TECHNICAL ISSUES FOR LARGE ACCELERATORS BASED ON HIGH GRADIENT SC CAVITIES

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Abstract

The perspective to build large accelerators based on high gradient superconducting cavities is posing a number of new problems that have been addressed in the preparation of the TESLA project. Starting from the experience gained with the past large installations, such as LEP2 at CERN and CEBAF at TJNAF, in this paper I discuss the new demands and the solution envisaged. Industrial production issues are focussed in terms of large scale production, reviewed quality control criteria and cost reduction.

INTRODUCTION

Superconducting radiofrequency (SRF) has been introduced in the particle accelerator community in the early '70, as a valid technology to efficiently transmit energy to a variety of particle beams.

When a superconductor is exposed to a time varying electromagnetic field the electrons which are not coupled as Cooper pairs lead to energy dissipation in a shallow layer from the superconductor surface, the skin depth region. Nonetheless, it was soon realized that in the practical frequency range of RF accelerators the use of superconducting cavities leads to an overall increase in the conversion efficiency from RF to beam power of a few orders of magnitude [1].

A few laboratories and universities started fundamental investigations and experiments to demonstrate the technical feasibility of SRF acceleration. Very rapidly the results reached severe technological limitations, mainly due to the modest purity of the superconducting material being used to produce the cavities prototypes.

For the first few decades the maximum accelerating field reached in the experiments has been limited by the technologies used for the superconductor and the cavity treatments and handling procedures.

In spite of these limitations, the construction and operation of hundreds of moderate gradient (5-8 MV/m) cavities at TJNAF for CEBAF and at CERN for LEP II has been the basis for setting a new level of quality control and industrialization. A deeper understanding of the limiting factors contributed then to revise the SRF technology further, in order to be compatible with the new challenging demands emerging from the High Energy Physics community.

In this context the TESLA challenge to employ SRF as the baseline technology for the future TeV e^+e^- Linear Collider impressed the required momentum to bring forward the SRF technology to a new era:

- Accelerating fields exceeding 35 MV/m,
- Quality factor higher then 10^{10}.

A number of new project based on SRF technology have been recently proposed or are in the construction stage. The experience on large existing cryogenic infrastructures and the ongoing work for the LHC allows to most of the accelerator community to be confident that a SRF TeV collider could be built at a cost and with a foreseen reliability that are equivalent to the high frequency normal conducting competitors, while showing a better conversion efficiency and lower operating costs.

SRF LIMITS AT THE PIONEER AGE

The pioneer age

The High-Energy Physics Lab (HEPL) at Stanford University has been the pioneer laboratory in studying SRF application to accelerators. The first acceleration of electrons with a lead plated single cell resonator dates back to 1965 [2]. Bulk niobium multi-cell cavities were then developed, reaching an operating accelerating gradient of about 2 MV/m. A number of technologies - as electron beam welding and pure water rinsing - were pioneered by the project, which was limited by multipacting phenomena and by the poor niobium quality.

In the late 1960s at KFK (Karlsruhe) and few years later at ANL, SRF was considered for the design of proton and ion linacs in CW operation. In order to be superior to the competing technology of normal conducting RF a moderate field of few MV/m was necessary. Unfortunately, the unexpected problem of mechanical vibrations induced by the helium flow on high Q structures delayed this promising application. The new "split ring" design developed at Caltech [3] gave the start to a number of nuclear physics projects for low energy linacs, all aiming to accelerate ions above the Coulomb barrier. At that stage, the superconducting material was a thin lead film electroplated on an underlying copper structure. Bulk niobium was more expensive in terms of the associated technologies and gave similar results.

Major limitations for high performances

Unexpected and underestimated problems emerged as soon as new demands were posed to the SRF technology:

- **Mechanical vibrations**, amplified by the high quality factor of the resonators;
- **Multipacting**, i.e. resonant electron multiplication, which easily loads a high Q structure and is difficult to be crossed because of the long cavity filling time;
- **Thermal quenches** at moderate fields, mainly in the bulk niobium structure cases, due to the poor quality of the superconducting material, especially concerning inclusions of different materials during the fabrication process, usually associated with a modest thermal conductivity.

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- **Field emission** at moderate field, again driven by the poor surface quality and foreign inclusions.

