STATE OF THE ART SRF CAVITY PERFORMANCE

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Abstract

The paper will review superconducting RF cavity performance for β=1 cavities used in both linear and circular accelerators. These superconducting cavities are used in two kinds of applications: High current storage rings and efficient high duty cycle linacs. In recent years the performance of those cavities has been improving steadily. High accelerating gradients have been achieved using advanced surface preparation techniques like electropolishing and surface cleaning methods like high pressure water rinsing. High intensity beams can be handled with advanced higher-order-mode damping schemes.

INTRODUCTION

Superconducting radiofrequency (SRF) cavities are used for several applications. All species of particles are accelerated using SRF for several reasons:

- Surface resistance at microwave frequencies is a few nOhm (10^6 times smaller than for normal conductors)
- High efficiency for transforming wall-plug to beam power
- Continuous-wave operation
- Low frequencies
  - Large aperture
  - Large acceptance
  - Smaller wakefields
- Potential for energy recovery operation
- High accelerating gradients

This paper will describe the state-of-the-art for cavities used for electron acceleration (β=v/c=1). Electron accelerators are used for elementary particle physics (storage rings, linear collider) or light sources (storage rings, linacs).

SUPERCONDUCTING CAVITY TECHNOLOGY

For superconducting cavities at very high electrical and magnetical surface field great care has to be taken during manufacturing and preparation for beam acceleration. Normalconducting inclusions in the material and contaminations on the surface need to be avoided. For example, the preparation and assembly in in clean rooms and ultrapure water supplies for rinsing the surfaces are a must. In this paper the focus will be on the surface preparation with electrochemical methods before the final high pressure rinsing.

Material Quality

The niobium bulk material used for cavity fabrication needs to have good thermal conductivity as the heat produced on the inner side of the cavity needs to be conducted to the coolant (liquid helium) on the outside. The thermal conductivity is usually not quoted as the figure of merit but the RRR (residual-resistivity ratio) value. Typical RRR values in the cavities described in this paper is around 200-300 and 500-600 for cavities subjected to a postpurification using a furnace treatment at 1300°C with a titanium getter layer.

As an example of quality control for the niobium sheet material an eddy-current scanning system which currently is used for SNS (build by company based on a design by Bundesanstalt für Materialforschung and DESY) is shown in figure 1. A similar system is in use for the TESLA cavities [1,2]. The eddy-current system also allows to certain degree to determine the type of inclusion. Any niobium sheet showing defects is rejected from the cavity manufacturing process. The rejection rate is about 5 %. Most of the rejected sheets will be recoverable by applying some chemical etching. The iron inclusions were caused by mechanical wear of the rolls used for sheet rolling. In the meantime new rolls have been installed. The eddy-current check has turned out to be an important quality control not only for the cavity manufacturer but also for the supplier of the niobium sheets.

Figure 1: Setup for quality control of niobium sheet material for SNS.

Surface Treatment

The niobium sheets are deep drawn and electron beam welded to fabricate a cavity. A damage layer of about 100 µm thickness is removed from the inner surface to obtain optimum performance in the superconducting state. Often cavities have been chemically etched [2,3]. Niobium metal has a natural Nb_2O_5 layer with a thickness of about 5 nm which is chemically rather inert and can be dissolved only with hydrofluoric acid (HF). Chemical etching of niobium consists of two alternating processes: dissolution of the Nb_2O_5 layer by HF and re-oxidation of the niobium by a strongly oxidizing acid such as nitric acid (HNO_3) [4,5]. To reduce the etching speed a buffer substance is added, for example phosphoric acid H_3PO_4 (concentration of 85%) [6], and the mixture is cooled

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below 15°C. The standard procedure with a removal rate of about 1 μm per minute is called buffered chemical polishing (BCP) with an acid mixture containing 1 part HF, 1 part HNO_3 and 2 parts H_3PO_4 in volume.

An alternative surface preparation method to etching is electrolytic polishing (EP). The material is removed in an acid mixture under the flow of an electric current. Sharp edges or tips are smoothed out and a very glossy surface can be obtained. This is an essential difference to the BCP process which tends to enhance the steps at grain boundaries (see micrographs in Fig. 2). Using electrolytic polishing, scientists at the KEK laboratory in Tsukuba (Japan) achieved gradients of up to 40 MV/m in single-cell cavities [7].

