mounted on a spring and could directly measure the temperature on the back of the

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TE Sample Host Cavities Development at Cornell *

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Abstract

In order to measure surface resistance of new materials other than niobium such as Nb_3Sn and MgB_2, two sample host niobium cavities operating at TE modes have been developed at Cornell University. The first one is a 6GHz pillbox TE_{011} cavity modified from an older vision enabling testing 2.75 inch diameter flat sample plates. The second one is an optimized mushroom-shape niobium cavity operating at both 4GHz TE_{012} and 6GHz TE_{013} modes for 10cm inch diameter flat sample plates. First results from the commissioning of the two TE cavities will be reported.

INTRODUCTION

In the past three decades, different types of sample host cavities were designed and used to test niobium or alternative materials for superconducting cavities [1], [2], [3], [4]. Most of them employed oscillating TE modes in the host cavities. However, none of them has achieved magnetic field higher than 650Oe (65mT) on the sample, and often the sensitivity in surface resistance is well above the desirable nΩ range. Since niobium is approaching its theoretical superheating field around 2000Oe, a high field and high sensitivity sample host cavity is ideal for studying various field-dependent loss phenomena in niobium. Also since the alternative materials such as Nb_3Sn and MgB_2 are expected to have a very high breakdown field, a sample host cavity can reach above 2000Oe is especially needed to test those materials.

At Cornell University, two sample host TE cavities have been designed and are currently under commissionning. In the following sections, rf design considerations, the cavity preparation apparatus and RF test results using baseline niobium bottom plates will be presented.

TE PILLBOX CAVITY RF DESIGN

Various versions of TE pillbox cavities have been used at Cornell University to study surface resistance of high temperature superconductors $YBa_2Cu_3O_7$, ultra-high vacuum cathodic arc films coated samples and MgB2 [3], [4], [5]. For the first TE pillbox cavity, the sample was introduced into the cavity by a sapphire rod through a niobium cutoff tube aligned along the cavity axis. A thermometer was attached to the sapphire rod near the sample and a heater was attached to the bottom of the sapphire rod. The heater and both thermometers were placed well beyond RF cutoff. This cavity was used to measure $YBa_2Cu_3O_7$ rf surface resistance at various temperatures with magnetic field on the sample of 1 Oe [3]. The highest magnetic field reached on the sample surface was around 11 Oe. Later the bottom plate of the cavity was replaced by the Nb/Cu end plate with a groove on the surface of the sample which was intended for removing the degeneracy between TE_{011} and TM_{110} modes. This cavity had a very high residual resistance above $1\mu\Omega$ and the maximum surface field achieved was around 300 Oe. Therefore, a new TE pillbox cavity was designed to enable testing flat surface samples and was aimed to reach high surface magnetic field by using carefully treatments and improved rf designs.

In order to test a flat sample, the groove was moved to the top plate near the coupler port. Fig.1 shows the magnetic field distribution of the new TE pillbox cavity. The maximum field on the cavity surface is located near the coupler port due to the presence of two separate grooves. S21 data measured by a network analyzer during cool down confirmed that the new groove design successfully seperated the two degenerate modes TE_{011} and TM_{110}. Fig.2 shows another bottom plate design that introduced two symmetric ports. One of the port is blanked off by a niobium plate. The other port enables placing a sample into the high magnetic field region by using the existing cutoff tube with the sapphire rod. Compared with single cutoff tube aligned with the cavity axis, the new design increase the surface magnetic field on the sample placed on the sapphire rod. The design parameters of this TE pillbox remake are shown in Table.1

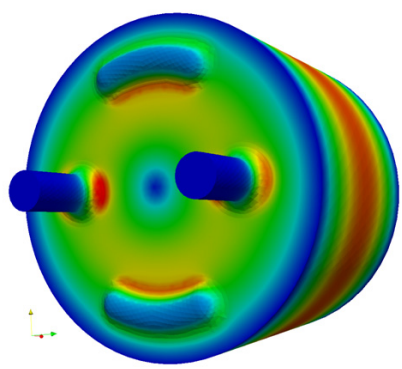


Figure 1: Surface magnetic field distribution of the TE_{011} mode of TE pillbox cavity.

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LASER RE-MELTING INFLUENCE ON NB PROPERTIES: GEOMETRICAL AND CHEMICAL ASPECTS

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Abstract

Repair of SRF cavities has provided improved yield at 35 MV/m. Laser melting is one technique to remove quench limitation by altering the niobium defect topography. In this paper we present a part of our recent R&D using a single laser pulse to deposit enough energy to entirely melt the defect area. The pulse produces morphology analogous to an impact. Also, the short time takes advantage of the argon cover gas to minimize oxidation. Materials characterizations are presented and discussed with regard to the advantages of the technique from the materials point of view.

INTRODUCTION

A significant fraction of cavity quench locations can be traced to surface irregularities, usually hemispherical pits and crack - like terraces. It has been suggested that magnetic field lines are enhanced on the edges of those objects, which leads to the exceeding of the local critical field and to the initiation of the thermal runaway process when flux lines then penetrate [1]. The model ties in the external magnetic field with geometrical parameters of the pit, predicting higher quench field for bigger defects [2]. Thus, it is essential to smoothen such local imperfections so field enhancement no longer imposes a limit to the accelerating field.

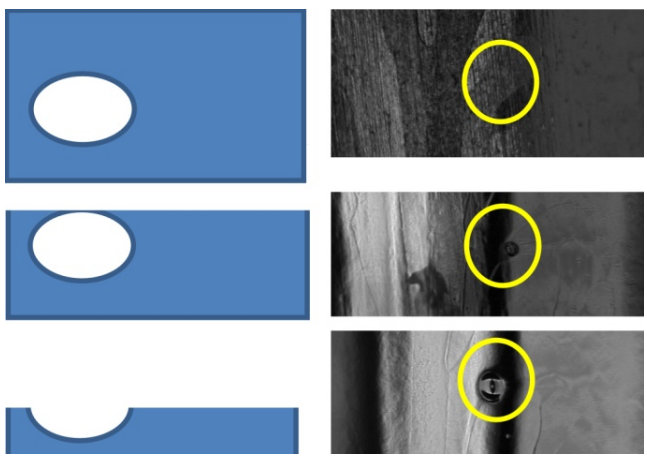


Figure 1: Defect uncovered by consequent EP and tracked by optical inspection (FNAL, D. Sergatskov).

The origin of pits is presently being debated. One explanation is that hydrogen bubbles are uncovered during chemical polishing. This suggests local repair approaches are valuable to repair pits, since bulk re-polishing might expose new irregularities (see Fig.1). Taking into account that the size of pits varies from 100 μm to 1000 μm, as well as the constraints imposed by working from the inside of the cavity, repair techniques can be highly technical. Laser melting provides a highly collimated, high intensity beam capable of altering the Nb surface. The proof of this principle has been demonstrated by G.Wu and M.Ge on a 1-cell cavity [3]. Here, we analyze in more depth the effect of various parameter choices on Nb surface morphology and composition. to better understand the advantages of the laser over other local repair techniques. We also aim to develop an appropriate post processing, if any. To achieve that goal the Electron Backscattered Diffraction (EBSD) microscopy has been used on the same level with Laser Scanning Confocal Microscopy (LSCM). In this paper we present only the results of single pulse melting, as used by Ge and Wu earlier. Multiple pulses can also be used to more gently heat the surface and produce different effects, which will be the subject of another article.

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EXPERIMENTAL DETAILS

Single pulse melting has been performed on the both single grain and fine grain Nb coupons with indented pits. The indentation of artificial defects is supposed to model both the geometrical perturbation (hemispherical pit, Fig.4 middle row) and subsurface microstructural perturbations (enhanced dislocation content, Fig.2 middle row) found in actual cavity pits. After remelting microscopy analysis has been performed in the FNAL Microscopy Lab by means of the EBSD (Oxford INCA 200) system built upon a scanning electron microscope (JEOL JSM-5900LV). Topography was analyzed with a LCSM (Keyence VK-9700 Color 3D).

RESULTS AND DISCUSSION

In Figure 2 the single crystal data is presented. The left column consists of electron microscope snapshots of initial surface, of indent on the surface and of remelted indent (from top to bottom respectively). Right column represents the local misorientation maps. This EBSD capability shows changes of grain orientation over a small scanning area, which can be associated with the presence of dislocations and stress. The color amplitude is significantly increased after indenting (second row, right picture) due to the plastic deformation, whereas after remelting the dislocation density drops to the initial value observed before indenting. Hence, these data imply that the laser does indeed anneal the Nb surface over the broad

INVESTIGATION OF NEAR-SURFACE HYDROGEN IN CAVITY-GRADE NIOBIUM

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Abstract

Details of the distribution of near-surface hydrogen in niobium cavities are important for research into possible mechanisms involving hydrogen, which affect the dependence of the cavity quality on the magnitude of surface fields. We utilized an elastic recoil detection (ERD) technique with the depth resolution of about one nanometer on samples, which underwent different treatments similar to the ones with the known effect on cavity performance. Results of the study indicate a significant segregation of hydrogen within the first few nanometers near the surface. Standard heat treatments, such as 600°C, 800°C and 120°C heat treatments, do not systematically change the near-surface hydrogen content.

INTRODUCTION

Recent developments in the research on the high field Q-slope and mild baking effect highlighted the need to understand in detail the distribution of hydrogen in niobium.

Superconducting RF (SRF) cavities made of bulk niobium are used as primary accelerating structures in a number of present and future accelerators based on the superconducting technology. Significant progress has been made in the last few years in achieving better accelerating gradients in SRF cavities. Nevertheless, full understanding of surface structure of niobium used in cavities is not yet developed. One area of recent active research is the contributions of different near-surface lattice defects to the cavity performance at high fields, and in particular on a *high field Q-slope* (HFQS) (see [1] for review). An underlying mechanism of a strong effect of the in situ vacuum baking at 120°C for 48 hours on the high field performance of niobium cavities remains controversial.

A key question is what particular material intrinsic or extrinsic properties are leading to the RF losses in the HFQS. A closely related and equally important question is what changes in the niobium near-surface composition and structure at 120°C. Several niobium defects, such as dislocations [2], vacancies [3], and near-surface interstitial hydrogen [4] are currently considered as possible causes of the HFQS and all can be active in the experimentally observed mild baking effect. For all three types of defects, it is crucial to understand their distribution and change on the scale of magnetic field penetration depth (about 40 nm) during cavity processing treatments. In particular, for dislocations and vacancies, hydrogen may be involved in the mild baking effect via vacancy-hydrogen complexes [5], while the interstitial hydrogen model relies on the changes of hydrogen content itself during different treatments. An earlier study [6] explored the effect of different chemical etching solutions on the near-surface hydrogen content with the depth resolution limited at the time to about 30 nm due to the detection method. In this study we advance the hydrogen distribution issue by using ERD on samples treated using different thermal and chemical etching steps with known outcomes on RF cavities. Additionally ERD spectra of two cavity cutout samples were measured and correlated with their drastically different RF behavior.

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EXPERIMENTAL

Samples Preparation and RF Tests

We used two types of samples for the studies: (i) rectangular 1.2×1.5 cm, 3 mm thick samples cut with wire electrical discharge machining (EDM) from RRR 300 single grain niobium sheet and subjected to 150 μm buffered chemical polishing after cutting; (ii) circular cutouts from a large grain buffered chemical polished (BCP) cavity limited by the HFQS and a fine grain electro polished (EP) cavity free of the HFQS.

Niobium sheet samples were subjected to a sequence of surface treatments similar to those performed on cavities with the known outcomes on RF performance. Several different surface treatments were tried including (i) vacuum baking at 600°C for 10 hours, (ii) 800°C for 4 hours, (iii) 120°C for 48 hours, and (iv) rinsing in a concentrated (48%) hydrofluoric acid (HF) for 20 minutes. Details of the treatments with the list of samples used in the studies are shown in Table 1. Cavity cutout samples come from two different cavities: large grain BCP cavity LE1-37 with the grain size of about 10 cm, and a fine grain TE1AES004 EP cavity with the grain size of about 50 μm. TE1AES004 was subjected to 120°C 48 hours vacuum treatment to eliminate the HFQS. LE1-37 cavity was limited by the HFQS and the cutout represents an area with high RF losses in the HFQS regime (hot spot). Details on LE1-37 cavity tests and surface analytical techniques applied on cutouts are reported elsewhere [5, 7, 8]. TE1AES004 cutout represents an area without any RF losses (cold spot) up to the highest field reached, which was determined by the localized quench at a different location. Full analysis of other TE1AES004 cutouts using alternative techniques is currently underway and will be published elsewhere. Temperature increase of the outside cavity wall was registered with carbon resis-

MATERIAL FOR FABRICATION OF DESY LARGE GRAIN/SINGLE CRYSTAL CAVITIES

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Abstract

Material for large grain LG and single crystal SC cavities of TESLA shape has been developed in collaboration with industry. One of the aspects of LG material was electron beam melting of the ingots with required structure. The second was slicing of the discs cost effectively with tight thickness tolerances, high surface quality and high purity. Surface and structural properties of SC on the LG discs are investigated. Measurements of the crystal orientation on the LG discs of three companies have been done by complete penetration using synchrotron radiation. Two LG material features have been stressed in cavity production: the influence of the LG crystal orientation on the anisotropic behavior during deep drawing and the impact of pronounced steps at grain boundaries on cavity behavior. 11 LG 9-cell cavities of XFEL-like shape are fabricated. The procedure of increasing the crystal size by rolling of LG discs and cut out of SC discs, followed by subsequent forming and welding without destroying of the SC structure, was developed. A method of fabrication of single crystal cavities was proposed. Several SC cavities with different crystal orientations were produced.

CONTRIBUTION NOT RECEIVED

INVESTIGATION OF SAMPLES SEPARATED FROM PROTOTYPE CAVITIES OF THE EUROPEAN XFEL

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Abstract

XFEL prototype cavities fabricated in industry and treated at DESY mainly meet the specification. Few cavities demonstrated low performance (13-20 MV/m) limited by thermal breakdown. The T-map analysis detected quench areas mainly close to the equator. Optical inspection by high resolution camera allowed tracking the several stages of preparation (as received, after the main electropolishing EP, after RF test) and in some cases makes possible monitoring the evolution of defects. In order to understand the nature of reduced performance and get more detailed information on the origin of defects, some samples have been extracted from four cavities and investigated by light microscope, 3D-microscope, SEM, EDX and Auger spectroscopy. Several surface flaws with sizes from a few μm to hundreds of μm have been detected. The defects can be grouped in four categories. The first category of defects indicates foreign elements (often with increased content of carbon). Deviation from smooth surface profile characterizes the second type of defects (holes, bumps). Damaged surface areas at high pressure water rinsing and etching pits belong to the third and fourth category of defects.

CONTRIBUTION NOT RECEIVED

SUPERCONDUCTING DC AND RF PROPERTIES OF INGOT NIOBIUM*

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Abstract

The thermal conductivity, DC magnetization and penetration depth of large-grain niobium hollow cylindrical rods fabricated from ingots, manufactured by CBMM subjected to chemical and heat treatment were measured. The results confirm the influence of chemical and heat-treatment processes on the superconducting properties, with no significant dependence on the impurity concentrations in the original ingots. Furthermore, RF properties, such as the surface resistance and quench field of the niobium rods were measured using a TE_{011} cavity. The hollow niobium rod is the center conductor of this cavity, converting it to a coaxial cavity. The quench field is limited by the critical heat flux through the rods' cooling channel.

INTRODUCTION

Bulk niobium (Nb) has been the material of choice for the superconducting radiofrequency (SRF) cavity used in particle accelerator because of its highest transition temperature (T_c) and highest lower critical field (H_{c1}~ 190 mT) among the elemental type-II superconductors [1]. The overall performance of these SRF cavities is measured by its quality factor, Q_0 as a function of the accelerating gradient, E_{acc}. Higher Q_0 for the reduction of cryogenic loss and higher E_{acc} for the use of high energy accelerators are desired. In the last four decades, much work has been done to push the performance of SRF cavity to its theoretical limits of the accelerating gradient (~55 MV m^{-1}). One of the issues towards achieving those limits is the occurrence of a sharp increase of the radio frequency (RF) losses when the peak magnetic field, B_p, reaches about 90 mT, consequently limiting the operational accelerating gradient of SRF cavities [2]. This phenomenon is referred to as "high field Q-slope" or "Q-drop". Besides the Q-drop, several factors are limiting the high gradient and Q_0, such as, field emission, multipacting, residual resistance and thermal instabilities. Efforts have been made to overcome these problems using, buffer chemical polishing (BCP), electropolishing (EP), centrifugal barrel polishing (CBP), high temperature (HT) treatment, low temperature baking (LTB) and (or) its combination.