The first two points - while very serious - were not strictly related to the concept of high gradient SRF technology. The field limitations induced by these effects were related to the coupling of well known phenomena with the unprecedented high Q associated to the low losses of the SRF structures. New cavity designs, taking care of the mechanical properties and the electron multiplication dynamics, have since then been developed with more performing computer codes.

Conversely, thermal quenches and field emission are still limiting the accelerating field of a superconducting cavity. These effects are ruled by the surface defects and in general by the quality of niobium and cavity surface.

Since the scope of this short paper focuses on high gradient operation, I will limit the following discussion to electron accelerators, which have been the driving force for the first significant steps toward the development of the SRF high gradient technology.

LARGE PROJECTS DISCOVER SRF

As soon as it was understood how to avoid the limitation induced by multipactoring by using a "spherical" geometry [4], higher field were obtained in multi-cell cavities for electrons and, more generally, for ultra-relativistic particles. This achievement triggered both the high energy and the nuclear physics communities to consider SRF as the best possible candidate for the accelerating system required for new challenging projects. The use of the SRF technology by the strongest physics communities and the subsequent impressive boost of the allocated resources to R&D activities generated the conditions for the first crucial step in the direction of the development of the high gradient SRF technology.

The first successful test of a complete multi-cell cavity at high gradient and with beam was performed at Cornell. At the end of 1984 a pair of 1.5 GHz, 5-cell bulk niobium, cavities were tested in CESR with a beam current of 26 mA at an average gradient of 4.5 MV/m [5]. This cavity design was then used as the basis for one of the two largest SRF installations ever built, namely CEBAF at TJNAF.

The decision to apply this novel technology in the largest HEP accelerators forced the laboratories to invest in R&D, infrastructures and quality control, widely using the industrial experience as a guideline. Moreover, the need of building hundreds of cavities pushed the laboratories in the industrial transfer of a large part of the production, thus closing a virtuous cycle between basic research and industrial production.

R&D and basic research on SRF made also a progress, thanking to the work of many groups distributed worldwide. The understanding of SRF limiting problems at high fields had an important improvement in following decade. In chronological order the major projects during this phase were TRISTAN, HERA, CEBAF and LEP II, and the committed laboratories were, respectively, KEK, DESY, TJNAF and CERN. Because of the relative project size, TJNAF and CERN played the major role in SRF technology development and industrialization, moving in two different directions for the cavity production: bulk niobium and thin niobium coating on copper substrate.

Bulk niobium based Projects

TRISTAN, HERA and CEBAF decided to produce bulk niobium cavities, thus using the same material as the superconductor and the structural substrate. Niobium was produced by different companies distributed worldwide, with a consistent improvement in term of purity and quality with respect to the past. Lower gas and tantalum content were present in the material and the reference parameter RRR (Residual Resistivity Ratio) was pushed above 100. Nevertheless, because of the relatively small quantity of high purity niobium required by the SRF applications, the industry was not willing to invest huge amount of resources, especially in term of people and investments. As a consequence niobium, mainly derived during the tantalum production process, was not sufficiently post-purified by electron beam melting under vacuum and the subsequent production steps to produce sheets of polycrystalline material with proper grain size and isotropy was still done in a "dirty" environment.

For CEBAF, the largest installation, more than 300 cavities were produced by the industry, based on the original Cornell design: 1.5 GHz and 5-cell. The CEBAF design goal was to operate the SRF cavities in CW at an average gradient of 5 MV/m. in order to obtain an electron beam of 4 GeV through 5 recirculations. Since 1993, CEBAF is now routinely delivering a 200 mA CW beam at the maximum energy of 6.5 GeV, limited by the RF and cryogenic power installed.

A large infrastructure was created at TJNAF in order to develop cavities and ancillaries. This infrastructure was used to develop and build complete cavity prototypes based on the state of the art in terms of present knowledge and quality control. Since it was recognized that the performances are limited by field emission and thermal quenches, the following procedure were introduced, specified and controlled:

- Use of the **best niobium** in term of purity, inclusions, grain size and regularity. High RRR for thermal conductivity, in order to increase the quenching field for a given defect size.
- **Electron beam welding under vacuum** of clean niobium cavity subcomponents, avoid dust.
- **Grinding** on the internal surface to smooth welding defects.
- **Closed loop chemistry** with controlled acid batches.
- **Ultra Pure High water rinsing** and clean drying.
- Class 100 **clean room** environment for all final assembly of treated cavity components. Figure 1 shows the TJNAF clean room facility.
- High pressure water rinsing and high temperature **heat treatments** were introduced at the R&D level.