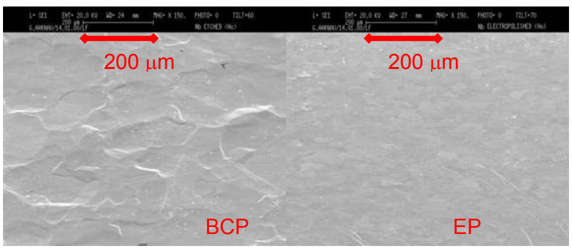

Figure 2: SEM surface picture of etched (BCP=Buffered Chemical Polish) and electropolished surface.

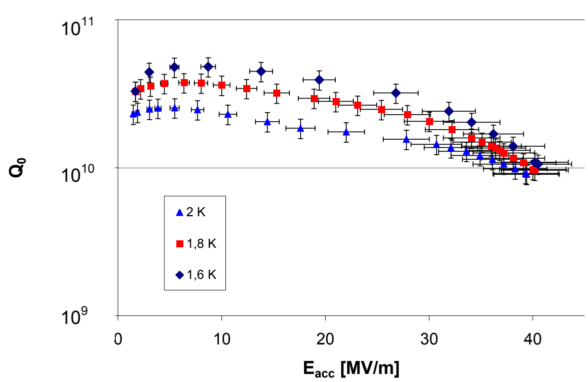

Figure 3: Performance of a TESLA cavity after EP at DESY. A gradient of 40 MV/m was achieved in the low power continuous wave measurement.

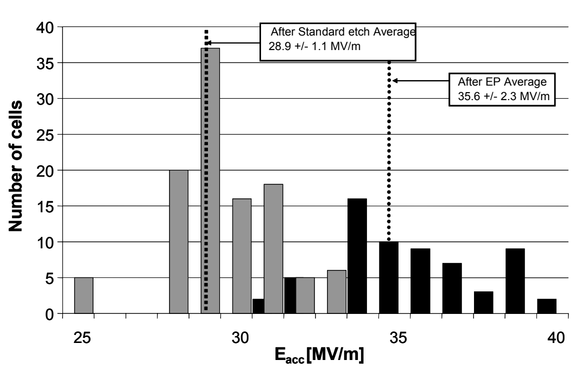

Figure 4: Comparison of the achieved gradients in the individual cells of several nine-cell cavities after standard etching (grey) and after electropolishing (black).

The EP technique has been successfully transferred to nine-cell cavities within a joint KEK-DESY R&D program [8]. Cavities were sent to KEK/Nomura Plating after furnace treatment at DESY (5 cavities treated 800°C, 4 cavities at 1400°C) where electropolishing and first high pressure rinsing were carried out. Final assembly, final high pressure rinsing and bakeout at 120°C were carried out at DESY.

For an energy upgrade of TESLA to center-of-mass energy of 800 GeV (TESLA-800) a gradient of 35 MV/m at a Q_0 of 5×10^9 is needed. Out of the 9 cavities from the last production series of TTF cavities four cavities achieved this specification and six cavities more than 30 MV/m. Two cavities were strongly loaded with field emission. One of these cavities has been electropolished for the second time in the EP facility at DESY. The test results of this cavity at helium temperatures between 1.6 and 2.0 K are shown in figure 3. Accelerating fields of up to 40 MV/m have been reached which is a record for multi-cell niobium cavities.

The clear advantage of electropolishing can be seen in figure 4. The single cell statistics derived from the coupled mode measurements are compared for chemically etched and electropolished nine-cell cavities. The average maximum gradient is 28.9 MV/m for BCP-treated cavities and 35.6 MV/m for EP-treated cavities.

Additionally high power tests have been performed on electropolished cavities: Several measurements at nominal pulse length (500 μs, filling time, 800μs flat-top) at a repetition rate of 1-10 Hz confirmed the very good performance of the cavities in the vertical test (figure 5). The quality factor of larger than 7×10^9 at a gradient of 35MV/m is larger than required for TESLA-800 in all cases. One cavity achieved a gradient of 37 MV/m at a Q_0 of 1×10^{10}. Warm-ups of the cavity to 300 K and 150 K respectively did not change the cavity behaviour in any case.

In a long term test of more than 1100 hours at 35 MV/m there was no sign of performance degradation. Thermal breakdowns (quenches) of the cavity induced during the setup of the LLRF (Low-level RF system) were not influencing the quality factor. This is a well-known behaviour for superconducting cavities. Breakdowns in the coupler also caused during setup of the Low Level RF system were not detrimental to the coupler performance.

