STATE OF THE ART OF MULTICELL SC CAVITIES AND PERSPECTIVES*

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Abstract

Superconducting cavity technology has made major progresses in the last decade with the introduction of high purity niobium on an industrial scale and, at the same time, by an improved understanding of the limiting processes in cavity performance, such as multipacting, field emission loading and thermal break-down. Multicell niobium cavities for beta = 1 particle acceleration, e.g. for the TESLA project, are routinely exceeding gradients of E_{acc} = 20 MV/m after the application of surface preparation techniques such as buffered chemical polishing or electropolishing, high pressure ultrapure water rinsing, UHV heat treatment and clean room assembly. The successes of the technology for beta = 1 accelerators has triggered a whole set of possible future applications for beta < 1 particle acceleration such as spallation neutron sources (SNS, ESS), transmutation of nuclear waste (TRASCO, ASH) or rare isotopes (RIA). The most advanced of these projects is SNS now under construction at Oak Ridge National Laboratory. This paper will review the technical solutions adopted to advance SRF technology and their impact on cavity performance, based on the SNS prototyping efforts.

1 INTRODUCTION

Superconducting cavity technology has become quite attractive in recent years for accelerator builders around the world due to the successes of operating machines such as CEBAF, LEP and the B-factories at KEK and Cornell University. A variety of proposed applications is under consideration/construction in major accelerator centers. This includes, besides the TESLA Linear Collider and the associated 50 GeV FEL, also a whole set of FEL's and energy recovering linacs (ERL's) based on the pioneering work carried out at Jlab's 1 kWatt FEL. In addition to the application of SRF technology to β = 1 accelerators, a whole set of applications for β < 1 particle acceleration has evolved, namely spallation neutron sources in the United States (SNS), in Europe (ESS) and in Asia (Korean Spallation Neutron Source, Joint JAERI/KEK Project), transmutation of Nuclear Waste (TRASCO, ASH) and accelerators for rare isotopes (RIA). This increased interest is a result of a better understanding of the phenomena, which have in the past limited the performance of superconducting cavities, such as, e.g., multipacting, field emission and quenches. Improved materials, better surface treatment and assembly procedures contributed significantly to improved cavity performances, and the spectacular success of the TESLA cavities has given the technology a strong boost. Gradients of $E_{acc} \geq 20$ MV/m and Q- values of $Q \sim 10^{10}$ at 2K at these high gradients are no longer out of reach.

For the accelerator builder the challenge remains to come up with a good and reasonable design, which takes into account the status of the technology and does not over-estimate the achievable cavity performances in a large assembly such as, e.g., a multi-cavity cryo-module.

In the following the criteria for multi-cell sc cavity design are reviewed and it is attempted to give a snapshot of the present status of multi-cell cavity performances.

2 "STANDARD" ELLIPTICAL CAVITIES

"Standard" elliptical cavities in the context of this contribution are cavities for beta values of $0.47 \leq \beta \leq 1$ with a cross section schematically shown in figure 1.

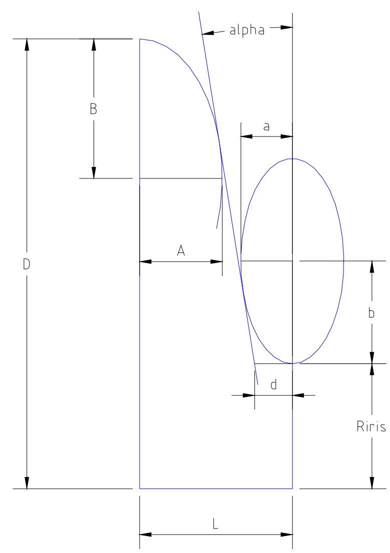

Figure 1: Cross sectional view of an elliptical cavity

2.1 Design Parameters

Prior to designing a multi-cell cavity using electromagnetic and mechanical codes one has to determine the operational parameters for the cavities and exercise some reasonable judgement about the feasibility to achieve those. Important considerations are for:

- **Peak surface electric fields** ($E_{peak} \leq 27.5$ MV/m for SNS) at a given E_{acc}
- **Peak surface magnetic field** ($H_{peak} \leq 60$ mT for SNS) at a given E_{acc}
- **Shunt Impedance** influences the cavity losses at a given surface resistance and gradient.

*Work supported by the U.S. Department of Energy, contract DE AC05-84ER40150.

