LATEST DEVELOPMENTS IN SUPERCONDUCTING RF STRUCTURES FOR BETA=1 PARTICLE ACCELERATION*

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Abstract

Superconducting RF technology is since nearly a decade routinely applied to different kinds of accelerating devices: linear accelerators, storage rings, synchrotron light sources and FEL's. With the technology recommendation for the International Linear Collider (ILC) a year ago, new emphasis has been placed on improving the performance of accelerating cavities both in Q-value and in accelerating gradients with the goal to achieve performance levels close to the fundamental limits given by the parameters of the choice material, niobium.

This paper will summarize the challenges to SRF technology and will review the latest developments in superconducting structure design. Additionally, it will give an overview of the newest results and will report on the developments in alternative materials and technologies.

INTRODUCTION

Two years ago the International Technology Recommendation Panel (ITRP) recommended the use of superconducting RF technology for the implementation of the International Linear Collider (ILC). This decision gave a tremendous boost to the SRF technology activities around the world, adding to the activities of existing projects and proposals such as the Spallation Neutron Source (SNS) at Oak Ridge, the XFEL at DESY, the B-factories at KEK and Cornell University, the CEBAF Upgrade at Jefferson Lab, various ERL projects at Cornell University, 4GLS at Daresbury, ELBE at the Forschungszentrum Rossendorf , the BESSY-ERL and the 1 MW ERL/FEL at Jlab. Whereas most of the CW applications have design goals of "moderate" aspirations ($15\ MV/m \le E_{acc} \le 20\ MV/m$ with Q – values of $\sim 8 \times 10^9$), the XFEL and more so the ILC have design goals, which are much more ambitious. Especially for ILC, where a Q – value of $\sim 8 \times 10^9$ at a gradient of $E_{acc} = 35$ MV/m is required, the technology is challenged close to its fundamental limits. Such cavity performances have until now been achieved with multi-cell cavities only in a few cases in a rather large number of attempts and to the knowledge of this author, the ILC is the only proposed project using SRF technology, which still has to establish a solid base for the design goals at this very high performance levels. It is one thing to demonstrate the high performance levels in laboratory tests ("proof of principle") over many attempts, but quite another to reliably and reproducibly achieve such performance levels in a production environment, where app. 20 000 cavities have to be assembled into cavity strings and cryomodules in a few years. The difficulty and complexity of such an undertaking has been realized more recently by the ILC community and particular efforts are being dedicated to performance and reliability R&D. The implementation of the XFEL at DESY, starting next year, will be an excellent "pilot – project" for the ILC.

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TECHNOLOGY CHALLENGES

Critical Magnetic Field

The fundamental limitation for a superconducting cavity made from high purity niobium with residual resistivity ratios RRR > 250 is given by the critical magnetic field of the material, at which the superconducting state is being destroyed. In the case of niobium this is a field of ~ 190 mT at 2K. In an optimized cavity design this can translate to an accelerating gradient of $E_{acc} \sim 50$ MV/m; the surface electric peak field reaches in this case values of $E_{peak} > 100$ MV/m (see below). However, often a "quench" occurs at lower field levels, caused by defects in the material. Pre-selection of material by eddy current or squid scanning has been developed and used successfully at DESY to find defective sheets of material.

Field Emission

Very high electric field levels can only be reached, if the interior cavity surfaces are extremely clean and no field emission is occurring. However, this is still very rare and more typical, cavity performances are limited to surface fields between $50\ MV/m < E_{peak} < 70\ MV/m$, at which level the exponentially increasing field emission currents can degrade the Q – value of the cavity by more than a decade and all the power supplied to the cavity is converted into dark currents and subsequently X-radiation. Remedies against early onset of field emission are extreme contamination control measures during cavity surface treatment, assembly and testing, such as the use of semi-conductor grade chemicals, ultrapure, high pressure water rinsing (HPR) for extended periods of time, clean room assembly in a class 10 clean room, oil – and particulate free pumping systems and the use of appropriate, particle-free hardware. Most important are reliable, reproducible and clever procedures, which reduce the spread of cavity performances.