In recent years, large grain ingots Nb become an alternate to the fine grain Nb for the fabrication of high performance SRF cavities. Simpler fabrication procedures, potential cost reduction, higher thermal stability at 2K, as well as reproducibility in the performance of cavities has attracted the SRF communities towards the fabrication of SRF cavities with ingot Nb [3,4]. The study of the superconducting properties of these ingots Nb is important to optimize the chemical and heat treatment procedure during the fabrication of SRF cavities. Recently [5-7], the DC and low frequency magnetic and thermal properties of large-grain ingot niobium samples subjected to different chemical and heat treatment were reported. In this contribution, we extend the similar study to the cylindrical hollow rods of larger diameter (12 mm compared to previously measured 6 mm samples) fabricated from new niobium ingots, manufactured by CBMM (Companhia Brasileira de Metalurgia e Mineração), Brazil, subjected to the chemical and heat treatment used in cavity fabrication. Furthermore, RF properties such as the surface resistance and quench field of the niobium rods were measured using a TE_{011} cavity [8]. The combination of these measurement techniques may help in finding correlations between superconducting parameters which can be measured more easily on samples and their RF properties, which are directly related to SRF cavity performance. So far, there has been limited availability in the SRF community of systems capable of measuring the RF surface resistance of superconducting samples at peak magnetic field values (B_p) greater than about 40 mT [9].

EMPERIMENTAL SETUP

The system used to measure the thermal conductivity, DC magnetization, the penetration depth and surface pinning characteristic is described in Ref. [5]. As described in Ref. [8], the RF tests of the Nb pill-box cavity which was going to be used to measure the RF properties of the Nb rods showed very strong multipacting at B_p ~ 20 mT. This problem was mitigated by cutting the bottom plate of the pill-box and replacing it with a grooved plate designed to increase the frequency separation between the operating mode (TE_{011}) and the neighbouring TM_{111} mode from the initial 7 MHz to about 32 MHz. The new bottom plate was machined from ingot Nb and is sealed to the rest of the cavity with indium wire.

It was found that the next limitation of the system to allow achieving high B_p-values on the surface of the rod inserted in the center of the cavity was given by the critical heat flux for He-II, because the long cooling channel in the hollow rod was only 2 mm in diameter.

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PHASE-SENSITIVE NONLINEAR NEAR-FIELD MICROWAVE MICROSCOPY ON MGB2 THIN FILMS

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Abstract

MgB2 has recently attracted much attention as a coating for Nb to enhance the RF critical field in Superconducting Radio Frequency (SRF) cavities. However the surface properties of MgB2, including its intrinsic nonlinearities as well as various types of defects, can limit the RF performance of such cavities. This work presents phase-sensitive nonlinear near-field microwave microscopy on MgB2 films. An intense localized RF magnetic field is induced on the surface of MgB2 films by means of a magnetic write head, and the amplitude and phase of the third harmonic voltage generated by the film are measured. Power and temperature dependence of the third harmonic response are studied to identify the dominant mechanism of nonlinearity in the film under different operating conditions, and a phenomenological model is developed to relate the nonlinear response to the local critical RF field. The method could be generalized by scanning the probe over the sample, and possibly over various defects, to generate a map of the critical RF field and enable classification of different types of defects in terms of their effect on the RF performance of MgB2.

CONTRIBUTION NOT RECEIVED

CORRELATION OF MICROSTRUCTURE, CHEMICAL COMPOSITION AND RRR-VALUE IN HIGH PURITY NIOBIUM (NB-RRR)

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Abstract

Specification and working point of linear accelerators reaches the limit for the niobium cavities from a physical and metallurgical point of view. From literature it is known, that increased level of interstitial impurities and the presence of residual stresses after the final heat treatment can cause a severe degradation of the RRR value.

The possible influence of different impurity levels on the RRR value were calculated and discussed with regard to the current material specification for the XFEL project. For verification the results were compared with measured values from a melted niobium ingot. Sheet sections from one production lot, with RRR-values in the range of 360 to 430, have been analysed in the scanning electron microscope (SEM) utilizing EBSD (Electron backscattered diffraction) to study the scattering of the crystallographic texture.

The scatter of grain size, hardness and texture are in a typical range and in agreement with results from literature. Measured gas contents and RRR values on bulk niobium are in good agreement with the material specification. An influence of the observed texture variation on the RRR-value wasn't observable.

INTRODUCTION

High-purity niobium with a high residual resistivity ratio (Nb-RRR) is the key issue for the fabrication of superconducting accelerating cavities for future particle accelerators (XFEL, ILC). Starting material for fabrication of cavities are rolled polycrystalline Nb-RRR sheets with uniform grain sizes, which are subsequently processed by deep drawing, e-beam welding and surface treatment. To obtain high accelerating gradients and quality factors constant material properties in terms of thermal conductivity and RRR-values surface quality are necessary. [1,2]

In the course of cavity testing a high scatter of RRR-values has been observed throughout different investigation programs. The reason for these fluctuations could not be revealed by standard examination methods. Beside parameters for chemical and thermal treatment and surface condition of the inner surface of the cavity, material properties play an important role. Thermal conductivity and RRR values are strongly influenced by the content of interstitials (O,C,H and N), amount and distribution of impurities, grain size, texture, residual stresses and density of dislocations. [3]

In the context of our research we applied further investigations to get a comprehensive understanding about the influence of micro structural properties and impurity concentrations on the RRR value.

The influence of different impurity levels on the RRR value were estimated by calculation and discussed with regard to the current material specification for the XFEL project. For verification the results were compared with measured values from a melted niobium ingot used for production. On different sheet sections from the same production lot the homogeneity of microstructure and material properties were investigated in the annealed condition.

INFLUENCE OF IMPURITIES AND MICROSTRUCTURE ON RRR VALUE

To determine the quality of the niobium material, simple methods have been implemented for quality assurance. A common method to determine the purity and homogeneity of niobium is to measure the RRR-value. In the specification for XFEL the RRR value is determined with 300 or higher. The electrical resistivity is measured by using four point technique, with an applied magnetic field, to suppress the superconducting state. The RRR-value is defined as follows:

$$RRR = \frac{\rho(295K)}{\rho(4{,}2K)} \quad (1)$$

where ρ is the electrical resistivity at given temperature.

It is well known that the electrical resistivity of metals at temperatures close to T=0 K is mainly caused by impurities ρ_{fa}, defects ρ_d and for thin specimens by electron-surface-scattering ρ_s. At this temperature the intrinsic resistivity from electron-phonon scattering $\rho_{i(T)}$ is negligible, but it becomes dominant at room temperature. Hence,

$$\rho = \rho_i(T) + \rho_{fa} + \rho_d + \rho_s \quad (2)$$

The proportional constants for several impurities and micro structural defects (like e.g. vacancies, dislocations and grain boundaries) in niobium are shown in Figure 1. [4].

In order to achieve RRR values of 300 and higher the concentration of impurities must be kept as low as possible (see valid material specification for XFEL in Table 1). Zirconium is not included in the XFEL specification, the maximum value was taken from ASTM B 393-05, Type 5 for the sake of completeness. The

FIRST PRINCIPLES INVESTIGATION OF HYDROGEN IN NIOBIUM

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Abstract

Niobium hydride is a contributor to degraded niobium SRF cavity performance by Q-slope and Q-disease. Hydrogen is easily absorbed into niobium when the protective oxide layer is disturbed, such as during electropolishing and chemical treatments, and the structure and distribution of hydrogen in niobium is altered during other processing steps such as baking. To optimize cavity performance and production efficiency, it is important to understand the structures of hydrogen in niobium, including the interactions of hydrogen with structural defects and other impurities such as oxygen. In this study density functional theory was used to evaluate these interactions. Hydrogen was examined as a dissolved interstitial impurity and in ordered niobium-hydride phases; and the interactions between hydrogen, niobium, vacancies on niobium sites, and oxygen dissolved in niobium were evaluated. The results yield information about the thermodynamic, electronic, magnetic, and geometric properties of these systems, which lead to important implications concerning the mobilities of impurities and vacancies in niobium and the precipitation of phases that are detrimental to cavity performance.

CONTRIBUTION NOT RECEIVED

ACTIVATION OF FIELD EMITTERS ON CLEAN NIOBIUM SURFACES

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Abstract

Systematic investigations of the influence of heat treatments of high-purity Nb samples at temperatures between 122°C and 800°C on the parasitic field emission are reported. Two large grain and two single crystal Nb samples were used. The samples got up to 40µm final BCP polishing and high pressure ultra pure water rinsing at DESY. The heat treatment of the Nb samples has lead to a definite activation of field emitters on the surface. The emitter number density increases significantly with temperature of the heat treatment.

INTRODUCTION

Heat treatments (HT) of superconducting Nb cavities have become a very important part of the preparation procedure for hydrogen degassing after electropolishing of the cavities [1]. Furthermore, a bakeout at temperature between 100°C and 170°C for 48 hours improves the quality factor Q_0 of cavities at high gradients. This effect is confirmed for cavities that got buffered chemical polishing (BCP) as well as for electropolished (EP) ones before the final high pressure rinsing (HPR) with ultra pure water [2-3]. The improvement of Q_0 is explained by the diffusion of oxygen away from the oxide layer at the surface into the superconducting Nb bulk. Thereby the surface resistance R_s decreases and the critical field increases [2, 4]. The cavity preparation for the European XFEL contains two bakeouts: early at 800°C after the initial polishing and finally at 120°C just before the vertical test [5].

Former results have shown that annealing of the Nb surface at temperatures of 400 to 800°C can activate field emission (FE) at electric onset field E_{on} (required for 1 nA FE current) down to 40 MV/m [6]. Experiments with large grain Nb samples have also shown a grain boundary assisted FE at about 200 MV/m after a bakeout at 150°C for 14 hours [7]. Since FE is one of the main field limitations of the high gradient superconducting cavities required for XFEL and ILC, we have systematically investigated the influence of such different HT on the FE behaviour of single crystal (SC) and large grain (LG) Nb samples prepared at DESY.

EXPERIMENTAL TECHNIQUES

For the systematic investigations of parasitic FE from the Nb samples we have used a specially constructed non-commercial field emission scanning microscope (FESM) shown in Fig. 1 [8]. The FESM is an advanced microscope for investigation of FE site distributions on

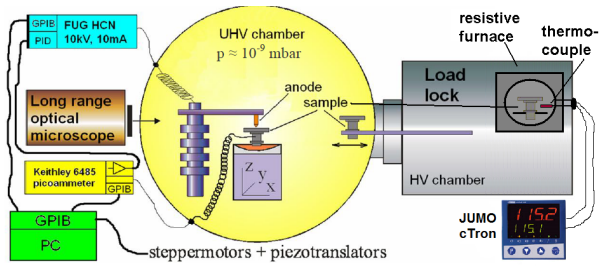


Figure 1: Schematic view of the FESM microscope.

"flat" cathodes of up to 25 x 25 mm^2. The cathode is xy-surface tilt-corrected with respect to the anode to achieve a constant gap Δz within ±5 µm for the full scan area. The measurements are done in ultrahigh vacuum (UHV) of 10^{-9} mbar by means of non-destructive regulated voltage scans V(x, y) at a fixed FE current (typ. 1 nA). It employs a PID-regulated power supply FUG HCN100M-10000 controlled by the FE current as measured with a digital picoammeter Keithley 6485 or an analog electrometer Keithley 610C described elsewhere [9]. The power supply provides up to 10 mA current and 10 kV voltage, which corresponds to 500 MV/m macroscopic field at 20 µm gap. By in-situ exchange between needle-anodes and truncated cone anodes, the emitter distribution and emitter number density on selected areas of the samples can be verified with the required resolution. The activation field E_{act}, onset field E_{on} as well as field enhancement factor β and emitting area S of arbitrarily chosen individual emitters can be measured as well. The last two parameters are calculated from the measured I-V characteristics of the emitters using the modified Fowler-Nordheim law [10] for field emission:

$$I_{FN} = A\frac{SE^2}{\varphi\ t^2(y)}\exp\left(-B\frac{\varphi^{3/2}v(y)}{E}\right)$$

The needle anodes have a tip apex radius of $R_a \geq 1$ µm, while the truncated cone anodes are up to 300 µm in diameter. The macroscopic electric field E is calibrated for each emitter as the linear slope of the PID-regulated $V(z)$ dependence for 1 nA current. Moreover, the real distance d between the tip anode and the relevant emitter is determined by the linear extrapolation of each $V(z)$ curve to zero voltage [11].

The load lock (preparation) chamber of the FESM was recently equipped with a resistive furnace which is used for the annealing of samples up to 1200°C under HV conditions (<10^{-6} mbar). The temperature inside the

INVESTIGATION OF EPITAXIAL NIOBIUM THIN FILMS GROWN ON DIFFERENT SURFACES SUITABLE FOR SRF CAVITIES*

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Abstract

Superconducting radio frequency (SRF) technology used in linear accelerators is based on bulk Nb cavities that have high costs and are approaching the maximum field gradients they can withstand [1]. Thus, development of a suitable alternative to bulk Nb is needed. Several attempts with varying degrees of success have been made to implement Nb-coated Cu cavities since the thermal conductivity of Cu is better than bulk Nb [2]. Our studies show that the transport properties of Nb, in particular the residual resistance ratio (RRR), are better when Nb is epitaxially grown on crystalline ceramics (i.e. MgO and Al_2O_3) compared to Cu templates. Since grain boundaries are one of the main obstacles to superconducting transport, we show how the increased number of crystallographic domains that can occur during epitaxial Nb growth onto Cu surfaces leading to higher density of grain boundaries can explain these results. We propose a route to improved performance while keeping thermal efficiency advantages by using epitaxial seed-layers on Cu templates that can decrease grain boundary density in the final Nb film. We will show our correlated studies of microstructure and surface morphology and the resulting transport/susceptibility properties illustrating possible mechanisms to improve cavity performance of such films.

EPITAXIAL NIOBIUM FILMS

Film Deposition

Epitaxial Nb films have been prepared by DC magnetron sputtering at 1 mTorr on various surfaces including MgO (100), Al_2O_3 (11-20), Cu (100), and MgO reactively sputtered onto Cu (100). The ceramic MgO and Al_2O_3 substrates used were acquired commercially while the Cu surface was prepared by depositing fresh Cu layers onto Si (100) [3] in UHV in order to avoid native oxides as well as surface treatments that might complicate our growth studies. The thickness of the films studied ranged from 500-600 nm. On both MgO and Al_2O_3 substrates, the growth temperature was held at 600 °C which was found to lead to optimized films, while the Cu/Si substrate temperature was constrained below 175 °C in order to prevent silicide formation at the Cu/Si interface. The micro-structure of the films was studied *in-situ* with reflection high-energy electron diffraction (RHEED) and the surface morphology of the films was examined *ex-situ* with atomic force microscopy (AFM) and associated software [4]. In order to simplify the discussion, the samples that were investigated here have been designated as sample A-E and their growth conditions are listed in Table 1.

Table 1: Summary of Sample Parameters

Name	Substrate	Nb Orientation	Nb Thickness	Nb Growth Temp
A	MgO (100)	(100)	500 nm	600 °C
B	MgO (100)	(110)	600 nm	600 °C
C	500 nm Cu (100) / Si (100)	(110)	500 nm	150 °C
D	1 nm MgO/ Cu (100)/ Si (100)	Polycrystalline	500 nm	150 °C
E	Al_20_3 (11-20)	(110)	600 nm	600 °C

Microstructure and Surface Morphology

The epitaxy of the deposited Nb film is highly dependent on the choice of substrate. In the case of an MgO (100) surface, Nb films will either grow (100) oriented with only one possible grain structure, Nb(100)[011]||MgO(100)[001], or (110) oriented with two possible grain orientations, Nb(110)[-1-10]||MgO(100)[001] and Nb(110)[001]||MgO(100)[001] [5]. In the case of Nb growth on Cu (100), there are four possible grain orientations that can form such that Nb(100)[111]||Cu(100)||[110] [6]. A visual depiction of the possible orientations of Nb on MgO (100) and Cu (100) is shown in Figure 1. Nb also grows (110) oriented on Al_2O_3 (11-20) [7].

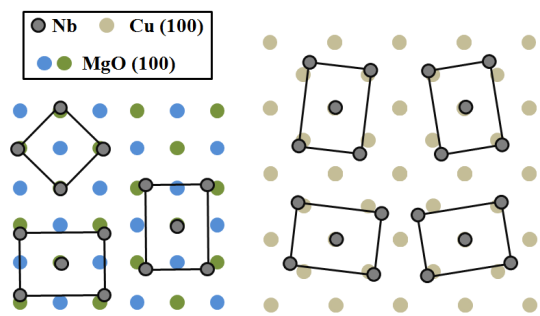


Figure 1: Overlays of a relaxed Nb lattices on MgO (100) and Cu (100).