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- **Number of cells N** and **cell–to-cell coupling factor k**: this affects E_{peak} / E_{acc} , H_{peak} / E_{acc} and the sensitivity to mechanical tolerances. A good quantity for comparing different structures is the "unflatness factor" $N^2 / \beta k$. For the SNS cavities this is 3934 for $\beta = 0.61$ and 2964 for $\beta = 0.81$ in comparison to 4050 for the TESLA 9-cell cavities. Higher numbers mean higher sensitivity to tolerances.
- **Slope angle** α of sidewall affecting the mechanical stability and the ability for chemical cleaning.
- **Lorentz Force Detuning Coefficient k_L** (for SNS $k_L \leq (-2 \pm 1)$ [Hz/(MV/m)^2]) is determined by rf control system issues, especially for pulsed machines such as SNS or TESLA. It influences the choice of the material thickness and the need for stiffeners.
- **Q_{ext} of input coupler** is determined by beam dynamics and influences the size of the beam pipe, the location of the coupling port and the penetration of the center conductor.
- **Higher order mode damping** requirements are set by beam stability criteria and shunt impedances of particular longitudinal and transverse modes. They determine the location, orientation and number of HOM dampers.
- **Cryostat**: typically the newer generation of cavities have helium vessels as shown in figure 4, which are an integrated part of the cavity. Their volume is determined by the losses in the cavity at the operating temperature and gradient. The chosen materials (Ti, Nb55Ti) are influencing the stiffness of the assembly, the degree of microphonics noise and also the requirements for the tuners.

2.2 Influence of Cell Geometry on RF Parameters

The cavity shape as shown in figure 1 is determined by 6 parameters as following:

- The **cell length** (L) determines the geometrical beta value of the cavity; $L = \beta \lambda/2$
- The cell **iris radius** (R_{iris}) is mainly determined by the cell-to-cell coupling requirements.
- 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 walls.
- 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 behaviour of the cavity.
- The **cell radius** (D) is used for frequency tuning without affecting any electromagnetic or mechanical cavity parameter.

The dependencies on these parameters have been evaluated by means of a design tool developed at INFN, which uses the rf code SUPERFISH; a recent paper [1] describes in detail the dependence of the electromagnetic parameters of Epeak/Eacc, Bp/Eacc, R/Q, cell-to-cell coupling k, Lorentz force detuning coefficient and stresses in the material on the 6 geometrical parameters discussed above.

2.3 Multipacting

Resonant electron loading ("Multipacting") has for a long time limited superconducting cavity performance for $\beta = 1$ cavities, until it was recognized that the conditions for 1- and 2-point multipacting could be destroyed by appropriately shaping the cavity cells to spherical or elliptical cross sections and by applying improved surface cleaning techniques, which lowered the secondary electron emission coefficient of the niobium surfaces significantly. However, the development of "flatter" cavities for $\beta < 1$ particle acceleration demanded a re-evaluation of the multipacting behaviour of such cavities. Several computer codes had been developed over the years and were applied to $\beta < 1$ cavities [2-5]. For the SNS cavities multipacting calculations have been performed at INFN Genoa [2] and the University of Helsinki [5]. These calculations showed that even though the kinematic conditions for MP exist for the chosen geometrical shapes of the cavities, the electrons do not gain sufficient energy during their excursions into the cavity volume to generate secondary electrons when impacting onto the surfaces.

2.4 Higher Order Modes (HOM)

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). Both coaxial and waveguide HOM couplers have been developed and can in principle fulfil the damping requirements based on beam dynamics calculations. However, one has to keep in mind that dangerous HOM's are not always only located in the cavity itself, but can also exist in the connection between cavities. Therefore it becomes a crucial part of the design considerations to calculate HOM patterns not only in single units but also in the cavity strings for a full cryomodule. [6, 7]

2.5 Mechanical Stability

Lorentz force detuning is an effect, which has to be taken into account in the mechanical design of a cavity. This is especially important for pulsed operation as for TESLA or SNS or the KEK/JAERI machines. The location of stiffening rings between cells and the material thickness of the cells impact on the Lorentz force detuning coefficient. Both should reduce the cavity detuning under Lorentz forces, but not restrict the tunibility of the cavity or the possibility to achieve field flatness in the cavities. Figure 2 shows an example of the variation of the Lorentz force detuning vs position of the stiffening rings (reference is the distance form the beam axis). More details can be found in ref. [1]

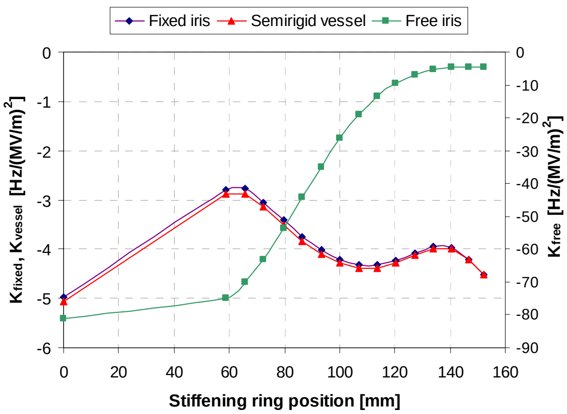

Figure 2: Lorentz force detuning coefficient vs position of stiffening rings (example β=0.61 SNS cavity).