Another cavity was installed into an accelerator module for TTF. The final preparation and assembly (e.g. cavity-to-cavity connection) for the module did not change the performance of the cavity. At a gradient of 35 MV/m the cavity has been measured with a quality factor of 9×10^9 which is far above the specification for TESLA-800. The RF gradient calibration was crosschecked using an energy gain measurement of the electron beam.

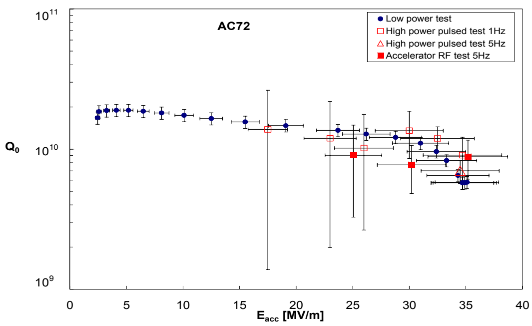

Figure 5: High power test of an electropolished TESLA nine-cell in the TTF linac. 35 MV/m were achieved with a quality factor of 9×10^9.

Pulsed Operation of Cryomodules

The performance of full TESLA accelerator modules in use today demonstrates that the gradient achieved in the low-power acceptance tests can be used in the accelerator. (figure 6)[9]. This is a sign that the final assembly steps are well enough defined for reproducible results. The most recent module assembled with has an accelerating gradient of more than 25 MV/m limited by the last cavity. Some cavities show gradients of 30 MV/m which seems near the maximum which is achievable using post-purified (RRR~500), etched cavities. The results of the acceptance test are also shown in figure 6.

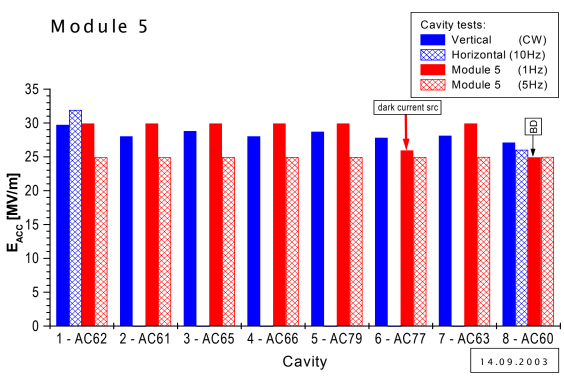

Figure 6: Performance of a TESLA accelerating module assembled with etched cavities. The maximum gradient achieved in the module is compared to the gradient achieved in the acceptance test[9].

CW Operation of Cryomodules

CW operation is typically limited to gradients around 15 MV/m for economical reasons. JLab has build a module for the infrared FEL which can deliver more than 15 MV/m in seven out of eight cavities [10]. The module is also build from etched cavities. The cavities have not been subjected to a post-purification treatment like the TESLA cavities in TTF. The single cavity test yields a higher gradient than the operational gradient as the beam energy requested by the FEL users was lower. At the lower energy no trip of the system was observed for several weeks.

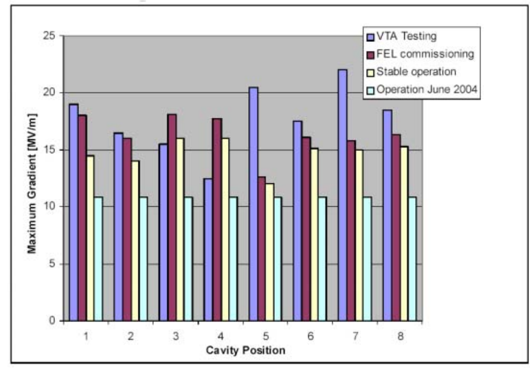

Figure 7: Performance of the IR-FEL module build at JLab[10].

CAVITY DESIGN

With the accelerating gradient approaching the theoretical limit and fabrication technology in hand the new challenges for SRF cavities are increasing the beam current further thus introducing many new ideas about cavity shapes and HOM damping. This will be illustrated using three examples: The superstructure concept, the CEBAF upgrade cavity shapes and the HOM damping concepts for the Cornell ERL prototype.