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STRUCTURAL PROPERTIES OF NIOBIUM THIN FILMS DEPOSITED ON METALLIC SUBSTRATES*

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Abstract

Particle accelerators rely on SRF cavities to create the accelerating gradient for beam lines. Solid niobium cavities are widely employed throughout the community despite high material, fabrication, and operation cost. Energetic condensation deposition techniques for thin film technologies are being explored for the suitability of niobium coatings in accelerating cavities. Thin layers of niobium are deposited on a base material that has lower material and fabrication cost. Copper is a strong candidate for the cavity base due to availability, cost, machinability, higher thermal conductivity, and potentially improved performance characteristics of the niobium SRF surface. Preliminary results of EBSD and XRD of ECR deposited niobium thin films on copper substrates are presented to demonstrate the feasibility of the technology and establish lower limits of performance characteristics. Correlation of RRR data with the structure of niobium thin films will demonstrate the importance of thin film structural quality.

INTRODUCTION

Selecting a suitable substrate for a given thin film is driven by its application. SRF cavities have complex organic shapes which are most easily fabricated with metals. The cavity needs to have a high thermal conductivity and heat capacity at 4K while maintaining mechanical strength. A moderately soft material is desirable to reduce machining and polishing efforts. Copper (Cu) and aluminum (Al) both meet the requirements for an SRF cavity base. Various groups have produced Nb (niobium) coated Cu cavities and samples by magnetron sputtering [1-2], LPCVD (Low Pressure Chemical Vapor Deposition) [3], HiPIMS (High Impulse Magnetron Sputtering) [4], MBE (Molecular Beam Epitaxy) [5], ALD (Atomic Layer Deposition) [6], ECR (Electron Cyclotron Resonance) [7], CED™ (Coaxial Energetic Deposition) [8] and e-beam evaporation [9]. The quality of the resultant thin film is heavily influenced by the deposition technique utilized. The energy condensation methods, ECR, HiPIMS, and CED provide ions with controllable energy, resulting in high quality films.

Understanding the theoretical arrangement of thin film atoms on a substrate is a first effort to understand if epitaxy will occur in a given thin film/substrate system. Theoretical calculations and experiments [10] predict that the bcc Nb on fcc Cu system follows the following hetero-epitaxial relationships: [110]Nb || [100]Cu, [100]Nb || [110]Cu and [110]Nb || [111]Cu. Theoretical calculations also estimate the level of lattice mismatch (or misfit) between the coating and the substrate. The degree of misfit gauges the nature of stress developed in the film and can be used to estimate the density of volume defects. Any structural defects will contribute to a reduced SRF performance. By minimizing the structural contributions to SRF characteristics, other Nb thin film properties may be investigated properly without masking from structural effects.

All metals have a passivation layer, usually a native oxide, which must be considered in epitaxial calculations. The native oxide thickness for most metals is usually on the order of nanometers, but must be removed or replaced with a well ordered surface to enable epitaxy. Without a well ordered surface the deposition will likely produce a highly textured film with an increased density of grain boundaries and other scattering centers. Cu has a native oxide layer that must be removed before epitaxy can proceed [11]. On an oxide-free Cu surface, Nb will deposit according to the reported epitaxial relationships. Deposition of Nb on native CuO will proceed in an uncoordinated manner producing close-packed plane [110] Nb fibers with a highly textured nature. The texture is developed from the random in-plane rotation of the fibers as nucleation of the thin film occurred uncoordinated and independently of the surface.

The oxide can be removed by thermal dissolution into the bulk, via in-situ chemical reactions on the surface, in-situ plasma treatments or by a combination or series of these processes. The most effective method is probably thermal and plasma treatments in cycles as utilized in Bagge-Hansen *et al.* for cleaning Cu samples [12]. If plasma treatments are chosen, the energy and anistropy of the plasma must be carefully examined to ensure that there is no sub-surface damage to the substrate, excessive roughening of the surface, process gases are not embedded and that the process is isotropic, low degree of grain or defect etching. Heating the substrate during plasma treatments will assist in point defect removal created from ion bombardment while heating alone will encourage more desorption of volatile compounds. The process chosen for this study was thermal dissolution of the oxide at temperatures just below the roughening

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ANAMOLOUS MORPHOLOGICAL SCALING IN EPITAXIAL NIOBIUM THIN FILMS ON MGO(001)*

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Abstract

Surface and interface roughness are critical factors in determining the properties and technological viability of many systems. These considerations are of principle importance for the development of next-generation superconducting radio frequency (SRF) cavities where the ultimate surface determines the cavity performance. The predominant SRF technology currently used in linear accelerators is based on bulk niobium cavities, however on-going efforts to improve cavity performance have considered the possibility of multi-layered thin film coatings on SRF cavities. In particular, Superconducting / Insulating / Superconducting (SIS) multilayer structures have been proposed as a means to achieve higher field gradients in SRF cavities and overcome fundamental SRF limitations of bulk niobium [1].

Nucleation and growth kinetics influence epitaxial thin film growth on different substrates. In addition, film properties differ from those in bulk systems mainly because of limited material supply as well as stress contributions due to lattice mismatch, which can induce significant surface roughness. Rough surfaces may lead to undesirable effects for SRF applications, many of which can be minimized with suitable choices of thin film growth parameters.

We have undertaken a systematic effort to understand the dynamic evolution of the Nb surface under specific deposition conditions. Here we examine the morphology of epitaxial Nb grown on MgO ceramic substrates at very low growth rates and closely examine the dynamical scaling of the surface features during growth.

DYNAMICAL SCALING

Family-Vicsek Scaling

The Family-Vicsek scaling ansatz assumes that non-equilibrium processes take on a scale invariant form in both space and time and can be fully characterized by a finite set of scaling parameters. It is assumed that stochastic processes drive the surface evolution and that the resulting features will have a self-affine form. In this scenario, the dynamic evolution of the roughness of the system in question can be fully described by a pair of scaling exponents, α and β, the global roughness exponent and growth exponent respectively. These experimentally determined parameters, when compared with ones calculated from growth models, will implicate particular, responsible growth mechanisms and serve to classify these processes within scaling universality classes [2].

Here it is assumed that the correlation functions will assume a power-law form and that the Family-Vicsek dynamic scaling ansatz

$$w(L,t) = t^{\beta} f(L/\xi(t))$$

will hold. The function $f(u)$ takes the form

$$f(u) \sim \begin{cases} u^{\alpha} & \text{if } u \ll 1 \\ \text{constant} & \text{if } u \gg 1 \end{cases}$$

The surface interface width $w(L,t)$, taken essentially to be the RMS roughness of the surface averaged over the lateral length L after certain time t (or equivalently film thickness), has two distinct asymptotic regimes depending on the length scale examined: $w(L,t) \sim L^{\alpha}$ for $L \ll L_c$ and $w(L,t) \sim t^{\beta}$ when $L \gg L_c$. Here, L_c (nominally taken to be morphological island size) defines a critical length scale over which the surface features are no longer correlated and scales as $t^{1/z}$, where $z = \alpha/\beta$ is the dynamic exponent.

General Dynamical Scaling

The self-affine approach to dynamical scaling has been successfully applied to a vast array of dynamic surfaces (such as the erosion of coastlines, chemical etching processes, ballistic deposition, etc.); however, there are certain systems in which the scaling patterns demonstrate aberrant behaviour between the global (long range or saturated) and local (short) length scales. In this case, a common set of scaling exponents is no longer adequate to simultaneously characterize the disparate global and local dynamic scaling behavior; hence, additional local scaling parameters are necessary to fully classify surfaces that demonstrate this so-called *anomalous* scaling.

General Dynamical Scaling applies a more generic, yet analogous, scaling ansatz, formulated in Fourier space, which introduces an additional independent scaling parameter that can be used to classify anomalous scaling into invariant subclasses [3]. Here the ansatz is that the Power Spectral Density (PSD) defines a structure factor S

$$S(\boldsymbol{k},t) = \langle H(\boldsymbol{k},t) H(-\boldsymbol{k},t) \rangle$$

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STOICHIOMETRIC Nb3Sn IN FIRST SAMPLES COATED AT CORNELL*

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Abstract

A cavity coated with the superconductor Nb_3Sn theoretically will be able to reach more than twice the maximum accelerating field of Nb in a cavity under the same operating conditions and will have a much lower BCS surface resistance at a given temperature. The SRF group at Cornell has recently developed facilities to fabricate Nb_3Sn on Nb. The first samples have been coated, and several tests have been performed to characterize them. Results presented include SEM images of the surface, anodization tests, a critical temperature measurement, a test for RRR degradation, and stoichiometry measurements using EDS and XPS.

INTRODUCTION

After years of development, niobium SRF cavities are now being fabricated that are limited in gradient by the RF critical field, not multipacting, thermal instability, field emission, or high field Q slope. To reach even higher gradients, new materials must be used that will allow the RF surface to tolerate higher magnetic without quench. Theory [1] predicts that coating a cavity with Nb_3Sn will allow it to reach twice the accelerating gradient of a niobium cavity. Nb_3Sn also benefits from a critical temperature that is nearly twice as high as that of niobium, which allows cavities coated with Nb_3Sn to operate with quality factors far exceeding those of Nb cavities at the same temperature.

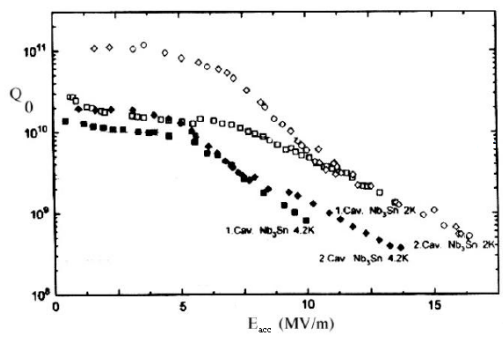


Figure 1: The best results obtained at University of Wuppertal for 1.5 GHz cavities vapor-diffusion coated with Nb_3Sn. From [4].

The great potential of Nb_3Sn-coated cavities has already been shown in the results obtained by researchers at University of Wuppertal in the 1980s-90s [2] [3]. They produced cavities with quality factors of 10^{11} at 2 K and accelerating gradients competitive with the gradients of niobium cavities produced at the time. Some vertical test results are shown in Figure 1. Guided by their work, facilities at Cornell have been developed to fabricate Nb_3Sn films on niobium. This paper discusses those facilities and the first results obtained.

COATING PROCESS

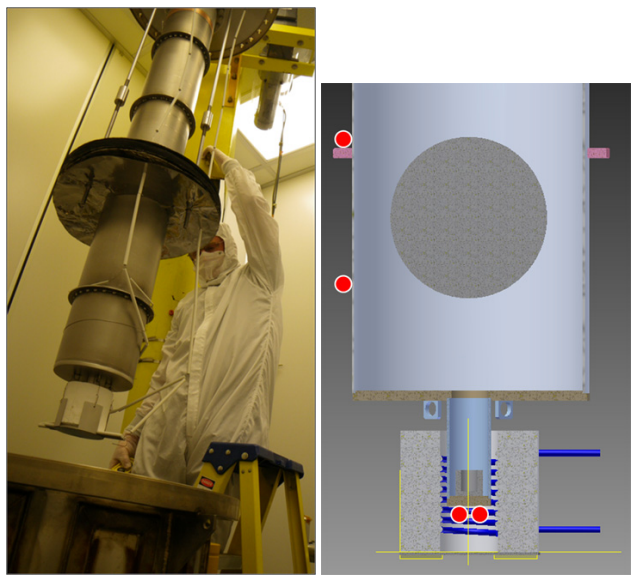


Figure 2: The Nb_3Sn coating chamber being inserted into the UHV furance (left) and a cross section (right) showing the tin crucible surrounded by the heater and the substrate suspended above. The red circles represent thermocouples for temperature monitoring.

The vapor diffusion coating process was based on [2]. A UHV furnace containing a niobium substrate (e.g. a cavity), a tungsten crucible containing 99.999% Sn pellets, and a tungsten crucible containing a small amount of $SnCl_2$ is evacuated and degassed at 200°C. The coating chamber, shown in Figure 2, is self-contained to avoid contaminating the furnace with tin. The valves to the pumps are then closed and the temperature is raised to 500°C, at which point the vapor pressure of $SnCl_2$ is high enough for it to create tin nucleation sites on the Nb surface. After 5 hours, the furnace temperature is raised to 1100°C, and a heater raises the temperature of the Sn slightly higher, to 1200°C. The elevated temperature from the heater increases the vapor pressure of tin in the coating chamber. The furnace temperature and the tin temperature control respectively the rate of interdiffusion of niobium and tin in the sample and

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CHARACTERIZATION OF LARGE GRAIN NB INGOT MICROSTRUCTURE USING OIM AND LAUE METHODS*

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Abstract

Large grain niobium (Nb) is being examined for fabricating superconducting radiofrequency (SRF) cavities as an alternative to using rolled sheet with fine grains. It is desirable to know the grain orientations of an Nb ingot slice before fabrication, as this allows heterogeneous strain and surface roughness effects arising from etching to be anticipated. Characterization of grain orientations has been done using orientation imaging microscopy (OIM, or electron backscattered pattern (EBSP) mapping), which requires destructive extraction of pieces from an ingot slice. Use of a Laue camera allows non-destructive characterization of grain orientations, a method useful for evaluating slices and deformation during the manufacturing process. Five ingot slices from CBMM, Ningxia, and Heraeus are examined. A pair of slices was deformed into two half cells and one of them was characterized again after deformation. The five ingot slices are compared in terms of their grain orientations and grain boundary misorientations. No obvious commonalities are indicated, which suggests that grain orientations develop randomly during solidification. A slab cut along the longitudinal direction of an Nb ingot was also examined, which showed the effect of machining on the grain orientations of the surface layer.

INTRODUCTION

Superconducting radio frequency (SRF) cavities fabricated from large grain Nb offers performance comparable to traditional fine-grain cavities [1-3]. The large grain approach allows simplification of the fabrication process, reduction of cost, and potentially better reproducibility in cavity performance [2]. Therefore, the SRF community has investigated this promising alternative fabrication path in recent years.

An important consideration arising from the large grain size is the mechanical and functional anisotropy associated with different grain orientations, which is discussed further in [3-5]. Therefore, characterization of grain orientations in an ingot slice is necessary prior to fabrication in order to anticipate potential forming problems and relationships between forming history and eventual performance.

* This work was funded by a research contract DE-S0004222 from DOE-OHEP. The Heraeus ingot slice was provided by DESY (W. Singer), the CBMM ingot slice was provided by Jefferson Lab (P. Kneisel), the Ningxia ingot slice was provided by the National Superconducting Cyclotron Laboratory (C. Compton), ingot slices H1 and H2 were provided by Jefferson Lab (G. Ciovati), and the ingot slab was provided by Niowave Inc. (TL. Grimm)
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EXPERIMENTS

OIM and Laue Methods

Being a well-established technique to measure grain orientations, OIM has been used to characterize ingot slices. However, this requires extracting small pieces from a slice, and thus makes the slice essentially unusable for cavity fabrication. The Laue Method based on X-ray diffraction provides a non-destructive alternative method to measure grain orientations.

Laue measurements do not need to be performed in vacuum, which greatly loosens the geometrical restrictions imposed by the chamber of an electron microscope. Therefore, samples with larger or more complicated dimensions can be characterized. Also, unlike in OIM where only "representative" locations are measured, the Laue method enables measurements from virtually anywhere on an ingot slice, and the ingot slice can be evaluated at various stages along the fabrication path. A more detailed discussion on both methods and their intrinsic accuracy is presented in [3, 6-7].

Measurements of Grain Orientations

Two ingots slices from CBMM and Ningxia were characterized with OIM (Fig. 1). An ingot slice produced by Heraeus (Fig. 1), and another two ingot slices from CBMM (denoted H1 and H2 respectively) were examined by the Laue method. H1 and H2 were cut right adjacent to each other, and the difference between them is very small as indicated by the results in Table 1. Consequently only H1 is shown in Fig. 1. Mounting error should only affect measurements in the first Euler angle, so the orientation variations presented are representative of real orientation gradients.

H1 and H2 were deep drawn into half cells and H2 was characterized again by the Laue method after deformation (Fig. 2).

A longitudinal Nb slab prepared by Niowave (Fig. 3) was also characterized with the Laue method. After a coarse saw cut, the slab was given a smooth surface using an end mill, and then mechanically polished to make the grains on the surface clearly visible.

NB FILM GROWTH ON CRYSTALLINE AND AMORPHOUS SUBSTRATES

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Abstract

This paper describes Energetic Condensation Growth of Nb films using a cathodic arc plasma on crystalline (a- and c-sapphire, MgO) and amorphous (borosilicate) substrates. The crystal substrates were heated to 700 ºC and subsequently coated at 300, 500 and 700 ºC. Film thickness varied from ~0.25µm up to >5µm. The borosilicate substrate was preheated and coated in the 150-700 ºC range. XRD spectra (Bragg-Brentano) and pole figures show a change in crystal structure on c-sapphire from textured (with twin-symmetry) to hetero-epitaxial as the temperature is increased. RRR-43 was measured on c-sapphire which is lower than RRR-330 on a-sapphire and RRR-585 on MgO. On borosilicate, the (110) and (220) planes of Nb show sharper spectra at higher temperatures with an increase from RRR-10 to RRR-31 at 500 ºC. The growth of crystalline Nb on an amorphous substrate is driven by energetic (90-160eV) ions from the cathodic arc plasma. The observation of crystal growth on amorphous substrates has implications for future, lower-cost SRF cavities made from cast Al.