3 "SUPER- STRUCTURE"

At DESY an ingenious design for the TESLA accelerator is being pursued [8]. It combines two 9-cell TTF cavities with an interconnecting beam pipe of a length equal to λ/2 into a weakly coupled (0.03%) structure of 18 cells, powered by only one input coupler. The unit is equipped with a total of four HOM couplers – one at each end of the cavity and two at the interconnection – to damp the dipole modes below the BBU limit. Each subunit has an integrated helium vessel as shown in figure 4 and a cold tuner. The whole structure is 2.38 m long and is produced, cleaned and tested in one piece. There are 18 resonances in the fundamental mode passband. The accelerating mode, for which the field profile is shown in figure 3, has twice the shunt impedance of the subunit; all other passband modes have negligible R/Q – values. The benefit of the super-structure is a large cost savings for a machine such as TESLA, because only half the fundamental power couplers are needed.

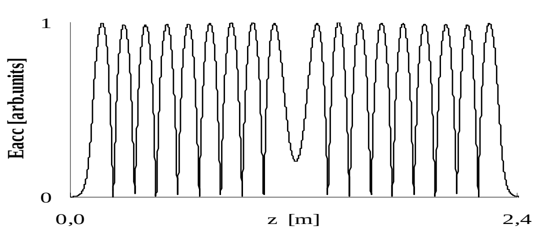

Figure 3: Field profile of the accelerating mode of the super-structure [9].

Presently a beam test with two 7-cell cavities is in preparation at DESY and is scheduled to start in July.

The assembled super-structure for this test is shown in figure 4.

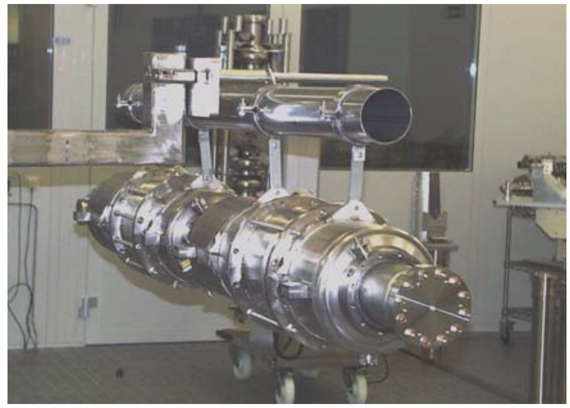

Figure 4: 2 x 7-cell super-structure

4 CAVITY PERFORMANCES

The application of advanced surface treatment and cleaning procedures in connection with clean room assembly of cavities and cavity strings has resulted in performances of cavities, which in some cases are close to the thermal limits predicted by thermal model calculations. These calculations take into account the thermal conductivity of the high purity niobium (RRR>250), the surface resistances, boundary resistances between niobium surface, and helium bath and the thermal conditions of the helium bath. One of the recently most appreciated surface preparation techniques in major labs involved in SRF technology is electropolishing in an acid solution consisting of a mixture of hydrofluoric and sulphuric acids [10]. A typical set-up for electropolishing of multi-cell cavities is shown in figure 5.

Figure 5: Typical electropolishing set-up as developed at KEK for multi-cell cavities. The cavity is rotated horizontally while acid is circulated through the cavity at an applied voltage of ~ 14 V.

Table 1 summarizes the various applied techniques and their impact on improvement of cavity performances.

The limitation of cavity performance by **quenches** way below the limits given by the superconducting material – in the case of Niobium the critical field limit is at ~ 240 mT – was traced back to defects in the superconducting material more than a decade ago [11], and improvements in the thermal conductivity of the niobium by one order of magnitude or more have shifted quench field levels towards much higher values. As a QA procedure, eddy current scanning of the niobium for defect detection has been pioneered at DESY [12]. A commercial system used at Jlab for the scanning of the material for the SNS cavities is shown in figure 6.

Table 1: Summary of advanced techniques for sc cavity performance improvements.