Superstructure Concept

In striving for highest collider energies not only the gradient in the cavities but also the active acceleration length have to be maximized. There are, however, two effects which limit the number of cells N_c per resonator. With increasing N_c it becomes more and more difficult to tune the resonator for equal field amplitude in every cell: the sensitivity of the field homogeneity to small perturbations grows with N_c^2. Secondly, in a very long multicell cavity 'trapped modes' may be excited by the short particle bunches. These are coupled oscillations at high frequency which are confined to the inner cells and have such a low amplitude in the beam pipe sections that they cannot be extracted by the higher-order mode (HOM) couplers mounted the beam pipe. Trapped modes may have a detrimental influence on the beam emittance and must be avoided. The number $N_c = 9$ chosen for TESLA appears a reasonable upper limit.

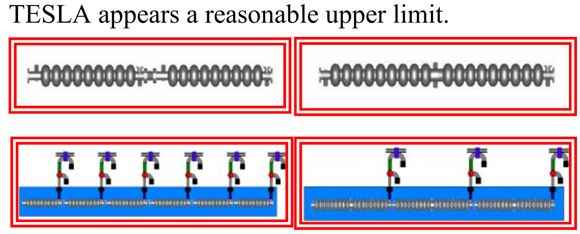

Figure 8: Comparison of the standard TESLA layout (left) with the superstructure layout (right).

The limitation in the number of cells can be overcome by the *superstructure* concept proposed by J. Sekutowicz [11]. Several multicell cavities are joined by beam tubes of length $\lambda/2$ ($\lambda = 230$ mm is the wavelength of the accelerating mode). Within each cavity there is an rf phase advance of π from cell to cell, while the phase advance between adjacent multicell units is zero. This ensures that the particles experience the same accelerating field in all cells of the superstructure. The superstructure is supplied with rf power by a single input coupler at one end. The interconnecting pipes have a sufficiently large diameter to permit the flow of rf power from one cavity to the next.

For the TESLA electron and positron linacs a superstructure consisting of two 9-cell cavities is envisaged [1], see figure 8. Compared to the layout with separated 9-cell cavities, this superstructure improves the filling factor by 6 % and saves a factor of two in input couplers and waveguide components.

The coupling between two adjacent cavities in a superstructure is about two orders of magnitude smaller than the cell-to-cell coupling within each subunit. To demonstrate that this small coupling is compatible with the requirement of a low beam energy spread a proof-of-principle experiment of two 2x7-cell superstructures was carried out at the TTF linac [12]. The rf power flow through the interconnecting pipe was found to be sufficient to replenish the stored energy in each cell between successive electron bunches. The measured bunch-to-bunch energy fluctuation was within the TESLA specification of $\Delta E/E$ (rms) $\leq 5{\cdot}10^{-4}$ (see figure 9). Besides this, it was confirmed that a field homogeneity of better than 90% could be achieved in the superstructure. The excitation of beam-induced higher-order-modes was thoroughly studied and sufficient damping was verified.

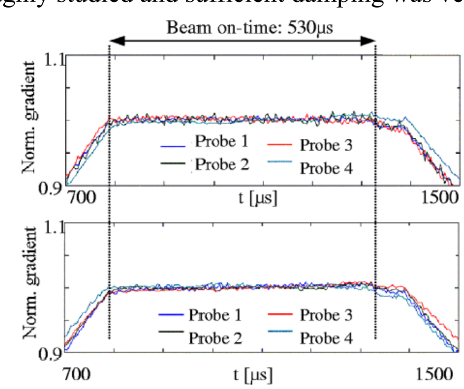

Figure 9: Measured: $\Delta E/E$ (rms) $\leq 2{\cdot}10^{-4}$ in the prototype superstructure .The TESLA-Specification is $\Delta E/E$ (rms) $\leq 5\cdot10^{-4}$.

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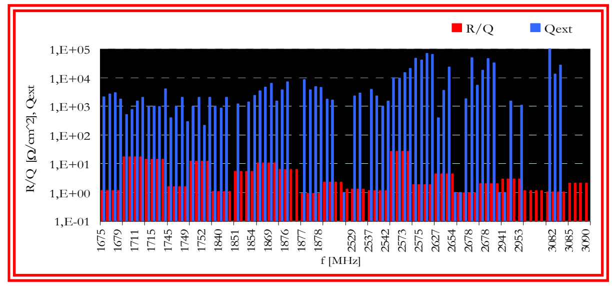

Figure 10: The damping of dipoles with (R/Q) ≥ 1 Ω/cm2 which are relevant for the TESLA beam was by factor 5 to 100 better then the specification.