Figure 1: Clean room final assembly of a CEBAF cavity pair at TJNAF.

After the successful test of prototypes, cavities were produced by industry under high level quality control procedures. Grinding, tuning, processing, assembling and tests were done at the dedicated infrastructure in TJNAF.

CEBAF experience was the first crucial milestone towards high gradients. At the end of the production the steps described above were routinely applied worldwide in all R&D laboratories. The basis for a new generation of higher gradient cavities was set, including the technology transfer of part of the production to industry. Other important lessons were learned and well understood:

- **Processing and conditioning** improves cavity performances, in absence of material defects (hard quenches). Field emission was moved to higher fields and the accelerating field improved in time.
- The **2 K operation** turned to be reliable and well understood. All the ancillaries performed well at 2 K.
- The physics experiments were given **a high beam availability**, and the only CEBAF warm-up was due recently to the Isabelle Hurricane.

The excellent reliability and availability of SRF systems was demonstrated in 10 years of operation above the design goals. SRF cavities and ancillaries contribute to less than 1 % of the accelerator down time, while the cryogenics contribution stays at 2.5 % [6].

Magnetron sputtering for LEP II at CERN

By substituting the RF system with a SRF one, at the frequency of 352 MHz, the energy gain per turn of LEP ramped from 360 MeV to nearly 3.7 GeV. The equilibrium energy of the electron and positron beams rose from 45 to 104.5 GeV [7]. The LEP II experience has been very important from many points of views:

- Cavities, ancillaries and cryomodule were developed at CERN and then fully produced by three industries. These included surface treatment, only the cold RF tests were performed at CERN.
- Bulk niobium was chosen for the first 36, 4-cell cavities, limited to about 5 MV/m due to material defects in the large (1 m^2) sheets.
- Magnetron sputtering of niobium on a copper structure was successfully developed and applied for the subsequent 256 cavities, exceeding 8 MV/m.

Figure 2: One of the 352 MHz LEP II cavity at one step of the clean room handling in industry.

Nowadays, magnetron sputtering can not compete with high quality niobium bulk performances, but at that time and at that frequency it has been the winning choice. For CW operation with high current beams, moderate accelerating fields (up to 10 MV/m) and for frequency below 500 MHz, this technology is still superior.

The successful effort of transferring to industry all the know-how and the required quality control for a large scale production has been probably the major contribution to stabilize the confidence of the HEP community on SRF [8]. Half a kilometre of total cavity active length was installed and operated with very high reliability. Like at CEBAF, the cavity processing continued during the machine operation and the field at the end was only limited by the allowable cryogenic power [7].

Lessons learned from large SRF accelerators

More than a decade of operation of large SRF accelerators showed that bulk niobium structures are preferred to push cavity gradients and quality factors, while magnetron sputtering looks better in some cases (LHC) when beam current is more important than accelerating field. Furthermore, cryogenics systems are highly reliable and are routinely produced by industry. All the SRF ancillaries can be designed to be as reliable as the one required by the Normal Conducting RF technology.

In order to obtain high gradients and quality factors the niobium quality needs to be pushed to the possible limit. Thus, quality control during cavity production and surface processing needs to be further improved. Experience has shown that High Pressure Rinsing (HPR) can make the difference concerning field emission aspects.

In order to move to higher gradients, the basic R&D and the technological solutions must move together and, as soon the fabrication procedures are fully understood and documented, the industry can produce good cavities (and even better than R&D laboratories).

THE TESLA MISSION

In July 1990 the first TESLA Workshop was organized at Cornell by H. Padamsee and U. Amaldi. Two years later the TESLA Collaboration was set up at DESY for the development of a SRF-based TeV e^+e^- Linear Collider.

The baseline idea was simply that pushing to the limit the niobium SRF technology, accelerating field up to 50 MV/m could be conceived, with efficiency from plug to beam power much higher than any other NC competitor [9]. Due to the lower frequency and larger beam apertures a better beam quality preservation could be expected. The combination of these two effects would have produced a higher luminosity for a cold machine, if compared at the same plug power and beam quality.

Three were the major challenges of this scheme:

- Push the gradient to at least 25 MV/m, at high Q.
- Reduce by a factor of 20 the linac cost per MV.
- Develop the technology for pulsed operation.