"Q – drop"

Cavities made from high purity niobium exhibit a field dependence of the Q – value : at gradients above ~25 MV/m (magnetic surface field ≥ 100 mT) the Q – value starts to decrease dramatically with gradient in the absence of field emission. The reason for this degradation is not yet fully understood, but a series of experiments have revealed that it is an effect related to the magnetic field on the surface of the material.

A remedy against this Q – drop, which is more pronounced on poly-crystalline niobium surfaces treated by chemical polishing compare to electropolished surfaces, is "in-situ" baking of the cavities at a temperature of ~ 120 C for an extended time (12 hrs to 48 hrs). There is increasing evidence that a re-distribution of the oxygen concentration in the penetration depth is responsible for the "flattening" of the Q – curve. Since high Q – values at high gradients are most important for keeping the cryogenic budget in check, the understanding and elimination of the Q – drop is an essential part of the technological challenge.

Reproducibility and Reliability

Presently high performance levels in niobium cavities are reached successfully after a flawless application of a large number of surface treatment and handling procedures – for 9-cell TESLA cavities in excess of 50 steps. As shown in figure 1, there is a large spread in obtaining reproducibly the high performance levels (28 to 35 MV/m) required for such projects as XFEL and ILC. It seems conceivable that a streamlining of procedures might reduce the performance spread and increase the reproducibility of cavity performances.

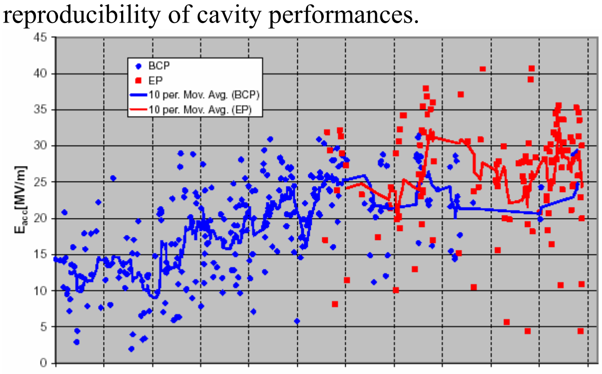


Figure 1: Statistics of TESLA 9-cell cavity performances between 1995 and 2006 [1]

CAVITY DESIGN CRITERIA

It has become clear over the years that there does not exist a universal cavity design, which can be used for any application of SRF technology in an accelerator project for beta=1 particle acceleration. For each application the cavity design has to be tailored to the specific project and the design criteria have to be established accordingly. One has to clarify, whether the cavity should be optimized for maximum achievable gradient or minimum cryogenic losses, whether it is for pulsed or cw operation and whether one wants to accelerate small currents (< 1 mA) or large currents (> 10 mA). Additionally, a reasonable judgement about the feasibility of achieving the design goals is important.

Design Parameters

For a "standard' elliptical cavity a design has to consider the following parameters [2]:

- **Peak surface electric field** at a given E_{acc}
- **Peak surface magnetic field** at a given E_{acc}
- **Shunt Impedance (R/Q)** is a measure of the power dissipated in the metal walls at a given gradient and surface resistance in combination with the geometry factor G : **G x (R/Q)**
- **Number of cells N and cell-to-cell coupling factor k_{cc} :** this affects the ratio of peak fields to the accelerating gradient and the sensitivity to mechanical tolerances. The "field flatness parameter" $a_{ff} = N^2 / \beta\, k_{cc}$ [$\beta = (v/c)$] is a good quantity to compare different structures; higher numbers of a_{cc} reflect higher sensitivity to mechanical tolerances. Cavities with values up to ~ 5000 (RIA, β =0.47) are still manageable. However, a large number N of cells can lead to trapping of higher order modes (HOM) and makes chemical treatment and final cavity preparation more complicated.
- **Slope angle α** of the side wall affects the mechanical stability and the ability for chemical cleaning
- **Lorentz force detuning coefficient k_L** as required by rf control system issues – especially for pulsed machines such as XFEL and ILC - influences the choice of the material thickness and the need for stiffeners.
- **Higher order mode damping** requirements are set by beam stability criteria and (R/Q) – values of particular longitudinal and transverse higher order modes. They determine the location, orientation and number of HOM dampers (coaxial or waveguide). Important parameters are the loss factors $k_{\parallel}$ and $k_{\perp}$, respectively, and loaded Q-values.
- **Q_{ext} of input coupler** is determined by beam current; it influences the size of the beam pipe, the location of the coupling port and the penetration of the center conductor (for coaxial couplers).
- **Cryostat:** typically the helium vessels are an integral part of the cavity with the cavity endgroups cooled by conduction only. The material (Nb55Ti, Ti, SS) influences the stiffness of the assembly, the degree of microphonic noise and the mechanical requirements for cold tuners.