CEBAF Upgrade Cavity Shape

For the CEBAF upgrade two new cavity shapes have been proposed (figure 11) [13]. One is optimized for high-gradient operation (HG) which features a lower E_{surf} to reduce field emission. The second shape is called low-loss (LL) and maximizes the shunt impedance and geometric factor to achieve the maximum gradient with a given cryo power (see table 1).

Tests on single cell cavities demonstrated that the shapes are multipacting-free. One cavity of the low-loss variety achieved an electric peak surface field of 87 MV/m (figure 12). Seven-cells have achieved 20 MV/m in first tests.

The HOM damping of niobium prototypes confirms calculations and copper model measurements. For the final application improved feedthroughs with better thermal design are under fabrication.

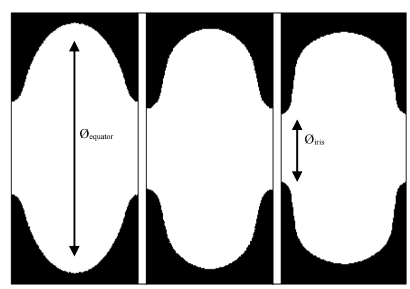

Figure 11: Geometrical shapes for the CEBAF upgrade cavities[13].

Table 1: Parameters for the cavity shapes for the CEBAF upgrade cavities

Parameter		OC	HG	LL
$Ø_{equator}$	[mm]	187.0	180.5	174.0
$Ø_{iris}$	[mm]	70.0	61.4	53.0
k_{cc}^{*}	[%]	3.29	1.72	1.49
E_{peak}/E_{acc}	[-]	2.56	1.89	2.17
B_{peak}/E_{acc}	[mT/(MV/m)]	4.56	4.26	3.74
R/Q	[Ω]	96.5	111.9	128.8
G	[Ω]	273.8	265.5	280.3
R/Q·G	[Ω·Ω]	26422	29709	36103

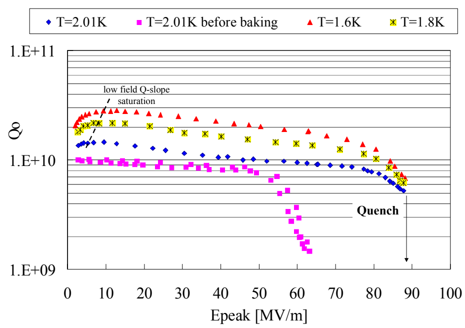

Figure 12: Test of a single cell of the low-loss shape. Very high electric surface field could be reached.

HOM Damping of the Cornell ERL Prototype Injector Cavities

Cornell University, in collaboration with JLab is exploring a 100 MeV CW prototype ERL with a beam current of 100 mA to study the energy recovery concept with high current, low emittance beams [14]. A key element of this machine is a high brightness injector with every bunch filled.

The injector system needs to deliver 150 kW per cavity to the beam through the input couplers. More than a hundred watts per cavity of beam induced power must be removed through HOM couplers. Power delivery and extraction must be accomplished without introducing an asymmetry that can lead to emittance dilution. This is done using two input couplers and HOM broadband absorbers in a region with enlarged beam tube which allows propagating of all HOMs. Figure 13 illustrates the injector cavities.

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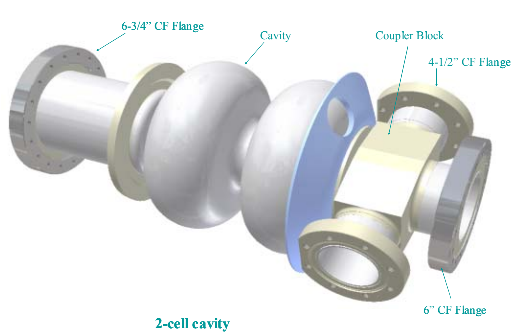

Figure 13: Two-cell injector cavity for the Cornell ERL prototype.

CONCLUSION

SRF cavities approach the physical limit in terms of maximum magnetic peak field. For electropolished cavities of the TESLA-type accelerating gradients of more than 35 MV/m have been achieved in multi-cell cavities in low and high power test. A test in the TTF accelerator shows that the means of assembling such high gradient cavities are at hand principally. Continuous wave operation of full cryomodules near the economically reasonable gradient of about 15 MV/m has been achieved at JLab. New cavity concepts like superstructures and heavily HOM damped structures are being explored thus opening up a new regime of increased beam currents suitable for a variety of accelerator projects.

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