Taking advantage of the experience of all the major laboratories investing in this technology, an optimum cavity design was developed and a large infrastructure was set up at DESY for the cavity processing and test. Stiffening rings were included in the cavity design to minimize the effect of Lorentz-force detuning in the high power pulsed regime. The major contributions came from CERN, Cornell, DESY and CEA-Saclay, but important inputs from TJNAF and KEK were essential.

In parallel, from the experience of designing and construction of long SC magnets for hadron colliders, FNAL, DESY and INFN jointly developed, together with the industry, a new concept of an eight-cavity cryomodule with unprecedented cryogenic efficiency.

More than 80 cavities have been industrially produced, all processed and tested at DESY. Additional 30 cavities are in fabrication. Details on the fabrication and processing can be found in Ref. [10]. A few key steps determined the success of the high gradient mission:

- **Detection of niobium sheet defects and inclusions** that pushed industry to invest in the production of a much better material for SRF application.
- More stringent requirement in term of **cleanness and quality control** for the industrial fabrication.
- More **stringent specifications and controls** for ultra high pure water, chemical compounds and close loop processing plant. Standard Buffered Chemical Polishing (BCP) was applied.
- Wide use of **high pressure pure water rinsing**, in clean room environment and with subsequent clean drying, to avoid particles residuals from chemistry.
- **800 °C annealing** for hydrogen desorption and **1400 °C** treatment to improve thermal conductivity.

Figure 3 shows the vertical test results from the 3rd production batch, i.e. at the end of the learning curve. Very low residual resistance (few nΩ) was obtained and the field emission onset was pushed up to around 20 MV/m. The Q drop at high fields was still not curable.

The following steps to approach the physical limits for niobium were mainly determined by the combined introduction of two new ideas originated by the ongoing R&D at KEK, TJNAF and CEA-Saclay:

- **Electro-polishing (EP)** instead of BPC to process the cavity active surface in order to smooth out asperities and improve the effect of HPR [11].
- **Moderate temperature baking** (100-140 °C) in ultra-high vacuum to re-distribute oxygen in the surface, to mitigate resistive effects [12].

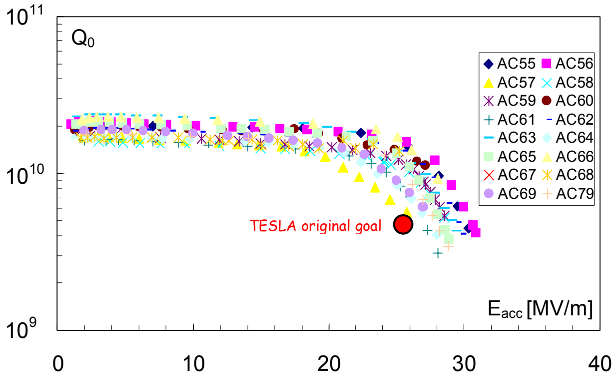

Figure 3: Vertical test results of the TESLA 9-cell cavities from the 3rd production. Standard BCP was applied.

The first step raised the onset of field emission by approximately 10-15 MV/m, while the second cured the Q drop. The two very important results from the R&D activity for high gradient were independent but, because of the better quality of the electro-polished surface, baking is simpler and more reproducible for the EP cavities.

Figure 4 shows the tests results of one of the recent TESLA EP cavities, as an example of the cure of the Q drop at high field by 120 °C baking. This cavity was electro-polished at DESY in a dedicated system built according to the experience and parameters developed at KEK. The technology transfer was successful, demonstrating that the EP process is well understood and under control. The outstanding results of this cavity, AC70, were obtained avoiding the 1400 °C heat treatment, thus giving a proof that the niobium quality has been substantially improved by industry [13].

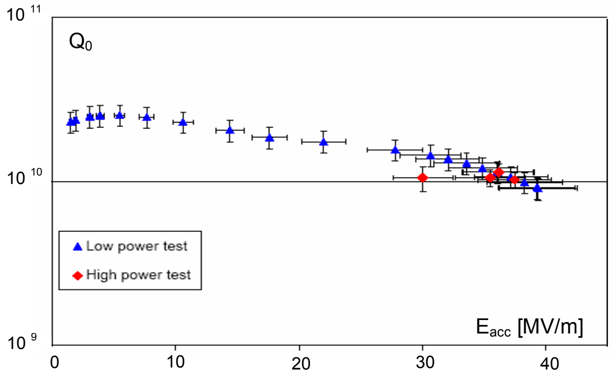

Figure 4: Low and high power tests of AC 70 at DESY.