INTRODUCTION

Most RF particle accelerators worldwide utilize copper RF cavities to accelerate the particle beam. A few large research accelerators such as the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (Jefferson Lab, or JLab) and the Spallation Neutron Source (SNS) at ORNL use superconducting radio frequency (SRF) accelerating cavities. SRF cavities consume less power than conventional cavities to produce a given accelerating gradient, even when the additional energy cost of the cryogenics system is taken into account. [1] Operation at higher temperature would further reduce the cryogenics costs. Niobium, the only presently accepted superconductor for SRF accelerators, has a transition temperature T_c of 9.3K, but operates at 2K, to reduce residual resistance and maximize critical magnetic field at the typically used 1.3–1.5 GHz RF frequencies. Increasing the operating temperature of the Nb cell accelerator from 2K to 4.5K could cut the cryogenics system costs in half [1] but would require use of an alternative superconductor with a transition temperature of 10K or higher. Since the RF (London) penetration depth on the cavity surface is only ~40nm, it is of interest to develop thin film coatings on the ~100nm scale for particle accelerators. One approach to reducing SRF accelerator costs is to replace the expensive, bulk Nb (~$300/lb) cavities with a Nb thin film deposited on a less expensive material, such as Cu (~$3/lb) or better yet, Al (~$1/lb). The added advantage of Al [2] over Cu is that the cavity can be cast instead of being machined, further reducing the installation cost.

Pioneering work [3-6] on Cu cavities coated with Nb thin film has been done at the European Organization for Nuclear Research, known as CERN. By 1998, 272 copper 352 MHz cavities, Nb thin film coated via magnetron sputtering, were deployed for the Large Electron-Positron Collider (LEP) project. The circular LEP collider, with a circumference of 27 kilometers, was one of the largest particle accelerators ever constructed and has recently been replaced by the Large Hadron Collider (LHC). Future accelerator facilities, such as the proposed International Linear Collider (ILC), require high accelerating field ~35 MV/m and $Q \geq 10^{10}$. It was reported [5,6] that at 1.7K the Nb thin film cavities for LEP had Q-drop to below 10^{10} at ≈15MV/m and to below 5×10^{9} at ≈20 MV/m. Thus there is a motivation to better understand these limits and to improve Nb thin films' performance for future SRF accelerator cavities.

The payoff of higher temperature SRF cavities and cavities made out of thin-film coated Cu or Al has motivated a multi-year research program at Alameda Applied Sciences Corporation (AASC). The goal is to utilize energetic condensation to produce Nb-on-Cu films of sufficient quality to determine if the thin film RF properties are adequate for high power SRF applications such as particle accelerators. Thorough characterization of the surface morphology and RF properties of Nb-on-Cu is a necessary first step toward qualifying Nb coated Cu SRF cavities. Given the high-cost (>$100M) and infrequent occurrence of large SRF accelerator upgrades and construction, it is difficult to imagine acceptance of an alternative superconductor in SRF accelerators without demonstrated performance equivalent to (or better than) that of bulk Nb (2K). Implementation of Nb-on-Cu coated cavities into commercial accelerators, our long-term goal, is likely to follow reliable operation on large accelerators.

EXPERIMENTS

The experiments were done in the CED™, a coaxial rotating vacuum arc plasma, described in detail in previous publications [7-11]. The CED apparatus allows coating of the inner surfaces of tubes and cavities, without the need of complicated structures, moving sources, bias

EFFECT OF FABRICATION CONDITIONS ON PROPERTIES OF BI-2212 THIN FILMS

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Abstract

High-quality epitaxial c-axis oriented Bi-2212 thin films were deposited on single crystalline (100) MgO substrate using Pulsed Laser Deposition. The results show that these films are good quality with *c*-axis orientation and epitaxial growth, good electrical and magnetic properties. The critical current density J_c was found to be strongly dependent on the temperature and magnetic field. The critical current density for the film growth with the best deposition conditions (Jc=6,3x10^6 A/cm^2 in 0.5T magnetic field at 5 K).The onset temperature for superconducting transition $T_{c\text{-}onset}$ = 95K and the temperature for zero resistivity $T_{c\text{-}zero}$ =80K.

INTRODUCTION

High-temperature superconducting (HTS) thin films have a large critical current density Jc and small surface resistance Rs in the microwave and millimeter wave region compared with that of normal conducting films. It can be used to design high-performance passive microwave devices, for example, filters, antennas, resonators, and delay lines [1-5]. The $Bi_2Sr_2CaCu_2$ O_{8+y} system is one of the most promising high -Tc superconducting compound to be used in applications ranging from power transmission cables to Josephson -junction -based electronic devices [10].

Therefore, Bi-2212 thin films are very important for submillimeter wave devices. Several fabrication techniques of Bi-2212 films have been performed, such as pulse laser deposition (PLD), a molecular beam epitaxy (MBE) [7], a liquid phase epitaxy (LPE) [8], a metal chemical vapor deposition (MOCVD) [9]. The PLD method suitable for fabricating films with complex stoichiometry.

Pulsed laser deposition (PLD) or laser ablation is one of the most often used techniques for production of high-quality BSCCO thin films. The ablation process results in con-servation of the target stoichiometry in the initially ablated cloud [6]. Ablated species from a target come into oxygen environment and transfer to the substrate. A relatively high oxygen background pressure can be used with this technique. This allows for the fabrication of oxide films with nearly perfect stoichiometry.

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In this paper, we report the deposition of $Bi_2Sr_2Ca_1Cu_2O_{8+y}$ (BSCCO) thin films on MgO substrate prepared by the PLD method. Electrical properties such as the superconducting transition temperature (Tc) and the transport critical current density (Jc), surface morphology, crystal structure were investigated.

EXPERIMENTAL DETAILS

Precursor powder with Bi_2O_3, $SrCO_3$, $CaCO_3$ and CuO were prepared by solid state reaction. The powders were calcined at 835^{0}C for 24 hours in air. The calcinations were repeated three time at 835^{0}C for 24 hours in order improve the homogeneity by intermittently grinding the powder. The calcined powder was compressed into a disk of 15 mm in diameter and 4mm. We have used the polyvinyl alcohol as a binder. The compacted powder disk was heat-treated at 845^0 C for 160 hours.

The $Bi_2Sr_2Ca_1Cu_2O_{8+y}$ (BSCCO) thin films in this study were prepared by pulsed laser deposition (PLD). Before deposition, the (100) MgO substrate was washed. The excimer laser (λ = 248 nm) was operated at 300 mJ/pulse (the laser frequency is 3 Hz) for 30 min for each deposition. The temperature of the substrate which was mounted on the heater in the cross- area of the plume caused by the beam was 730^{0}C. The oxygen pressure was kept at 0.2 mbar. After deposition the films were annealed in situ a temperature at 680 ^{0}C for about 2 hours and cooled down to room temperature for in 3 hours in an ambient oxygen pressure of 800 mbar. The thin films T84, T92 and T93 were ex situ annealed at 845^{0}C for 3 hours, 2 hours and 1 hour. The films thickness was about 272 nm. The crystallographic texture of the film was studied by X-ray diffraction. SEM and FESEM. Superconducting transition properties were measured by resistance, MVSH, and inductive measurements. The critical current density Jc of the film was calculated by model Bean: $J_c = \frac{60a|\Delta M|}{b(3a-b)}$;

where a and b are the length and width (a>b, in cm) of the sample plane perpendicular the applied magnetic field. ΔM is the difference of the magnetization (emu /cm^3) between the field-up and field-down branches.

DETAILED SURFACE ANALYSIS OF INCREMENTAL CENTRIFUGAL BARREL POLISHING (CBP) OF SINGLE-CRYSTAL NIOBIUM SAMPLES*

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Abstract

We performed Centrifugal Barrel Polishing (CBP) on single crystal niobium samples/coupons housed in a stainless steel sample holder following the polishing recipe developed at Fermi Lab (FNAL) in 2011 [1]. Post CBP, the sample coupons were analyzed for surface roughness, crystal composition and structure, and particle contamination. Following the initial analysis each coupon was high pressure rinsed (HRP) and analyzed for the effectiveness of contamination removal. We were able to obtain the mirror like surface finish after the final stage of tumbling, although some defects and embedded particles remained. In addition, standard HPR appears to have little effect on removing embedded particles which remain after each tumbling step, although final polishing media removal was partially affected by standard/extended HPR.

INTRODUCTION

Superconducting radio-frequency (SRF) cavity technology is one of the key technology driving current particle accelerators. Modern SRF cavities are made out of high purity niobium sheets which are then formed into cavities. To achieve state–of–the art performance, these cavities must go through a multi-step process which condition the inner surface to support a high Q and maximum acceleration gradient (E_{Acc}). The usual method to treat the inner surface included initial bulk buffered chemical polish (BCP) and/or electropolishing (EP), followed by a high temperature bake to remove hydrogen, followed by another light BCP/EP, high pressure rinse (HPR), and low bake. This technique can achieve $Q_o > 2 \times 10^{11}$ and $E_{Acc} > 40 \frac{MV}{m}$ for a ILC 1.3 GHz cavity at 2K [4].

One of the alternate techniques to reduce bulk and light chemistry is mechanical polishing, pioneered at KEK in Japan [2]. In addition to reducing chemistry, recent work at FNAL by Cooper *et. al* [1] has shown that centrifugal barrel polishing (CBP) can reduce the surface roughness by a order of magnitude lower than chemistry alone [3]; which in turn possibly raises the Q thereby improving the performance.

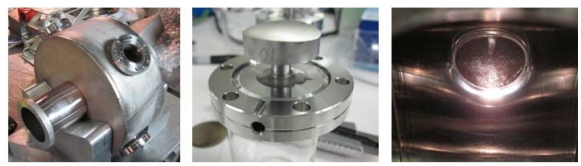


Figure 1: Sample mounting of niobium coupon in CBP holder. Left, the stainless steel holder - diameter is 9 inches; middle, coupon mounted on a 2 $\frac{3}{4}$ conflate flange before CBP, the hole in the flange contains a set screw to adjust the height of the rod; right, coupon mounted inside SS container - looking though the opposite coupon holder port.

Most CBP recipes rely on cavity testing with trial and error to ascertain a recipe for optimal performance. While this technique works, there should be a physical quantity which can help guide further recipe refinement. These CBP quality factor could include visual appearance, surface roughness, contamination size and shape, and/or crystal structure deformation. There are two readily available ways of ascertaining this information; one is to CBP a cavity until it reaches a "good" performance and then sacrifice the cavity by cutting out samples which can then be placed in a analysis equipment such as atomic force microscopy (AFM), scanning election microscopy (SEM), and electron back scatter diffraction (EBSD); the other would be to perform the analysis on sample housed in a host sample holder. While the first may be ideal, the second is cheaper and throughput can be much higher.

In this work, we perform CBP on single crystal niobium samples/coupon housed in a stainless steel coupon holder following the mirror smooth CBP recipe developed at FNAL, and analyzed the coupons with multiple surface characterizing techniques. We were able to reproduce the mirror finish published yet our mirror finish also contained scratches and embedded media. Our results indicate that each step in the process removes all signs (embedded media) of the previous steps, yet residual embedded media from each step always remain. The effects of high pressure rinsing were also evaluated with promising results for complete colloidal silica removal with multiple/extended

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RAMAN SPECTROSCOPY AS A PROBE OF SURFACE OXIDES AND HYDRIDES OF NIOBIUM*

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Abstract

Raman microscopy/spectroscopy measurements are presented on high purity niobium (Nb) samples and compared with density functional theory (DFT) calculations of vibrational modes of expected surface Nb complexes. The technique is shown to be an effective probe of surface oxides and hydrides of Nb relevant for superconducting radio frequency cavity (SRF) development. A principal result of the work is the observation, in the ordinary Raman backscattering, of Nb hydrides in rough patches (pits) of samples and in cold-worked regions of annealed Nb foils. This indicates that regions of high dislocation density attract hydrogen and form ordered hydride phases of sufficient size to be detected by Raman. Such phases are expected to suppress the local superconductivity and this may explain the connection between hot spots in SRF cavities and the observation of surface pits.

The ordinary Raman backscatter from smooth regions of Nb crystals is relatively featureless but surface enhanced Raman spectroscopy (SERS) has been achieved using deposited Au islands on the Nb. The SERS signal shows a highly reproducible spectrum consisting of dissolved hydrogen in Nb along with broadened peaks from hydride phases indicating hydrogen is present at some level in the near-surface of all Nb samples.

Surface oxides are clearly observed in the Raman spectrum of Nb powders and exhibit changes after a mild baking procedure similar to that used in SRF cavities to mitigate high-field Q-slope problems.

INTRODUCTION

It has been shown recently [1] that localized regions of high dissipation, "hot spots", occurred in a single-cell Nb SRF cavity, fabricated using a buffered chemical polish (BCP), that displayed a medium field Q slope. Furthermore, optical and electron backscattered diffraction (EBSD) imaging showed clearly that such hot spots were correlated with a high area density of etch pits, especially near grain boundaries. Cold spots had more shallow pits of significantly lower density. It is thus of high interest to examine in detail how etch pits might become a source of enhanced local RF dissipation, as chemical etching is integral to the fabrication of cavities.

* Work supported by DOE-HEP through FNAL Laboratory-University Collaboration to Understand Performance Limits of SRF Cavities

The standard spectroscopy tools of EBSD, namely Auger and energy dispersive x-ray, showed little difference between the regions inside and outside the pit. This is not surprising as such spectroscopic tools are cannot measure hydrogen, a gas which diffuses easily in Nb and is a well-known contaminant potentially affecting the cavity Q. [2] Also, these techniques measure an average composition over a relatively large electron probing depth, ~40 nm, and thus would be insensitive to subtle changes in surface oxide composition occurring over ~ 5 nm. This can be significant as it has been shown that < 3 % oxygen vacancies in Nb_2O_5 changes this compound from a nonmagnetic insulator to a conductor with localized magnetic moments. [3] The superconducting gap region probed by tunneling exhibits a smeared density of states consistent with pair breaking due to magnetic scattering. [4] There is thus a good chance that the source of RF dissipation in a pit is tied to the local chemistry, (e.g. oxides, hydrides, dissolved gases) near the surface which might suppress the superconductivity in a variety of ways and cause increased RF impedance and dissipation.

The need for continued development of surface analytical tools for SRF cavities is clear. Here we present Raman microscopy/spectroscopy, a technique which has not previously been used for Nb SRF cavity research. Raman is a simple, fast, non-perturbative optical method which reveals vibrational modes and phonons via inelastic scattering. As will be shown, Raman reveals surface molecular complexes of Nb not easily seen by other techniques. The probing depth (~10-20 nm), is estimated from the skin depth of the 785 nm laser in Nb and is a reasonable fraction of the magnetic penetration depth, ~ 45 nm. Furthermore, Raman has the potential to be an *in-situ* probe of completed SRF cavities by using optical fiber methods.

A comparison of Raman spectra with density functional theory (DFT) calculations of expected molecular complexes allows the identification of hydride and oxide phases. A principal discovery of the present work is the consistent observation of sharp, Raman peaks in regions of Nb which likely contain a high density of dislocations such as etch pits or cold-worked regions. Such peaks are not seen in smooth regions of Nb crystals or recrystalized foils, both of which are expected to have a low concentration of dislocations. These peaks are linked to Nb-H complexes, in particular, ordered hydride phases

LASER MELT SMOOTHING OF NIOBIUM SUPERCONDUCTING RADIO FREQUENCY CAVITY SURFACES*

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Abstract

Superconducting Radio Frequency (SRF) niobium cavities are at the heart of an increasing number of particle accelerators. Their performance is dominated by a several nm thick layer at the interior surface. Maximizing the smoothness of this surface is critical and aggressive chemical treatments are now employed to this end. We describe laser-induced surface melting as an alternative "greener" approach. Modelling predicts the surface temperature as a function of per-pulse energy density. Guided selection of laser parameters achieves melting that reduces the surface roughness and may also mitigate surface damage from the fabrication process. The resulting topography was examined by SEM, and AFM. PSD spectra computed from AFM data were used for studying the topography of the treated niobium.

INTRODUCTION

Accelerators based on superconducting niobium RF cavities will play a growing role in the future. The science and technology has been recently reviewed [1]. A key feature is that in the superconducting state the RF field penetration is limited to the surface adjacent 40 nm, lending great importance to the composition and topography of the cavity interior surface. Accordingly, the final steps of cavity fabrication seek to remove damaged or contaminated material by etching off approximately 100 microns. A disadvantage is that the etching processes uses aggressive acids (hydrofluoric, nitric, sulfuric) creating cost, safety and environmental impact issues.