Table 1 summarizes the criteria for different applications:

Table 1: Criteria for Cavity Design [7]

Criteria	RF-parameter	Improves when	Cavity examples
Operation at High Gradient	E_{peak}/E_{acc} B_{peak}/E_{acc} ↓	r_i iris, equator shape ↓	TESLA HG-12 GeV CEBAF
Low cryo losses	(R/Q) x G ↑	r_i equator shape ↓	LL-12 GeV CEBAF LL-ILC
High I_{beam} Low HOM impedance	$k_{\perp}$, $k_{\parallel}$	r_i ↑	B-factory RHIC 1MW FEL Jlab

Cavity Shape and RF Parameters

The rf parameters for an elliptical cavity shape are determined by 6 parameters [2]:

- The **iris ellipse ratio** (r=b/a) uniquely influences the electric peak surface fields
- The **equator ellipse ratio** (R=B/A) has very weak impact on the rf parameters, but influences the mechanical behavior of the cavity.
- The cell **iris radius (r_i)** is a very important parameter to trim the rf parameters of a cavity (see table 1). A smaller aperture increases the (R/Q) in the fundamental mode and lowers the ratio of B_{peak}/E_{acc} and E_{peak}/E_{acc} . Unfortunately, the cell-to-cell coupling gets weaker and the HOM impedances are increasing.
- The **slope** of the side wall (α) and the **position** (d) measured from the iris plane is a parameter, which determines the electric and magnetic peak fields on the cavity wall.
- The **cell length** (L) determines the geometrical beta value of the cavity; $L = \beta\, \lambda/2$
- The **cell radius** (D) is used for frequency tuning without affecting any electromagnetic or mechanical cavity parameters

Additional considerations

Multipacting has limited superconducting cavity performance for a long time until it was recognized that by appropriate shaping of the cavity cells the conditions for 1- and 2- point multipacting could be avoided in addition to improved surface cleaning techniques, which lowered the secondary electron emission coefficient of the niobium surfaces significantly. Nevertheless, multipacting simulation calculations are an integral part of a cavity design exercise. Several codes are available nowadays and the OMEGA3P/Track3P code, which is a 3D code [4] has recently been used to explain experimentally observed limitations in the 9-cell LL/Ichiro cavity at KEK (see below). As it turned out, the multipacting occurred in the beam pipe rather than in the cavity [5]

HOM damping

Higher order modes are excited, when the charged particle beam is traversing the cavity. These monopole and dipole modes have to be damped to appropriate levels to avoid beam break up (BBU) or excessive cryogenic losses. Both coaxial and waveguide HOM couplers have been developed and can in principle fulfill the damping requirements based on beam dynamic calculations. However, one has to keep in mind that HOM's are not always only generated in the cavity itself or trapped in the cavity, but can also exist in the connection between cavities. Therefore it becomes a crucial part of the design considerations – especially for higher current machines – to calculate HOM patterns not only in single units but also in the cavity strings for a full cryomodule.[3,4,5]

Mechanical Stability

The mechanical design of a srf cavity has to take into account the detuning of the cavity under the influence of the Lorentz force and of microphonics. This is especially important for pulsed machines such as the XFEL, ILC or SNS and has consequences for the rf control system. Location of stiffening rings between cells and material thickness impact on the Lorentz force detuning coefficient and should reduce the detuning without restricting the tuneability of the cavity both at room temperature and at He temperature.

UPDATE ON DEVELOPMENTS

As shown in table 1, there are basically two/three different applications of SRF cavities: high gradient/low loss and high current.