The effect of Electro-polishing on the onset of field emission is schematically shown in Figure 5, where the induced radiation level is plotted as a function of the gradient for different cavities, fully equipped with ancillaries, in a horizontal cryostat that simulates 1/8 of the TTF cryomodule.

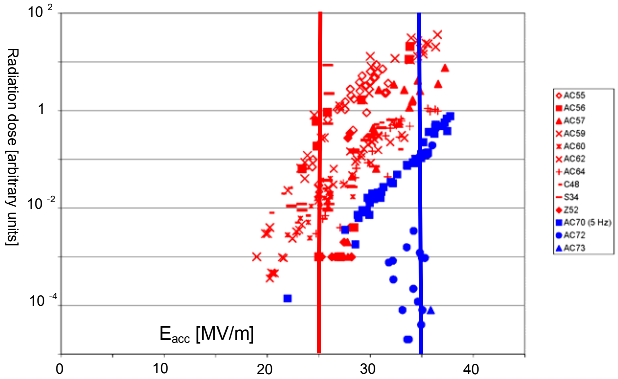

Figure 5: Field Emission-induced radiation dose, measured during the horizontal tests of fully equipped cavities. BCP cavity data are shown in red and EP cavity data in blue.

The exponential grow of field emission is shown and the processing at high field of the emitters can be recognized in some of the curves. The scattering of the field emission onset data demonstrates that further improvements can be expected both on niobium quality, mainly in terms of contamination by small particles, and on the quality control of the processing plant and fluids. Clean room assembly procedure could also be improved further for a large SRF based project, and qualified industries would be involved in the process.

One cavity, AC 72, has been recently installed inside a cryomodule and operated in TTF at 35 MV/m with beam. No detectable radiation was observed [14].

CRYOMODULES & ANCILLARIES

The TESLA collaboration developed all the required ancillaries to operate the SRF cavities at high gradient and in pulsed mode, as envisaged to set an adequate technology for the Linear Collider (LC) [9].

A very performing cryomodule has also been developed for the tight specifications of the LC. Very low static losses have been measured for a total cost that is compatible with the TESLA goals.

It is worthwhile to notice that a TESLA module looks from the outside very similar to an LHC one. Both are using for the external vacuum chamber a carbon steel tube of the standard 38" size. Most of the internal technical solutions for supports and connections are also similar and the LHC experience will be very beneficial for any future TESLA technology-based large accelerator that is going to be built. Figure 6 shows a pictorial comparison of the two cryomodule types, both connected in strings.

CONCLUSIONS

The worldwide coordinated effort behind the TESLA project has been driving a new level of understanding of the SRF technology limiting factors. High accelerating gradients, close to the physical limits, have been achieved and tested with beam in niobium prototypes.

Most of the recent accelerator projects, under construction or being proposed, are extensively using SRF technology. Industry is producing turn-key reliable systems, including SRF cavities and cryogenic ancillaries. Future large projects as the European X-FEL and the FNAL Proton Driver will possibly represent the first large scale applications based on the high gradient technology developed by the TESLA Collaboration. Their realization would be naturally synergic if a cold Linear Collider is going to be built, but also it is clear that the future of SRF technology is well established and somehow independent from the LC commitment.

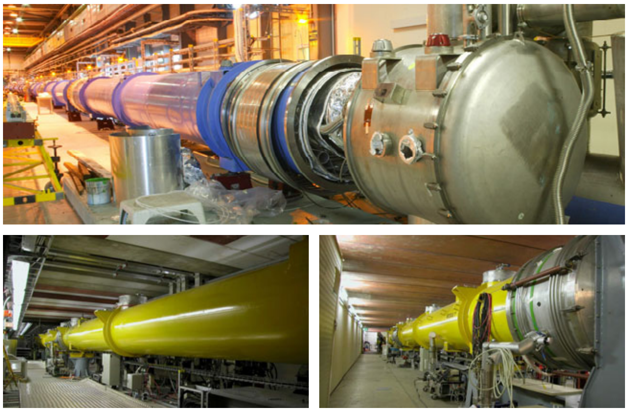

Figure 6: TESLA cryomodules in operation in the TESLA Test Facility (bottom) compared with a string of LHC dipoles assembled for test at CERN (top).

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