Laser Surface Melting (LSM) offers a greener alternative approach. Briefly, a laser pulse melts an area on the surface and surface tension causes some leveling before solidification intervenes. Advantages of LSM over conventional heat treatment are: localized treatment of a selected part of a surface, leaving the other parts unaffected [2], superior bonding as deposited layers, reduced distortion and improved physical properties (smoothing, hardness levels, and wear and corrosion resistance due to rapid quenching [3]. Characterizing the surface topography is a challenging task as it is unknown at what scale roughness is important to SRF performance; a recent review is available [4]. The present work gives results obtained by laser melting to smooth the surface of niobium. The resulting topography was examined by Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM). PSD's were computed from AFM data.

*Work supported by Thomas Jefferson National Accelerator Facility.
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LASER-MATERIAL INTERACTION

The optical absorption of metals depends upon the angle of incidence, plane of polarization and wavelength of the laser beam. Optical constants for niobium at 1064 nm wavelength were used [5] for calculating the absorption. If the pulse duration (τ_p = 15ns) is much longer than the electron-phonon collision frequency of the niobium ($\tau_{ep} \cong 60$ ps) [6] then, thermal Fermi distribution can be assumed for the electrons. Thus, the temperature rise can be described by Fourier heat conduction equations [7]. In the present work, the laser spot (≅80 μm) is much larger than the thermal diffusion length (≈nm), justifying use of a 1-D diffusion equation. The heat flow in niobium can be represented by [7, 8]

$$\frac{\partial T(z,t)}{\partial t} - \frac{\partial}{\partial z}\left(k(T)\frac{\partial T(z,t)}{\partial z}\right) = \frac{A(z,t)}{\rho(T)c_p(T)} \quad (1)$$

where T(z,t) is temperature at depth z at time t, ρ is mass density, k is thermal diffusivity, c_p is specific heat capacity and A(z,t) is the heat generation. As there is no analytical solution for the Eq.(1), we use the finite differences method (forward difference approximation) to solve. Time (t) and space (z) are divided equally such that, $t^i = i.\Delta t$ and $z_n = n.\Delta z$ (where n= 0…..N). Evaluation of the first order derivative with respect to time and the second order with respect to direction (here z direction), Eq.(1) can be rewritten in forward time centered space scheme.

The simulation for the surface temperature and other parameters are done using C++. We were interested in the fluence required to bring the surface temperature just above the melting point to facilitate the niobium particles do not ablate and it just melts the rough surface. Thermal calculations given by F.Spaepen [9] on metals were used to find the melt duration in niobium (4-5 ns) at different melt thickness produced by different fluences, which ensured the experiments performed for this experiment had long melt duration.

EXPERIMENTAL SETUP

A PVD Products Inc. PLD 5000 system was used to carry out the experiments, as shown in Fig. 1. The system consists of a vacuum chamber evacuated to 10^{-7} Torr by a rotary backed turbo pump. A reflecting mirror placed in

SRF MULTILAYER STRUCTURES BASED ON NBTIN *

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Abstract

For the past three decades, bulk niobium has been the material of choice for SRF cavities applications. In recent years, RF cavity performance has approached the theoretical limit for bulk niobium. To further improve RF cavity performance for future accelerator projects an interesting alternative has been recently proposed by A. Gurevich, a Superconductor-Insulator-Superconductor multilayer. This approach uses the benefit of the higher critical field H_{c2} of higher-Tc superconductors without being limited with their lower H_{c1} thereby avoiding early flux penetration.

JLab is pursuing this approach with the development of multilayer structures based on NbTiN via magnetron sputtering and High Power Impulse Magnetron Sputtering (HiPIMS). Insulators such as, AlN, Al_2O_3 and MgO are being investigated as candidates for the insulator layers.

This paper presents the preliminary results on the characteristics of NbTiN and insulator layers and a first attempt of a NbTiN-based multilayer structure on bulk Nb and thick Nb films.

SIS MULTILAYER APPROACH FOR SRF CAVITIES

A few years ago, a concept was proposed by A. Gurevich [1] which would allow taking advantage of high-Tc superconductors without being penalized by their lower Hc_1. The idea is to coat superconducting radio-frequency (SRF) cavities with alternating superconducting and insulating layers (SIS structures) with a thickness d smaller than the penetration depth λ (figure 1). If the superconducting film is deposited with a thickness d <<λ, the Meissner state can be retained at a magnetic field much higher than the bulk H_{c1}. The strong increase of H_{c1} in films allows utilization of RF fields higher than the critical field H_c of Nb but lower than those at which the flux penetration at grain boundaries may create a problem. The thin higher-Tc layers provide magnetic screening of the bulk superconducting cavity preventing vortex penetration. The BCS resistance is also strongly reduced because the superconducting materials used have higher gap Δ (Nb_3Sn, NbTiN …) than Nb. With such structures, Q-values at 4.2K could be increased two orders of magnitude above Nb values.

If a 50nm Nb_3Sn layer is coated on a bulk Nb cavity with an insulating interlayer and if the Nb cavity can sustain fields up to 150mT, this structure could potentially sustain external magnetic fields of about 320mT and therefore reach accelerating gradients without precedent.

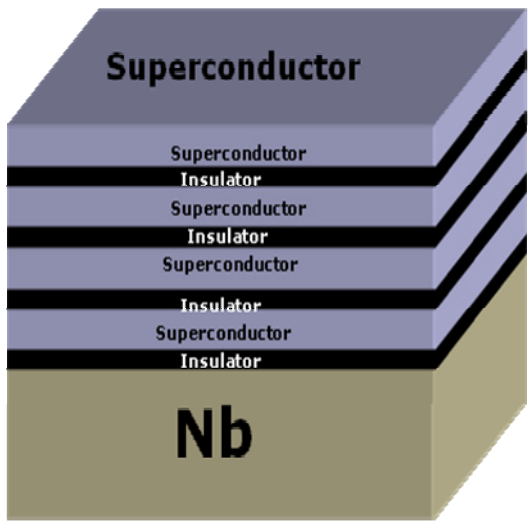


Figure 1: The SIS multilayer approach.

CANDIDATE MATERIALS

Superconductor: NbTiN

Although A15 compounds such as Nb_3Sn have a higher T_c, the Nb B1 compounds are less sensitive to radiation damage and crystalline disorder.

B1 compounds have a NaCl structure (figure 2) where metallic atoms A form a face centred cubic (fcc) lattice and non-metallic atoms B occupy all the octahedral interstices. These compounds are characterized by the fact that they always have a certain amount of vacancies, usually distributed randomly throughout the lattice [2]. The superconducting properties of B1 compounds are very sensitive to deviation from stoichiometric composition

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A MEASUREMENT OF THE LOSS TANGENT AND HEAT CAPACITY OF A LARGE SINGLE CRYSTAL AND THE IMPACT ON THE DESIGN OF WAFER SAMPLE CAVITY*

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Abstract

A large single crystal of sapphire was inserted into a CEBAF cavity, operating in the TE_{01} mode, to measure the sapphire's loss tangent and the heat capacity. These values were measured at cryogenics temperatures. The dielectric constant, heat capacity, loss tangent were calculated based on the experimental data and models produced by RF modelling software. The motivation for these measurements was to determine the performance capabilities of the Wafer Test Cavity. The Wafer Test Cavity uses the sapphire as a dielectric lens to focus the magnetic fields onto the sample wafer up to 3.75 times higher than the surface of the cavity to test characteristics of sample materials. The tentative design the Wafer Cavity will be presented.

INTRODUCTION

Current Niobium SRF single cell cavities can nearly achieve the fundamental magnetic field limit on a routine basis. Even though the ability to reach such fields is achieved, the reasons as to why most cavities do not attain such a limit are not well understood. These limiting phenomenon are known, but the manner and degree in which they affect the performance is not understood.

It was hoped that such a relationship could be established by creating a sample test system that can place consistent conditions on sample materials. These samples could have all the individual processes used in cavity manufacturing, or combinations thereof, and assesses each process on the performance of the cavity.

A second reason for such a system is to test materials that would be a SRF revolution rather than tweaking procedures causing an evolution. Gurevich [1] stated that alternating layers of insulators (such as Al_2O_3) and type-II superconductors (such as Nb_3Sn) could create a heterostructure capable of shielding the magnetic field from the bulk Niobium. This allows the cavity to withstand magnetic field twice the critical limit while simultaneously enhancing the Q-value (quality factor) by factor of four. The significance of this statement is an accelerator whose energy is doubled for the same power cost. If the concept is proven true then it will truly be a revolution in accelerator physics.

The Wafer Test Cavity (WTC) is designed to produce field 3.6 times higher field on the sample compared to the surface of the cavity which allows one to investigate heterostructures to their capabilities in a reproducible environment, as well as the current techniques used for conventional cavity production. It is the hope that the Wafer Test cavity will become a powerful analytical tool for present and future research.

RESULTS FROM THE SAPPHIRE TEST CAVITY

A crucial aspect to the high performance parameters is the sapphire located at the heart of the cavity. The loss tangent has been measured low enough by calorimetry to allow the Q of the cavity to be on the order of 10^{10}. The heat capacity of the sapphire must also be known for the losses generated by the sapphire will increase the temperature of the sapphire. The loss tangent is temperature dependant and therefore as the temperature gets larger the loss tangent increases leading to an ultimate limitation of the field on the sample for a given input power.

A CEBAF cavity was loaded with a sapphire about half the size of the crystal designed for the WTC and its properties were tested, see Figure 1. This Sapphire Test Cavity (STC) was tested 8 times producing varying results each experiment.

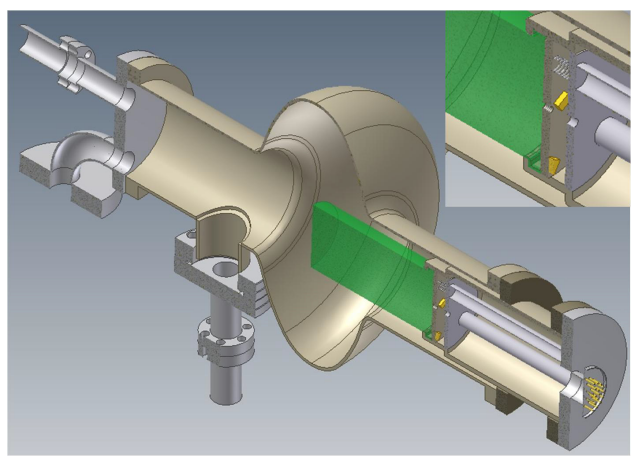


Figure 1: Drawing of the Sapphire Test Cavity. The sapphire's (green) end face is parallel with the equator. The side and end ports were the locations of the probe and input couplers. The end flange also included the vacuum line. The sapphire is held in place by a Nb holder with an indium seal that acts as a thermal bridge between the sapphire, backing plate with resistors attached, and the holder which is the pathway to the Helium bath. The backing plate is spring loaded ensure consistent contact with the seal.

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MO-RE FILMS FOR SRF APPLICATIONS

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Abstract

Single (sintered composite Mo3:Re1) and dual (separate Mo and Re) targets were used to grow superconducting films of Mo:Re, using cathodic arc plasmas. Sharp, superconducting transitions (at up to 13K) were observed in ~1 μm thick films deposited on a-sapphire and MgO crystals. XRD (Bragg-Brentano spectra) revealed a single sharp peak of Mo-Re (611) plane, from the composite Mo3:Re1 film. SIMS measurements revealed the role of impurity concentrations on superconducting properties. The XRD spectra in this case showed the (330) plane of Mo-Re. The transition temperature of the Mo-Re films depends upon the stoichiometry of the film. The dual-target approach allows control of stoichiometry by varying only the current to each target (cathode). This demonstration of stoichiometric control in dual-target arcs enables other compound films (e.g. Nb_3Sn, MgB_2 etc.) to be grown in a single-step. The measured RRR (defined as the ratio of residual resistivity at 300K to that at 14K) in the best films was 6, which is higher than measured by others at higher annealing temperatures. However, for SRF cavity applications, the RRR should be increased to >100, which is our next goal.

INTRODUCTION

All of today's industrial accelerators use normal conducting RF cavities to accelerate the particle beam. Normal conducting RF cavities are selected based on technology cost and maturity, the latter being an overriding factor as commercial use of RF accelerators demands turn-key and reliable systems, as evidenced by years of demonstrated use. The application of superconducting RF (SRF) technology to accelerators has been confined primarily to the scientific research and development arena. Superconducting RF cavities have been incorporated only in a small number of research oriented accelerators and most of these use bulk niobium cavity RF structures. SRF cavities consume less power than conventional cavities to produce a given accelerating gradient, even when the additional energy cost of the cryogenics system is taken into account [1]. However the cryogenics system costs do represent a significant portion of the operating expense of SRF accelerators. Operation at higher temperature would naturally reduce those costs. Niobium, the only presently accepted superconductor for SRF accelerators, has a transition temperature Tc of 9.3K, but a practical operating temperature of 2K at the typically used 1.3–1.5 GHz RF frequencies. Operation below T_c is required to minimize surface resistance and maximize critical magnetic field. Increasing the operating temperature of the accelerator from 2K to 4.5K could cut the cryogenics system costs in half [1], but would require use of an alternative superconductor with an operating temperature of 10K or higher, such as Mo_3Re, NbN, Nb_3Sn or MgB_2. Since the RF (London) penetration depth on the cavity surface is only ~50nm, it is of interest to develop thin film coatings on the nano-scale (~100nm) for particle accelerators. There is also strong motivation to understand and develop higher temperature superconductors, including the A-15 candidates [2-3]. In an article in Nature [4], Eric Hand states that the superconducting cavities that drive most of the world's particle accelerators are running out of room for improvement. But new theoretical work suggests that overlooked superconducting materials could be used to make cavities that accelerate particles to higher energies over shorter distances - thereby doing the job more cheaply. For decades, researchers have worked to improve the performance of superconducting cavities.

A higher temperature superconductor has not yet been qualified. Several A-15 compounds (such as Nb_3Sn, NbN, Mo_3Re and others), as well as MgB_2 are potential replacements to expensive niobium. However, A-15 coating development requires innovation to demonstrate the necessary properties to replace Niobium. An increase in operating temperature makes SRF technology more attractive for commercial applications in industry as well.

Alameda Applied Sciences Corporation (AASC), mostly with DOE SBIR Grant support, has been developing superconducting thin-films for over four years. We began with Nb films, progressed to MgB_2 films and are presently working on Mo_3Re films and on Nb_3Sn films (an ongoing PhII SBIR). Our approach uses a patented process that we have dubbed Coaxial Energetic Deposition (CED™) to grow the films. Recently we have brought into operation a different version of such an energetic condensation apparatus that we have dubbed Cathodic Arc Deposition (CAD).

EXPERIMENTAL ARRANGEMENT

The CAD apparatus (Figure1) is a vacuum planar arc between the front face of a cathode bar and a Mo mesh. An alumina insulator surrounds the cathode bar, to force emission only from the cathode face. The main arc plasma is initiated by a short duration secondary trigger arc plasma that provides enough metallic plasma between the electrodes to trigger the main arc/s.

No external magnetic field is applied so the movement of the arc spot is random across the cathode face.

SURFACE PREPARATION OF METALLIC SUBSTRATES FOR QUALITY SRF THIN FILMS*

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Abstract

Surface preparation is an essential prerequisite for thin film depositions. Rough or chemically impure surfaces adversely affect the nature of the thin film. Understanding the properties of the substrate and how they influence the quality of the thin film is necessary to transfer thin film deposition technologies to SRF cavity applications. A substrate that is flat, has sufficient grain size, and is chemically pure is the ideal starting point for thin film depositions. A method for copper substrate preparation is reviewed for niobium thin film deposition that provides epitaxy on large and fine grain copper as well as single crystal copper. Preliminary data on niobium substrate preparation will also be included.

INTRODUCTION

The deposition technique implemented in making a particular niobium (Nb) coated cavity in a vacuum system, as well as the specific nature of substrate, determine the resultant thin film quality. Determining the characteristics of a substrate that affect the coating process is an essential part of reliably creating a quality thin film. Characterizing what impurities may be in and on the substrate is necessary to avoid uncontrolled reactions and features. Particles, residues, and soils on the surface present alternative nucleation sites, disrupt the potential of the surface, and can be incorporated into the deposited thin film changing the film chemistry. Thin film process development must begin with substrate preparation and characterization. Inadequate substrate preparation can skew or randomly perturb process variable trending, increasing the difficulty of developing a reliable process with high yield. To be a competitive technology, the quality of Nb thin films on copper (Cu) SRF cavities needs to improve the benchmarks of bulk Nb cavities in cost structure and performance. For Nb coated SRF cavities to become practical, a suitable base cavity material must be demonstrated as a suitable thin film substrate.

Deposition of a material onto a surface is dictated by the structural and chemical aspects of the surface. The structure of the surface needs to compatible with SRF applications, dictating a surface with no protrusions or features[1] and general roughness of less than 50 nm.[2] From a thin film perspective, epitaxy requires substrates that are as smooth as economically possible, with an atomically flat surface being ideal although economically unfeasible in most applications. If a substrate is too rough, the thin film will most likely be a Zone 1 structure in the Thornton Zone Structure Model.[3] If the substrate is well prepared then the nucleation of the film can proceed in a coordinated manner yielding a high quality thin film.