Cavities for operation at high gradient

The 9-cell TESLA cavity has been designed in 1992; the cell geometry of the seven inner cells was optimized with respect to a low E_{peak} / E_{acc} - ratio (1.98 %) and cell-to-cell coupling k_{cc} = 1.9 %, because field emission and field flatness issues were of concern at that time. Two different end-cell geometries and two coaxial HOM dampers at the beam pipes provided adequate damping of the higher order modes. Meanwhile, this design has been adopted to many applications such as 4GLS, Elbe, BESSY-ERL and the Cornell ERL with some modifications. It is also the baseline cavity (**B**aseline**C**onceptual**D**esign) for the ILC and obviously the cavity to be used for the XFEL. Even though – as shown in figure 1 – there are still problems with reproducibility of cavity performance and improvements have been achieved over the years, several cavities have reached the design goals for ILC as shown in figure 2; these cavities will be in the near future assembled into a cavity string and a high performance cryo-module.

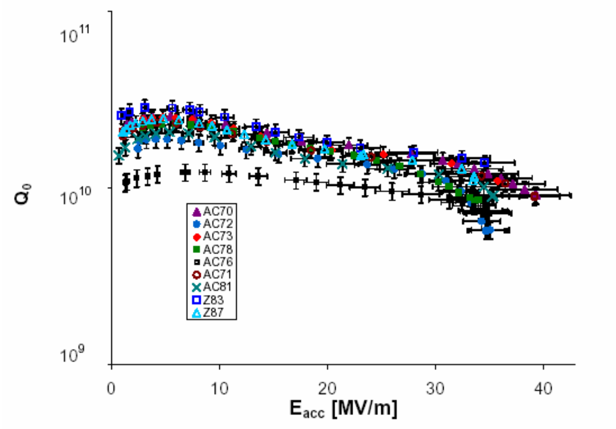


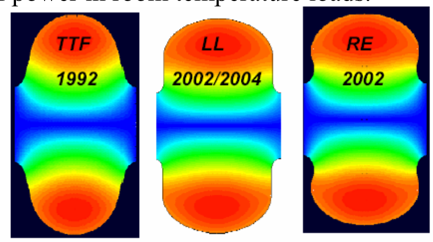
Figure 2: Best performances of 9-cell TESLA cavities after electropolishing [1]

In 2002 it was proposed [6] to optimize cavities with respect to a low ratio of H_{peak}/E_{acc} with the argument that field emission is not a fundamental limit of the material, whereas the critical magnetic field of niobium cannot be exceeded. Optimization in this direction meant an increase in volume at the equator region of the cavity and a closing of the iris; two new shapes as shown in figure 3 were proposed, [7 , 8], which would increase the accelerating gradient to ~ 50 MV/m, if the critical magnetic field could be reached. Unfortunately, the surface peak electric field is increased, the cell-to-cell coupling decreases and due to the smaller iris diameter the HOM loss factors are going up. On the positive side the cryogenic losses are reduced by ~ 20% in comparison to the TESLA structure and because of the higher (R/Q) there is reduced sensitivity to microphonics.

Both cavity shapes were prototyped at Cornell (RE) and at KEK (LL/Ichiro) as single cell cavities and excellent performances were achieved in both laboratories. In both types gradients > 50 MV/m ($H_{peak} \geq 185$ mT) were measured as shown in figure 4 for the LL/"Ichiro" cavity. In addition, four 9-cell Ichiro cavities were fabricated at KEK; initial tests showed multipacting as mentioned above and so far the best result obtained is an accelerating gradient of ~ 30 MV/m.

Cavities for high current application

Developments of several high current ERLs / FELs are being pursued at Cornell University, Brookhaven National Lab , Jefferson Lab and KEK [9]. The challenges for these projects are to a lesser extend the verification of design goals for Q-value and gradient – the gradient goals are typically "moderate" below 20 MV/m and Q-values < 10^{10}; the main challenges here are the damping of the higher order modes to appropriate levels and absorption of the HOM power in room temperature loads.



r_{iris}	[mm]	35	30	33
k_{cc}	[%]	1.9	1.52	1.8
E_{peak}/E_{acc}	-	1.98	2.36	2.21
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76
R/Q	[Ω]	113.8	133.7	126.8
G	[Ω]	271	284	277
R/Q*G	[Ω*Ω]	30840	37970	35123

Figure 3: New shapes for high gradient cavities: LL = low loss, RE = re-entrant [7]