Limitation	Action
Suppression/Elimination of multipacting	Modification of cavity shape to spherical or elliptical cross sections Very clean surfaces to suppress δ
Suppression/Elimination of defects	Improved inspection procedures (eddy current scanning of defects) Improved electron beam welding Improved chemical surface treatment ("internal chemistry" in clean room, filtered acids, electropolishing) Improved rinsing techniques (HPR, ozonized water) Deeper material removal, tumbling Class 10 clean room assembly
Stabilization of defects	Purer material: RRR >200 Post purification
Field Emission	High Pressure Rinsing Ozonized water rinsing Electropolishing Heat treatment Vacuum baking ("in situ") High Peak Power Processing Class 10 clean room assembly Improved contamination control

Figure 6: Eddy Current Scanning system used at Jlab for defect scanning of the niobium used for SNS cavities.

Field emission loading is still the dominant effect limiting the performance of niobium cavities. It is caused by artificial contamination of the surfaces either stemming from insufficient cleaning or from re-contamination during assembly steps. Procedures such as electropolishing, high pressure rinsing and clean room assembly in a class 10 clean room have become essential steps in controlling contamination. However, this is not always successful to the desired levels and further improvements are needed.

A spectacular performance as shown in figure 9 was recently achieved at DESY with an electropolished 9-cell structure in a vertical dewar test after several high pressure rinsing steps had been applied [13]. It shows the potential of the technology, if all the right procedures come together.

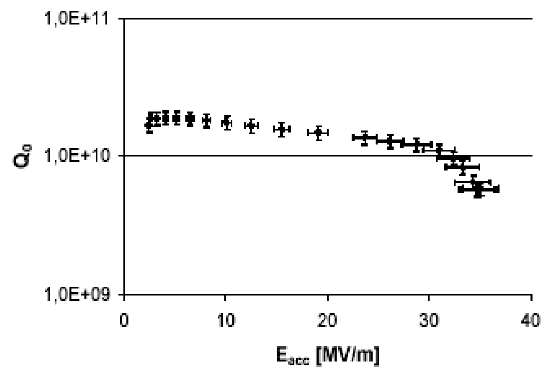

Figure 7: Best performing 9-cell TTF cavity, electropolished.

In table 2 the status and the more recently experimentally achieved performances of multi-cell cavities for various proposed projects are summarized.

5 CONCLUSION AND OUTLOOK

In the last several years significant progress has been made in understanding and eliminating limitations to cavity performances by establishing improved cavity design criteria and cavity treatment and handling procedures. This has attracted a new clientele for application of the technology to a variety of new projects.

Many of the excellent results reported by the SRF community are for well controlled laboratory tests in vertical dewars. What eventually counts is the performance in the accelerator environment. Understanding the sources for contamination and even more so for re-contamination during assembly steps seems most important. Many steps are being taken in this direction by stringent control of processes and procedures, by consciously reducing particulates on equipment, tooling and hardware, by use of high purity, low particulate processing chemicals and ultrapure water rinsing [24]. "In-situ" processes such as helium processing and high peak power processing can help to overcome re-contamination to some extent, but the main emphasis needs to be on contamination control.

For large projects such as TESLA reducing the costs of the sc linac system is essential. Efforts in this direction are aimed at lower material costs and less expensive manufacturing as, e.g., by seamless cavity fabrication [14].

TESLA as presently the most ambitious project in SRF technology is in many aspects showing the way.

Table 2: Summary of multi-cell cavity results at various Laboratories.

Project/Lab	**Structure**	**Results**	**Reference**
TTF/TESLA/DESY	9-cell, 1300 MHz ß = 1	$20 < E_{acc}$ [MV/m]< 35	[13,18]
Upgrade/Jlab	7-cell, 1497 MHz ß = 1	$10 < E_{acc}$ [MV/m]<19	[19]
SNS/JLab	6-cell, 805 MHz, ß = 0.61 and 0.81	$10 < E_{acc}$ [MV/m]<19	[20]
JAERI/KEK Joint JAERI	5-cell, 600 MHz ß = 0.604	$9 < E_{acc}$ [MV/m]<11.6	[21]
APT/LANL	5-cell, 700 MHz ß = 0.64	E_{acc} [MV/m]~ 12	[22]
RIA/MSU, Jlab	6-cell, 805 MHz, ß = 0.47	Under fabrication	[23]
JAERI/KEK Joint KEK	9-cell, 972 MHz ß = 0.6	Under fabrication	[17]
TRASCO/INFN	5-cell, 704 MHz ß = 0.85	E_{acc} [MV/m]~ 10 Sputtered Niobium	[16]
ASH/Saclay, Orsay	5-cell, 700 MHz ß = 0.65	Under fabrication	[15]

6 ACKNOWLEDGEMENT

I want to thank all my colleagues, who provided me with information about their activities. Special thanks go to L. Lilje and J. Sekutowicz of DESY, T. Tajima of LANL, K. Saito of KEK, N. Ouchi of JAERI and B.Visentin of Saclay.

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