METHODS AND MATERIALS

The Cu substrates prepared for this study were 99.999% OFHC (oxide free high conductivity) Cu. Fine and large grain Cu substrates were prepared for Nb depositions. The general process for preparing the fine grain substrates was mechanical polishing followed by electropolishing. Mechanical polishing was performed on a Buehler Ecomet 4 with an Automet 2 power head. The substrates were planed with 120 grit until uniformly scratched; followed by 320 grit, 400 grit, and then 600 grit SiC Carbimet 2 papers. At least two papers were used for each grit level with a thorough de-ionized (DI) water rinse and N_2 dry between every paper change. The Cu substrates were then finished with 3 micron polycrystalline diamond slurry on MicroCloths. The substrates were periodically rinsed with DI water and dried with N_2 to help reduce the embedded grit during the final polishing.

Substrates were ultrasonically cleaned for ~ 5 min then dried with filtered N_2 gun in acetone, then Micro90®, acetone, isopropyl, and finally methanol prior to electropolishing. The electropolishing setup consists of a square Cu cathode supported from the middle of a Teflon wheel. There are four positions for electropolishing with quick disconnect compression fittings to facilitate removal of the electropolished substrates. The Cu surface is very unforgiving once polished to an optical grade and can be easily damaged or contaminated. Once the substrates were mounted in the quick disconnect Teflon blocks and seated on the Teflon wheel with the cathode, the entire fixture was submersed into sulfamic acid (40 g/l) until most of the native oxide has been dissolved (~ 3 to 5 min). The samples were then rinsed in DI water and placed in the elctropolishing electrolyte, 45% H_3PO_4 / 55% n-Butynol. Fine grain Cu substrates mechanically polished were etched at a current density of 50 mA per cm^2 for approximately 1 minute. Electropolishing is utilized to remove any surface contamination, reduce the surface roughness, and remove any subsurface damage from mechanical polishing. The samples were quickly rinsed post-electropolishing and placed back into sulfamic

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ADAPTIVE COMPENSATION FOR LORENTZ FORCE DETUNING IN SUPERCONDUCTING RF CAVITIES

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Abstract

The Lorentz force can dynamically detune pulsed Superconducting RF cavities. Considerable additional RF power can be required to maintain the accelerating gradient if no effort is made to compensate for this detuning. An adaptive feed-forward Lorentz Force Detuning (LFD) compensation algorithm developed at Fermilab is described. Systems based on this approach have been used to successfully reduce LFD from several hundred Hz to several 10s of Hz or better.

INTRODUCTION

Superconducting RF cavities are in common use at accelerators around the world and cryomodules incorporating high-gradient (>30 MV/m) pulsed Tesla style 9-cell cavities are currently being constructed for the SCRF Test Area in NML [1] at Fermilab as a part of the ILC Global Design Effort.

The walls of SCRF cavities are deliberately kept thin (<= several mm) to allow the cavities to be kept cool but the thin walls make the cavities susceptible to mechanical deformations induced by:

- The force of the accelerating electromagnetic field on the cavity walls (the Lorentz force);
- Fluctuations in the pressure of the surrounding helium bath;
- Mechanical vibrations induced by external mechanical noise sources (e.g. pumps, cranes, etc.).

These mechanical deformations can change the resonant frequency of the cavity. For high-gradient, pulsed cavities operating in super-fluid helium, the Lorentz force is the dominant source of cavity detuning. If no efforts are made to compensate for LFD, cavities can dynamically detune by several bandwidths. Maintaining the accelerating gradient under these conditions would require considerable excess RF power.

The use of piezo actuators to compensate for LFD was pioneered at DESY but has since been adopted widely [2]. Actuators connected to the beam flange are driven by a short unipolar drive signal prior to the arrival of the RF pulse. The timing, amplitude, width and bias level of the piezo drive signal are chosen such that the detuning of the cavity by the resulting acoustic impulse cancels the detuning of the cavity induced by the Lorentz force. This technique can successfully reduce the detuning of the cavity during the RF pulse from several hundreds of Hz to several tens of Hz.

While the standard approach can provide acceptable compensation for LFD, the mechanical response of individual cavities to the Lorentz force and to the piezo actuator can differ. Changes in cavity operating conditions, for example the changes in the gradient or bath pressure can require corresponding changes in the compensating waveform. At present, the compensation parameters for each cavity are selected manually. Operating multiple cavities for extended periods will require control systems that can automatically determine the best parameters for each cavity and adapt to changing operating conditions. Because the cavity detuning does not respond linearly to the changes in some parameters of the standard unipolar pulse, the adaptive capability that can be incorporated in LFD systems based on this approach may be limited. Furthermore while a single unipolar pulse can compensate cavities driven by short RF pulses, it may not be suitable for cavities where the length of the RF pulse is comparable to or greater than the period of the dominant mechanical resonance.

MEASURING CAVITY DETUNING

The electromagnetic and mechanical behaviour of the cavity can be described well by the following equation [3] relating the complex envelopes of the forward, F, and probe, P, signals to the detuning, δ.

$$\frac{dP}{dt} = -(\omega_{1/2} - i\delta)P + 2\omega_{1/2}F;$$

The half-bandwidth, $\omega_{1/2}$, and detuning, δ, during the pulse can be extracted from the cavity probe and forward RF waveforms by rearranging the terms of the equation for the complex envelope of the cavity field:

$$\omega_{1/2} = \frac{Re(P^*\frac{dP}{dt})}{Re(2P^*F - P^*P)};$$

$$\delta = \frac{Im(P^*\frac{dP}{dt} - 2\omega_{1/2}P^*F)}{P^*P}.$$

Accurately determining the half-bandwidth and the detuning requires accurate measurements of the complex cavity forward and probe RF waveforms. On the flattop, a ten percent error in the amplitude of the forward signal could lead to an error in the detuning equal to 20% of the cavity half bandwidth.

In general, the relative gains and phases of the baseband signals are not known and the phases may drift with

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INNOVATIVE TUNING TECHNIQUES FOR LOW-BETA SRF CAVITIES *

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Abstract

Superconducting low-β cavities enable and often operate with high loaded Q's and small loaded bandwidths, making them extremely sensitive to RF frequency errors which are large relative to the loaded cavity bandwidth. Mechanical vibrations which couple to the cavity field drive RF frequency errors which require a combination of tuners and extra RF power to compensate. This paper presents an overview of innovate techniques for low-β ($0.05 < \beta < 0.6$) superconducting cavity design and tuning to maximize RF field stability.

INTRODUCTION

The radio-frequency (RF) field in accelerator cavities must be operated with stable amplitude and phase-locked to the particle-beam bunches. The accuracy and precision to which the cavity accelerating field's amplitude and phase are controlled determines:

1) The reliability and availability of beam for experiments
2) The beam quality
3) Beam losses (activation of the accelerator)

Mechanical vibrations, helium pressure fluctuations, and Lorentz detuning all combine to drive dynamic RF frequency errors, detuning. Extra RF power is required to prevent detuning which is a large fraction of the loaded cavity bandwidth from disrupting the amplitude and phase stability of the cavity accelerating field. This requires higher power amplifiers, increasing both the capital and operating expenses of an accelerator.

There are two schemes available to help reduce cavity detuning: design the cavities to decouple the accelerating field from the dominant mechanical vibrations and to employ tuners which introduce a controllable RF frequency perturbation which is used to destructively interfere with the cavity detuning. The first part of this paper reviews electro-mechanical design techniques which decouple the accelerating field from the mechanical vibrations in low-β cavities. The second part of this paper discusses several tuning techniques, both in use and proposed, for low-β cavities.

CAVITY DESIGN

The majority of frequency detuning effects can be minimized or even eliminated by design, whereas neglect can lead to an unusable system. This is accomplished by decoupling the cavity electromagnetic field from common mechanical vibrations, e.g. helium pressure fluctuations in cw operation, dynamic Lorentz detuning in pulsed operation, and resonant mechanical vibrations in both.

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The relationship between changes in RF frequency and mechanical deformations is given by the Slater Perturbation Theorem [1], which for a deformation in a cavity's wall is given in equation 1 where E_0 and H_0 are the unperturbed electric and magnetic fields respectively, U_0 is the stored energy, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, f_0 is the unperturbed cavity frequency, and Δf is the difference between the perturbed and unperturbed cavity frequencies. The Slater Perturbation Theorem and how it relates to cavity design is the focus of the next two subsections.

$$\frac{\Delta f}{f_0} = \frac{\int_{\Delta V}\left(\mu_0\left|\vec{H}_0(\vec{x})\right|^2 - \varepsilon_0\left|\vec{E}_0(\vec{x})\right|^2\right)d^3x}{4\cdot U_0} \quad (1)$$

CW Operation

In cw operation above the lambda point helium pressure fluctuations are the dominant driver of cavity RF frequency errors. Low-β cavities may be designed to minimize the total RF frequency shift due to changes in the helium pressure (df/dP) by balancing deflections of the cavity walls in areas with high magnetic fields (increasing frequency) with deflections in areas with high electric fields (decreasing frequency).

Figure 1 shows an example of this technique. The ANL β = 0.5 345MHz triple spoke cavity was designed to minimize df/dP, the frequencies sensitivity to changes in external pressure, by adding support ribs to the end walls and the cylindrical wall of the cavity [2]. These ribs stiffen the cavity walls but are not intended to reduce df/dP simply by stiffening; rather they balance the opposing electromagnetic field contributions. In actual construction, some of the ribs were made slightly oversize to allow for post-construction fine-tuning by cutting away part of each rib. After fine-tuning df/dP = -0.7 Hz/torr. However, after welding the helium jacket the sensitivity increased to -2.9 Hz/torr.

Lorentz Detuning

The dynamic Lorentz detuning, which dominates pulsed operation, is fundamentally different from the pressure fluctuations discussed above. Here regions of high magnetic field exert an outward force, while regions of high electric field exert an inward force on the cavity walls. These deflections conspire to decrease the cavity frequency under all conditions. To decrease the coupling strength of the cavity RF field to Lorentz detuning the rigidity of the walls must be increased, see for example [3]. Combining the cavity stiffening plan with a

RECENT PROGRESS IN HOM DAMPING FROM AROUND THE WORLD

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Abstract

Continuous progress in SRF technology is pushing the beam parameter envelope for SRF linacs towards higher currents and shorter bunch lengths. Therefore, the demands on the HOM dampers used in these SRF linacs are increasing continuously, and Higher-Order-Mode (HOM) damping remains a very active field of research and development. Different HOM damping concepts have been developed and improved over the last years to support high power handling and broadband HOM damping. In this paper we give an overview of recent progress on antenna, waveguide, and beamline HOM dampers.

CONTRIBUTION NOT RECEIVED

POWER COUPLERS FOR SPIRAL 2

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Abstract

The Spiral 2 facility is in construction phase. The driver is a super-conducting linac composed of two types of QWR cavities, beta = 0.07 and 0.12 operated at 88.05 MHz. Each cavity is fed by a radiofrequency antenna coupler designed to accept up to 40kW CW. The tests of the prototype couplers have been successfully achieved in the two types of cavities. The manufacturing is finished and the processing of the 26 couplers is under way. We report the technological choices and the major issues of the process, including the absence of TiN plating. We present the main results of the tests and the processing of the couplers.

INTRODUCTION

The coupler (See Fig. 1) transfers the power into two types of cavities and keeps the vacuum into the accelerator. The radiofrequency (RF) couplers have to provide 10 kW Continuous Wave (CW) nominal power to the cavities at 88.05 MHz for an nominal accelerating field of 6.5 MV/m. The coupler must handle 100% reflected power at maximum incident power. The theoretical thermal load to the cavities is limited to 1 W.

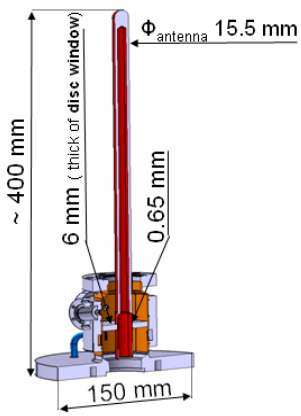


Figure 1: The power coupler.

LAST MECHANICAL CHOICES

The temperature measurements at 4.2 K in the cryomodules show, as predicted by the simulations, that the window temperature is < 5°C with no RF power. To keep the window's temperature close to 15°C in order to avoid water condensation, we have tested two systems: a hot, cleaned, dry air system, and a heating cable. Both systems gave good results but the hot air system was chosen as it allows a temperature regulation (it heats the window when RF is off and colds the window when the RF is on).

To minimise the heat flux to the cavities only a screen 70-100 K is utilised. We have not a screen 4.2 K at the coupler, the 4.2 K is given by the bottom of the cavity.

The series coupler mechanical design makes use of a hollowed antenna with an internal clamp [1] (See Fig. 2). This clamp makes the coupler more robust, especially during the transports. The maximum acceptable acceleration is 10g in order to avoid any deformation of the antenna. To make the external conductor as robust as the internal one, we have included a support for the CF40 flange. Therefore the maximum acceptable acceleration is raised from 4 to 8g to avoid any plastic deformation.

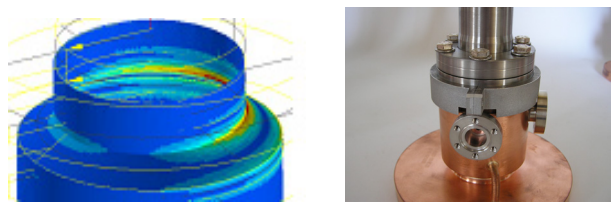


Figure 2: Constraint (left) and support of the CF40 flange.

TIN COATING WINDOW TESTS

TiN coating is usually used as a multipactor (MP) suppressor on RF ceramic coupler windows.

We have tested some 20 couplers with no window coating, one with 1±0.2 nm TiN coating and two with 30± 5 nm coating. One coupler with a 10±2 nm TiN coating, was also ordered, but the production failed as the coupler was not vacuum proof.

The TiN coatings were made by sputtering process, before window brazing, as the design of the coupler did not allow a post-brazing coating.

The stoichiometry of deposits and the effect of the brazing (similar to an 800°C baking) on the composition of the coating were quantified by Rutherford Back-scattering Spectrometry (RBS). The RBS measurement was made on samples of vitreous carbon with 10 nm TiN, 30 nm TiN coatings, and with 30 nm TiN coating after a 800°C baking.

The RBS validated the thickness of the coating and showed that TiO proportion is 10% higher after baking (see table 1); therefore the resistivity of the coating (ρ TiN ~ $25*10^{-6}$ Ω cm; ρ TiO2 ~ 10^{12} Ω cm) is increased but less than foreseen.

OVERVIEW OF CW INPUT COUPLERS FOR ERL

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Abstract

Various efforts for SRF R&D are in progress all over the world for ERL construction. CW (Continuous-wave) input coupler development is one of the key issues for realizing the stable ERL operation. For injector, high power handling is necessary to feed the CW RF power to continuous high current beam acceleration. Furthermore, the soft injector beam should not be disturbed by coupler kick. Thanks to energy recovery, a little power is needed for main linac. However, this feeding average power is also higher than that of the pulsed operation like XFEL or ILC to keep the accelerating field stable under the microphonics of cyromodule. Therefore, it is important for both coupler cases, not to leak the large heat load to He temperature and to avoid the continuous multipacting barriers. In addition, variable coupling is desirable for several beam operations. As a result, many new coupler designs were proposed and developed until now. In this paper, we present the various options and technical issues of ERL input coupler for both injector and main linac. Then we review existing designs associated with R&D testing and summarize the experience and progress in each laboratory around the world.

INTRODUCTION

General Aspects of Input Coupler for SRF Cavity

The input coupler is one of the important components of the cryomodule for operating superconducting cavity. Its design and property affect the cavity performance, beam dynamics, cryogenic system. Furthermore, its designing strategy also determines the overall of the cost of the project, in which the beam line are dominated by the superconducting cavities like XFEL, ILC & ERL. In general, there are several main roles of the RF coupler to operate the superconducting cavity.

1. RF input coupler is a passive deice, which is able to transfer RF Power from RF source to beam loaded cavity optimised reflection.
2. An input coupler works as a transmission line, with a coaxial or waveguide shape, and separate between the atmosphere and vacuum by RF window.
3. The input coupler must prevent the large heat leak from the outside of vacuum insulator at room temperature to cryogenic temperatures (2 to 4.5K). If the high power will be applied to the superconducting cavity, the careful RF and thermal simulation are needed not to add the large heat load, which come from not only the static loss but also dynamic loss caused by RF power feeding, to cryomodule temperatures.
4. For the different operation modes, an adjustable coupling will be required. One method is setting the three stab tuner of the upside of the RF transmission line. If the coaxial coupler is selected, a variable coupling can be done by directly changing the antenna position.
5. The perturbation of the cavity field caused by the input coupler should be minimized not to kick the beam.