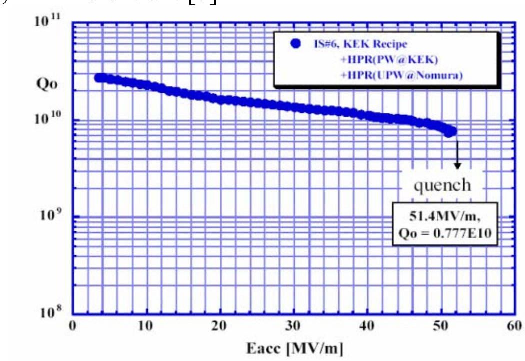


Figure 4: Single cell Ichiro cavity reaching E_{acc} > 50 MV/m

The BNL approach uses large cavity apertures and ferrite absorbers in the beam line; Cornell modified the 9-cell TESLA cavity by having eight coaxial HOM couplers per cavity plus ferrite rings at 80K in the beam pipes. The Jlab conceptual design uses six waveguides per cavity, terminated by absorbers at room temperature [10]. At KEK, radial line HOM dampers are developed to be used on a TESLA-type cavity.

For the ERL injector at Cornell a prototype cavity as shown in figure 5 was fabricated and tested, reaching E_{acc} = 21 MV/m; at 15 MV/m the Q – value was 10^{10} [12].

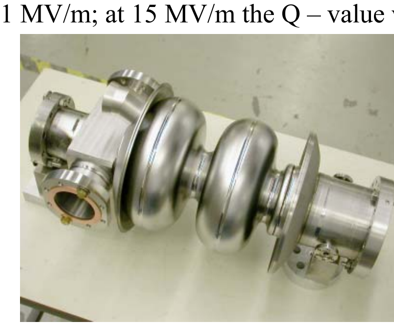


Figure 5: Prototype injector cavity for Cornell ERL 5 cavities of this type are needed.

The subject of a thesis project at MSU is the development of a high current cavity with large aperture and HOM damping via a circular waveguide operating in the TE_{11} mode. All HOM's propagate to a room temperature load [11].

Other developments

Cavities made from large grain and single crystal high purity niobium , initially manufactured and tested at Jlab [13], have shown promising performance. Several niobium manufacturers offer now large grain niobium and other laboratories have started to use this material for cavity fabrication. At DESY several single cell cavities have been tested and gradients in the vicinity of E_{acc} ~ 40 MV/m have been measured after electropolishing. At Cornell a single cell cavity exhibited after vertical electropolishing very high Q-values and E_{acc} = 30 MV/m. At Jlab a set of measurements of single cell TESLA-shaped cavities made from material of three different vendors has shown rather good agreement of the results as shown in figure 6, even though the materials differed significantly in RRR – value and Ta contents. The cavities were treated by buffered chemical polishing (BCP) only.

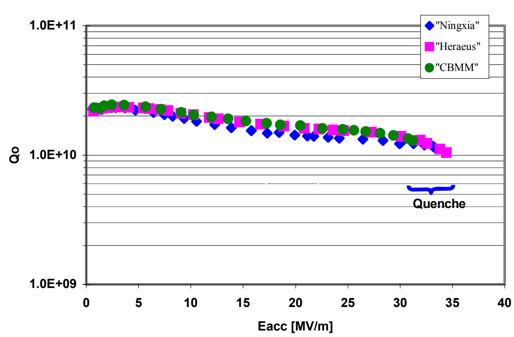


Figure 6: Performance of single cell cavities made from large grain niobium after BCP only.

Multi-cell cavities from large grain niobium are being manufactured at DESY and Jlab – their performance will be the real proof of the potential advantages of this material: lower cost, BCP only for smooth surfaces and elimination of the "Q-drop" and comparable performance to poly-crystalline niobium.

SUMMARY

Progress has been made in SRF technology in the last few years and it has in many cases become the choice technology for proposed future projects, both for high gradient and high current application. The challenges are – at least at the high performance end of cavities such as for XFEL and ILC application – reproducibility and reliability. A streamlining of stringently controlled procedures – mainly control of contamination – seems to be necessary. Large grain or single crystal niobium is potentially an alternative to the present technology based on poly-crystalline sheet material. In combination with a superstructure configuration [14] it could potentially reduce the costs of a large machine such as the ILC significantly.

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