In addition, to keep the quality of cavity performance, the following properties are to be cared in designing and testing the input coupler.

6. The mutipacting phenomenon and condition should be considered for the designing of the input coupler.
7. Input coupler should be performed in the clean cyomodule assembly procedures to minimize the risk of the contamination to the superconducting cavities. If many cyromodule assemblies are needed, two RF windows, cold and warm, are better to apply for the input coupler, especially for aiming to achieve the high accelerating field.
8. It is important to reduce the RF processing time. The sophisticated processing procedure and assembly are required to the input coupler.
9. Input coupler should be designed with the mechanical flexibility by considering the mechanical shrinkage under cooling.

Properties of Input Coupler for ERL

ERL consists of the DC or SRF gun, injector, merger, main linac with energy recovery, return loop and beam dump. In order to accelerating the beam continuously, superconducting cavity are needed at injector part and main linac parts. Especially ERL beam current is designed more than 100mA CW beam current.

In injector part including SRF gun, the beam is accelerated at least 5MeV and more. For injector, therefore, high power handling is necessary to feed the CW RF power to continuous high current beam acceleration. For example, we assume that the 2 cell 5 cavities with double input coupler accelerate up to 5MeV, whose condition is same as the parameters of the Cornell injector [1]. One coupler needs to feed at least 50kW RF power. If the number of cavities is decreased to shorten the injector part, a couple must be fed by higher RF power. It is the most challenging issues for the input coupler of injector parts of ERL. Furthermore, the soft injector beam should not be disturbed by coupler kick; the beam energy of injector is very low. In this case, the perturbation of the cavity field caused by the input

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CONSTRUCTION OF CERL CRYOMODULES FOR INJECTOR AND MAIN LINAC

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Abstract

The Compact ERL (cERL) project is advanced in Japan. Its aim is to demonstrate the circulation of 100 mA electron beams with energy of 35-200 MeV. Superconducting cavities are key components for realizing ERL and used for injector part and main linac part. Critical issue for the injector part is the development of input power coupler. Prototype input couplers were fabricated and high power test was performed. Cooling ability of HOM coupler is also important for CW operation of cavity. At main linac part, HOM damped 9-cell cavities are applied to avoid BBU instabilities. Prototypes were fabricated for the cavity, the input coupler and the HOM absorber. Their performance was investigated. For both parts, cryomodules are under construction and will be completed in 2012.

THE COMPACT ERL PROJECT

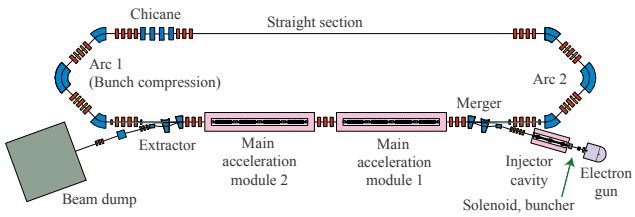


Figure 1: Conceptual layout of the Compact ERL.

Compact ERL (cERL)[1, 2] is a test facility, which is now constructing on the ERL Test Facility in KEK. Its aim is to demonstrate technologies needed for future 5-GeV class ERL. One of critical issues for ERL is development of superconducting cavities, which are applied for both the injector linac and the main linac.

Table 1: Main parameters for cERL project

Beam energy	35 – 245 MeV
Beam current	10 – 100 mA
Normalized emittance	0.1 – 1 mm mrad
Bunch length	1 – 3 ps (usual) 100 fs (bunch compression)

Main parameters of the cERL project are appeared in Table 1 and conceptual view of cERL is shown in Figure 1. At the first stage of cERL, minimum version of ERL will be constructed. Only two 9-cell cavities will be installed into one main linac cryomodule. Achievable beam energy is 35MeV. Beam current is also expected to be around 10 mA.

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At the ERL Test Facility, a 2K refrigerator system and a class-10 clean room were already constructed. A plan is that both cryomodules will be constructed, assembled and tested during 2012. After that, beam operation is awaited.

CRYOMUDULE FOR INJECTOR LINAC

At the injector linac [3, 4], 100 mA of electron beam is accelerated up to 10 MeV. Thus, total of 1MW RF power should be passed to the beam. The injector linac consists of three 2-cell cavities and each cavity is fed RF power by twin couplers. Still, one input coupler should pass the high power of 167 kW. This is most challenging task in the injector part.

Another important issue is cooling of HOM coupler. It is well known that original TESLA-type HOM coupler has a heating problem in the CW operation [5]. Design of HOM coupler was modified [6] and also cooling ability was strengthened.

Main parameters for injector cavity are summarized in Table. 2.

Table 2: Main parameters for injector cavity

Frequency	1.3 GHz
Number of cell	2 cell
R/Q	205 Ω
Operating Gradient	14.5 MV/m
Number of input coupler	2 / cavity
Coupler power	167 kW / coupler
Coupler coupling	3.3×10^5
Number of HOM coupler	5 / cavity
Operating temperature	2 K

Two-Cell Injector Cavity with HOM coupler

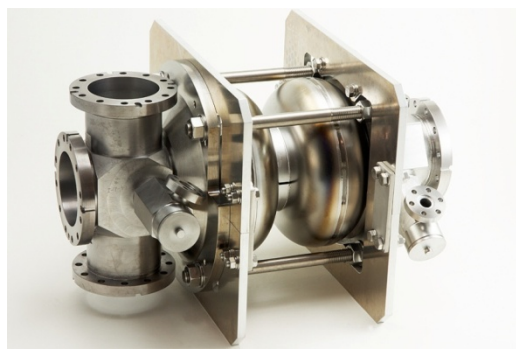


Figure 2: Prototype of injector 2-cell cavity.

SRF PHOTOINJECTOR TESTS AT HOBICAT*

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Abstract

In collaboration with Jefferson Laboratory, DESY and the A. Soltan Institute HZB developed a fully superconducting RF photo-injector as a first step towards a high average current electron source for the B*ERL*inPro ERL. This setup consists of a 1.6 cell superconducting gun cavity with a lead cathode plasma-arc deposited on the half cell backwall and a superconducting solenoid. The system, including a warm diagnostic beam-line section, was recently installed in the HoBiCaT test facility to study beam dynamics within the ERL parameter range. This paper will give an overview of the horizontal cavity tests, dark current studies and beam measurements.

INTRODUCTION

In the framework of the B*ERL*inPro Energy Recovery Linac project [1] HZB needs to develop a high current CW photoinjector delivering an average beam current of 100 mA at a normalized emittance of 1mm mrad and an exit kinetic energy above 1.5 MeV. This implies the usage of a high quantum efficiency normal-conducting cathodes at highest launch fields possible and a laser repetition rate of 1.3 GHz, filling every RF bucket, such that a CW operated SC photoinjector cavity is mandatory to achieve the required voltage. Thus also a damping of unwanted higher order modes has to be studied and a design has to be found which allows maximum field at strong beam-loading given the RF power constraints of the fundamental couplers. To achieve these challenging goals HZB will follow a three stage approach [2, 3]. The first step is a fully superconducting system of a 1.6 cell cavity, a superconducting lead photocathode and a superconducting solenoid for beam dynamics studies. It is being developed in a collaboration with DESY, Jefferson Laboratory and the A. Soltan Institute. This photoinjector will be used to demonstrate the short-pulse beam dynamics using a SC solenoid in the ERL parameter range. The following two injector systems will feature the insert of a normal conducting cathode including a choke filter system and finally a HOM damping scheme to handle the high average current.

This paper will give a first overview about the horizontal cavity tests, dark current studies and beam measurements.

Table 1: Cavity electromagnetic design parameters

Frequency π-mode	1300 MHz
Frequency 0-mode	1281 MHz
E_{peak}/E_{cath}	1.0
E_{peak}/E_{acc} (β=1)	1.86
H_{peak}/E_{acc}	4.4 mT/(MV/m)
Geometry factor	212 Ω
R/Q (linac, β=1)	190 Ω

Cavity Design and Fabrication

The cavity electro-magnetic design is based on a 1.6 cell all SC structure originally designed by Jacek Sekutowicz (DESY) with a lead cathode deposited on the half cell's backwall [4]. The cell shapes are optimized for maximum field on the cathode surface to allow a high launch field to minimize the beam's normalized emittance. Table 1 gives an overview of the figures of merit, Figure 1 shows the field distribution of the TM_{010} π-mode calculated by CST MWS™. The RF design was slightly changed in comparison to [4] to meet the 1.3 GHz and achieve the maximum electric field on the cathode surface. Further the mechanical passive stiffening was optimized by combination of electro-magnetic and mechanical ANSYS™ simulations [5] to reduce microphonics. This was of major importance as the cavity was foreseen without active tuning mechanism. Figure 2 shows the fully assembled gun cavity after fabrication, BCP and high pressure water cleaning, first vertical RF tests and installation of all ancillary components at JLab prior to shipping to A. Soltan institute for the cathode deposition. The manufacturing process is described in more detail in [6]. The 1.6 cells were made from polycrystalline RRR 300 niobium, whereas the halfcell's backwall was machined from large grain niobium with similar purity. After final tuning a field flatness of 94% was measured with a slightly lower field in the half cell.

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SRF ACTIVITIES AT PEKING UNIVERSITY*

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Abstract

Superconducting RF technology has been developed at Peking University for more than 20 years. In the recent years, the researches are mainly focused on producing high performance superconducting cavities and installing the DC-SRF photocathode injector as well as related 2K cryogenic facility and other auxiliary equipment. The cavities designed and fabricated by Peking University mainly include TESLA type 9-cell cavities, 1.3 GHz 5-cell cavity for high current electron beam acceleration and 450 MHz spoke cavity for low energy proton acceleration. Vertical tests of the cavities indicate that the cavities show good performances and can be used for superconducting accelerators. The gradient of a 9-cell TESLA type cavity with end groups (PKU3) reaches 28.6 MV/m. To promote the industrialization process in China, a new company, Ningxia Orient Superconductor Technology Co., Ltd., was founded jointly by Ningxia OTIC and Peking University in 2011. The goal of this company is to produce various types of superconducting cavities and pure niobium materials with high quality.

INTRODUCTION

Superconducting RF technology has been developed at Peking University (PKU) since 1988. In the past twenty years, significant progresses have been made on superconducting cavities. Based on the preliminary experience accumulated at the early years, the first superconducting cavity in china, an L-band high beta cavity using Chinese niobium sheets, was fabricated by Peking University in 1994. At the end of 20th century, Nb-Cu sputtering technology was developed for construction SRF QWR as a post Tandem accelerator. In the new century, efforts are made on high quality superconducting cavities for superconducting accelerators of free electron laser facility which is supported by China ministry of science and technology. Technologies for fabrication of multi-cell cavities are developed and a series of multi-cell cavities have been fabricated at PKU. To promote the SRF technology and meet the increasing demand for superconducting cavities in China and around the world, the idea to set up a company was agreed between PKU and Ningxia Orient Tantalum Industry Co. Ltd (OTIC). After 2 years preparation and based on the obtained SRF technology, a new company, Ningxia Orient Superconductor Technology Co., Ltd., was founded jointly by Ningxia OTIC and Peking University in 2011. In this paper, the recent progresses on SRF activities at Peking University are reported.

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PROGRESSES ON SRF CAVITIES

Technologies on fabrication of SRF cavities have been developed at PKU in the recent years. A series of superconducting cavities with Ningxia niobium have been fabricated, including both large grain cavities and fine grain cavities, single-cell to multi-cell cavities, high beta and low beta cavities.

Large Grain Cavities

Peking University has started researches on large grain niobium superconducting cavities since 2005. A series of large grain cavities have been made with Ningxia material by PKU under the collaboration with OTIC and Jlab. A 1.3 GHz single-cell cavity and a 2-cell TESLA type cavity were tested by Jlab and DESY respectively. Gradients are higher than 40 MV/m and Q values are higher than 1×10^{10} for both cavities [1,2]. A 3.5-cell large grain cavity for DC-SRF photoinjector is fabricated and the accelerating gradient reaches 23.5 MV/m and the Q_0 is above 1.2×10^{10} at the highest gradient [3].

Based on the above researches, a TESLA type 9-cell large grain cavity (PKU2) with end groups was fabricated at the end of 2009. After flatness tuning and RF measurement, the cavity was sent to Jlab for cold test. After 100 μm BCP, the cavity was degassed at 600°C for 10 hours. Another 80 μm BCP was added before the first cold test. At the first test in 2010, the maximum E_{acc} was 19.5 MV/m at 2.0 K with the Q_0 9×10^9, limited by quench. After the test, optical inspection was performed and defects were found near the equator electron beam welding seams. To improve the performance, the cavity was treated at 800°C for 2 hours and followed with 30 μm EP and 120 °C baking for 48 hours. The new RF test showed obvious improvement. The maximum gradient reached 22.4 MV/m at the final test at both 2.0 K and 1.8 K, see Fig. 1. The Q_0 is larger than 1×10^{10} at the high gradient: 2.0×10^{10} at 2K and 3.2×10^{10} at 1.8 K for 20 MV/m. The high Q value is very helpful to superconducting accelerator for ERL.

STATUS OF THE DC-SRF PHOTOINJECTOR FOR PKU-SETF*

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Abstract

DC-SRF photocathode injector developed by Peking University is a good candidate for obtaining high average current, low emittance, short electron beam pulse. Much progress has been made on the 3.5-cell cavity DC-SRF injector since SRF2009. The assembling of the cryomodule was completed with the 3.5-cell SRF cavity which has an accelerating gradient of 23.5MV/m in the vertical test. The preliminary RF experiment has been carried out soon after the installation and commissioning of 2K cryogenic system was finished. The accelerating gradient of the cavity is 11.5MV/m in a horizontal cold test and the Q_{ext} is 5×10^6. The limitation of the gradient is mainly from our present low RF power source. Higher gradient is expected with a new 20kW solid state RF power source which will be delivered to Peking University soon.

INTRODUCTION

Peking University (PKU) is developing a superconducting energy recovery linac (ERL) test facility – PKU-SETF. Figure 1 shows the schematic drawing of the layout of PKU-SETF. It has roles as accelerator physics and ERL technology test facility, and providing infrared free electron laser (FELs), THz (400-1200 μm), and further x ray through Compton Backscattering (CBS) for research in many areas such as chemistry, material science, life science, etc.

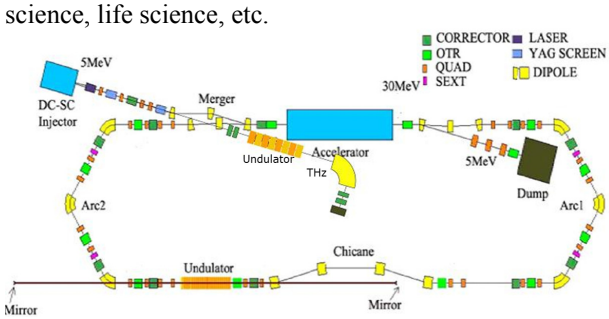


Figure 1: Schematic drawing of the layout of PKU-SETF.

The photoinjector for PKU-SETF is a DC-SRF photocathode gun [1, 2]. It combines a DC pierce gun structure and a 3.5-cell superconducting cavity, and can provide high average current, low emittance and short pulse electron beam. Figure 2 shows the sectional view of the DC-SRF injector. The injector has two different operation modes. One mode provides electron beam for ERL-FEL. The other is a RF bunch compression mode, and the injector works as a THz source.

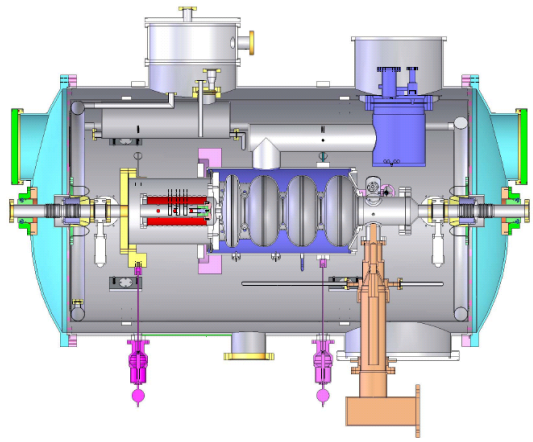


Figure 2: The sectional view of the 3.5-cell super-conducting cavity DC-SRF photoinjector.

KEY COMPONENTS OF THE DC-SRF INJECTOR

The key components of the DC-SRF photoinjector are a 100kV DC pierce gun and a 3.5-cell superconducting cavity. Figure 3 shows the sketch of the pierce structure and its corresponding high voltage isolation structure. The designed DC voltage is 90kV. The distance between the anode and the cathode is 14mm. Figure 4 shows the adaxial electric field distribution. The surface electric field on the cathode is almost 5 MV/m, and the peak electric field is lower than 13 MV/m. The electron beam gets a focusing force when it leaves the cathode and is defocused around the anode. The anode is connected to the 3.5-cell cavity though a small beam pipe. A single crystal niobium sheet with a diameter of 70 mm is used to make the anode and the entrance of the first half cell. This avoids discharging at high surface field. By controlling the concentricity of the connecting flanges, we can get good alignment of the pierce structure and the cavity.

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CHINESE PLANS FOR ADS AND CSNS

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Abstract

High intensity proton accelerator now has two major applications in China: one is Accelerator Driven Subcritical System for nuclear waste transmutation and another is spallation neutron source. ADS project launched in the first half of 2011 will build an ADS test setup with CW proton linac. China Spallation Neutron Source(CSNS) project will start construction in September 2011and it will operate at pulse mode at 25Hz repetition rate. This paper will briefly introduce these two projects, their accelerator design and the related technology development .

INTRODUCTION

High intensity proton accelerator is a new direction in China for its many important applications. Among them, Accelerator Driven Subcritical system (ADS) and spallation neutron source become major application field. A basic research program on ADS started in 2000 in China[1]. Recently a Chinese roadmap for long-term development of ADS was proposed by Chinese Academy of Sciences and the first budget of about $260M has be approved for an ADS test setup construction. It includes a CW proton linac consisting of a room-temperature RFQ and superconducting spoke cavities. The ADS R&D program started in the first half of 2011. The same amount of budget has also been approved for the project of China Spallation Neutron Source(CSNS) and it is going to be launched in September 2011. CSNS accelerator consists of a room-temperature H^- linac and a rapid-cycling synchrotron with beam power of 100kW at 25 Hz repetition rate[2]. It will be upgraded to 500kW beam power in future by adding some superconducting cavities to the linac to raise the beam energy for reducing space-charge effect in the synchrotron when the beam current becomes 5-times higher.

In the following sections of the paper we will briefly introduce the two projects and outline its present status. The accelerator design and technology development will be presented in more details, especially on their superconducting linac part.

ADS PLAN AND PROTON LINAC

China, as a developing country with a great population and relatively less energy resources, is rapidly developing nuclear energy. The nuclear electricity is foreseen to reach 75GWe, and meanwhile 30GWe power will be under development in 2020, according to the recently revised plan of the Chinese government in April 2009. This plan has no change after the Fukushima nuclear crisis, but the safety issue is much more emphasised. To develop nuclear power in such a large scale, long-lived radioactive nuclear wastes have to be safely disposed to reduce the impact on the environment and to eliminate public fear of nuclear power. The accumulated waste is estimated to be more than 10k tons in 2020, and it will be doubled in 2030. ADS has been recognized as the best option for the nuclear waste disposal. A basic research program on ADS started in 2000 in China. Recently a Chinese roadmap for long-term development of ADS was proposed by Chinese Academy of Sciences. It outlines a three-step plan with a small test setup, an experimental facility and a demonstration facility in a period from 2011 to 2032 , as plotted in Figure 1.

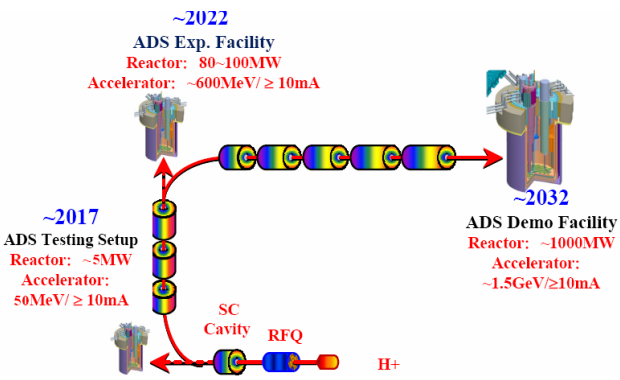


Figure 1: The road map of ADS development in China.

Step 1: From 2011 to 2017 we are going to construct an ADS test facility, called CIADS, which is the abbreviation of Chinese Initiative Accelerator Driven System. It is the first coupled system of an high intensity proton accelerator with subcritical reactor through a neutron production target. The thermal power of the reactor is designed at 5 MWth. Superconducting RF technology is one of the major subjects of this step, as it is still in the preliminary stage in China at present. CIADS project has been approved with a budget of $260M for construction of an linac, a subcritical reactor, a target, as well as the related technology platforms, but without land cost and infrastructure which will be supported by the local government. It has been launched in the first half of 2011 and is expected to be completed in six years. The Inner Mongolia in north part of China is a most possible construction site.

SRF ACCELERATOR FOR INDIAN ADS PROGRAM: PRESENT & FUTURE PROSPECTS

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Abstract

Accelerator Driven Systems (ADS) have evoked lot of interest the world over because of their capability to incinerate the MA (minor actinides) and LLFP (long-lived fission products) radiotoxic waste and utilization of Thorium as an alternative nuclear fuel. One of the main sub-systems of the ADS is a high energy and high current CW proton Accelerator. The accelerator for ADS should have high efficiency and reliability and very low beam losses to allow hands-on maintenance. With this criteria, the physics studies has been done for a 1 GeV, 30 mA proton Linac, using NC structures upto 100 MeV followed by Superconducting elliptical cavities, which accelerate the beam from 100 MeV to 1 GeV. We have also studied the configuration where superconducing spoke resonators are used to accelerate the proton beam from 3-160 MeV followed by elliptical cavities for 160 MeV to 1 GeV. The details of these studies are presented in this paper.

INTRODUCTION

Today most energy requirements including electricity generation are met by burning fossil fuel and hydroelectricity generation. However, with increase in the demand for energy, especially in the developing nations, nuclear power appears to be an attractive option for electricity generation. Presently, nuclear power constitutes about 17% of the total electric power generation in the world from about 430 operating reactors. Fission chain reaction is the only way known to harness nuclear energy, while the naturally occurring uranium and the man-made plutonium are the two key elements that are serving as nuclear fuel. In recent times, Accelerator Driven Systems (ADS) [1] are attracting increasing worldwide attention because of their capability to incinerate the minor actinides (MA) and long-lived fission products (LLFP) radiotoxic waste and utilization of Thorium as an alternative nuclear fuel. Due to its vast resources of Thorium in India, ADS is particularly important as one of the potential routes for large-scale Thorium utilization.

In ADS, a high-energy proton beam from an accelerator strikes a heavy element (e.g.; Pb, W, U, Th etc..) target which yields neutrons by (p, xn) spallation reaction. These neutrons can multiply in a sub-critical core through self terminating fission chains. It can be shown that total fission energy released in the multiplying medium is many folds larger than the energy of input proton beam. Thus such a system acts as an energy amplifier. The accelerator for such a system is required to deliver proton beams at energy typically around 1 GeV and operate in CW mode. For accelerator driven systems it is necessary that the accelerator is reliable, rugged and stable with very low number of beam interruptions, which could affect the lifetime of key components such as windows, reactor parts and structure, as well as the ADS operation.

DESIGN OF THE ACCELERATOR

Several countries are working towards making a demonstration system for ADS. In India too, efforts have started in designing and building a proton linac for ADS. The primary concern in building such high-power linac is the minimization of beam losses, which could limit the availability and maintainability of the linac and various subsystems due to excessive activation of the machine. A careful beam dynamics design is therefore needed to avoid the formation of beam halo that would finally be lost in the linac or in transfer lines. An accelerator configuration for a 1 GeV, 30 mA linac has been worked out and the physics design studies have been done in detail [2]. It consists of a 50 keV ion source, 4 vane 3 MeV Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL) upto 40 MeV, Cavity Coupled DTL(CCDTL) upto 100 MeV and 5 cell Superconducting elliptical cavities to accelerate the beam to 1 GeV.

In our design of superconducting cavities, we have taken a value of 15 MV/m for accelerating gradient. The SC cavities are designed to perform over the given velocity range and are identified by a design velocity called the geometric velocity, β_G. This design approach takes advantage of the large velocity acceptance of the superconducting cavities. The transverse and longitudinal phase advances per unit length are maintained constant at all transitions between the structures to provide a current independent match into the next structure. While the RFQ and DTL will operate at 352.21 MHz, the operating frequency of CCDTL and SC linac is 704.42 MHz. The total length of the designed accelerator is about 400 m and the overall beam transmission is 98%. The 2% beam loss takes place in RFQ during bunching of the beam at low energies; and hence poses no serious radiation problem. The total length of the designed accelerator is about 410 m and the RF requirement is about 38 MW.

One of the most challenging parts of such a CW proton accelerator is the low-energy injector, typically up to 10-20 MeV, because the space-charge effects are maximal at lower energies. With this challenge in mind, a low energy (20 MeV) high intensity (30 mA) proton accelerator (LEHIPA) [3] is being built at BARC as a front-end injector for the 1 GeV linac for ADS. It consists of a 50 keV ECR ion source, a 3 MeV, 4-vane Radio

CRAB CROSSING FOR LHC UPGRADE *

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Abstract

The LHC luminosity upgrade aims at reducing the collision point betas by a factor of 2-3 of the design value. Consequently the Piwinski angle is increased well beyond 1 to keep a normalized beam separation in the common focusing channels, thus diminishing the benefit of the beta* reduction. Crab cavities will not only recover this luminosity loss but also enable luminosity leveling, a vital ingredient for the upgrade. The baseline scenario for a crab crossing implementation in the LHC, primarily focusing on the RF cavity development is presented. Constraints from aperture, impedance and machine protection are also highlighted.

INTRODUCTION

The LHC interaction region (IR) employs a common focusing channel for both beams. Due to the 25ns bunch spacing, the two beams encounter each other in 36 places on the left and the right of the collision point. Therefore, a crossing angle is induced to physically separate the beams to about 10σ to avoid the parasitic encounters. The luminosity upgrade of the LHC aims to squeeze the collision point β^* by factor of 2-3 below the design value. Table 1 shows some relevant parameters for the nominal and subsequent upgrade of the LHC.

Table 1: Relevant LHC nominal and upgrade parameters.

	Unit	Nominal	Upgrade
Energy	[TeV]	3.5-7	7
Protons/Bunch	[10^{11}]	1.15	1.7
Average current	[Amps]	0.58	0.86
Bunch Spacing	[ns]	50-25	25
ϵ_n (x,y)	[μm]	2-3.75	
σ_z (rms)	[cm]	7.55	7.55
$IP_{1,5}$ β^*	[cm]	55-150	15-25
Betatron Tunes	{Qx, Qy}	{64.31, 59.32}	
Rev. Freq	kHz	11.245	
Piwinski Angle	Φ	0.64	1.1-1.4
Peak luminosity	$[x10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.1-1	5

This requires an increase in the crossing angle to maintain the normalized beam to beam separation near the IR. Consequently the effective luminosity gain is reduced due to the larger crossing angle given by

$$L \approx L_{\circ}.\left(1+\Phi^2\right)^{-1/2} \quad (1)$$

where $\Phi = \sigma_z\theta_c/\sigma_x^*$ is the Piwinski angle. For Φ sufficiently large (see Tab. 1), the luminosity reduction becomes large.

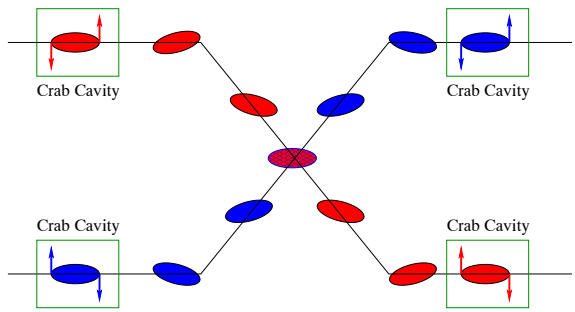


Figure 1: Concept of crab crossing scheme using RF cavities to maximize the bunch overlap at the collision points.

To fully exploit the beam size reduction a compensation of the crossing angle and in addition leveling of luminosity with crab cavities (see Fig. 1) is required [1, 2, 3]. In addition, the crab cavities offer a natural luminosity leveling knob to maximize the integrated luminosity and the lifetime of the IR magnets due to radiation damage. This paper will describe the present status of the crab project and forthcoming R&D focusing on superconducting deflecting cavities.

LAYOUT & SPECIFICATIONS

A local crab scheme (see Figure 2) where the cavities are placed in the interaction region offers the most flexibility in optics and satisfy the alternating crossing schemes as in IP_1 & IP_5.

A draft optics (Ref. [4]) to reach the desired low beta (15cm) for the upgrade with approximately 10m of physical space to accommodate the crab cavities within the interaction region is depicted in Fig. 3. The cavities are placed between the D_2 separation dipole and insertion quadrupole Q_4 which is presently the closest location to the collision point while the beams being completely separated.

The cavity voltage required for each scenario can be calculated using

$$V_{crab} = \frac{2cE_0\tan\left(\theta_c/2\right)\sin\left(\mu_x/2\right)}{\omega_{RF}\sqrt{\beta_{crab}\beta^*}\cos\left(\psi^x_{cc\rightarrow ip}-\mu_x/2\right)} \quad (2)$$

* This work partially supported by the US Department of Energy through the LARP program.

THE ESS ACCELERATOR

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Abstract

In 2003 the joint European effort to design a European Spallation Source resulted in a set of detailed design reports. Lund was agreed as the site in 2009, and a company, ESS AB, has been created to design, build and operate ESS. A collaboration has been formed for the accelerator work and an update project has been agreed and financed. Detailed planning for the prototyping in a Prepare-to-Build (P2B) project has also started. The current status of the Design Update project for the accelerator will be presented, together with an outline of future work. The baseline for the updated design delivers 5 MW of 2.5 GeV protons to a single target, in 2.86 ms long pulses with a 14 Hz repetition rate. The linac will have a normal conducting front end with an ion source, an RFQ and a DTL. The superconducting part starts with spoke cavities followed by two families of elliptical cavities. It will be the first time that spoke cavities are used in a major accelerator. Work is being done to optimize the energy efficiency and to make further use of the heat from the cooling water coming out of the facility. Finally, potential future upgrades of power are considered.

INTRODUCTION

Spallation is a nuclear process in which neutrons of different energies are emitted in several stages following the bombardment of heavy nuclei with highly energetic particles. The spallation process is the most practical and feasible way of producing neutrons for a reasonable effort (or cost) of the neutron source cooling system. Spallation sources come in at least three types: short pulse sources (a few μs), long pulse sources (a few ms) and continuous sources. The future European Spallation Source (ESS) will be a long pulse source and the first spallation source with a time average neutron flux as high as that of the most intense research reactors.

The highest power spallation source currently in operation – the Spallation Neutron Source (SNS) in Oak Ridge – combines a full energy SC linear accelerator with an accumulator ring to provide very high intensity short pulses of neutrons to the instruments. The European Spallation (ESS) source will provide even higher intensities, but is developing instruments able to use longer linac pulses directly for spallation, avoiding the need for a costly and performance-limiting accumulator ring [1].

The obvious advantage of a linac is that beam passes only once through the accelerating structures, enabling it to accelerate a high current beam with a minimum of constraints. The current limit is mainly set by space charge effects at low energy, as well as the power that can be delivered to the beam in each accelerating cavity at medium and high energies, and by beam losses.

The spallation cross section for protons on heavy nuclei increases as a function of proton energy up to several tens of GeV [2]. Nonetheless it is generally agreed that a kinetic proton energy between 1-3 GeV is optimal for practical target and moderator designs, and in order to keep the shielding requirements reasonable.

The ESS has the ambitious goal of becoming a sustainable research facility with zero release of carbon dioxide. This will be achieved through a combination of actions, but with the linac being the most energy hungry part of ESS, the energy efficient design of the RF power sources and the cryogenics systems and high-Q cavities are important issues.

THE ESS BASELINE

The ESS accelerator high level requirements are to provide a 2.86 ms long proton pulse at 2.5 GeV at repetiton rate of 14 Hz, with 5 MW of average beam power on target. The general lay-out of the ESS linac can been seen in Fig. 1.

Since there is no need for a charge injection schemes into an accumulator ring for a long pulse source, the ion source for ESS will produce a proton beam. The source is proposed to be a compact Electron Cyclotron Resonance source (ECR) similar to the VIS source [3] in Catania and the SILHI source [4] at CEA Saclay.

The beam from the ion source is transported through a Low Energy Beam Transport (LEBT) section to the RFQ for bunching and acceleration up to 3 MeV. The RFQ will be of four vane type [5] and a first test run at realistic ESS requirements will be performed at the IPHI RFQ which is presently under commissioning at CEA-Saclay in Paris. The beam is transported from the RFQ and matched to the first normal conducting Drift-Tube Linac (DTL) structures with a Medium Energy Beam Transport (MEBT) section. It is still an open issue if the MEBT will contain a fast buncher.

The transfer to the first superconducting structures will be at 50 MeV. The first superconducting section will consist of double spoke cavities which will take the beam to 188 MeV. Spoke resonators have a large transverse and longitudinal acceptance and are mechanically very stiff, reducing their sensitivity to microphonics and to Lorenz force detun-

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