HIGH GRADIENTS IN SUPERCONDUCTING MULTI-CELL CAVITIES

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Abstract

Niobium bulk multi-cell cavities have recently become the technology of choice for several accelerator projects. The application ranges from cavities for the acceleration of electrons, protons and ions. For elliptical cell shapes the particle velocity ranges from $\beta=0.47$ up to $\beta=1$. The paper gives an overview on the most important technology issues as well as on the achieved performance at several different projects illustrating the degree of maturity superconducting RF cavities have achieved. The typical peak surface magnetic fields achieved are in the order of 100 mT. A surface preparation using electropolishing can lead to a further increase of the achievable fields.

TYPES OF CAVITIES

Around 1980, the major limitation to superconducting RF cavities was multipacting where electrons are accelerated in resonance with the RF field. Depending on the electron energy and the secondary emission coefficient this can cause an electron avalanche and a subsequent cavity breakdown. Changing the cavity shape from pill-box to elliptical solved the problem as this causes the energy gain of the electrons being reduced while they travel toward the equator region [1].

Since this discovery the SRF community concentrated on the elliptical shape for $\beta=1$ applications and is pursuing many different projects

- high current storage rings
- CW Linacs
- TESLA linear collider
- synchrotron light sources
- XFEL Driver Linacs

More recently [2], this cavity shape is becoming more attractive also for $0.47<\beta<1$

- Protons (SNS, KEK/Jaeri, XADS/Eurisol, APT/AAA, Trasco)
- Ions (RIA/MSU)

While the cavity shape allowed to pass beyond limitations posed by multipacting, further developments like improved niobium material quality and better surface treatment methods facilitated larger peak magnetic and peak electric surface fields for a variety of frequencies. Of course, this also led to higher accelerating gradients as will be shown below.

Material

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.

In addition the niobium needs to be free from normal conducting inclusions like iron and weak superconductors like tantalum. The size of those inclusions needs to be well below 100µm even if the niobium material itself is a good thermal conductor to allow magnetic peak fields of more than 100mT. Those inclusions can be introduced into the sheet material for example in the sheet rolling process. Therefore a quality control on the niobium sheets before deep drawing the half-cells is mandatory. Methods used for this quality control are eddy-current scanning [5] and more recently SQUID scanning [6].

In most projects the cavities are subjected to vacuum furnace treatments after fabrication and a first cleaning of the surface (see below). Typically, high temperature treatments are done for stress annealing and hydrogen degassing at temperatures of 600-800°C.

Figure 1: Bulk niobium cavities for various particle velocities. From top: a) TESLA niobium 9-cell cavity for $\beta=1$. b) SNS six-cell for $\beta=0.81$. b) SNS six-cell for $\beta=0.61$. b) RIA/MSU six-cell for $\beta=0.47$.

[+] More details on niobium bulk material can be found in references [3,4], for Nb/Cu thin film multi-cell cavity performance refer to [22].

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In some cases heat treatments for post-purification (>1000°C with getter materials) are part of the fabrication process. This treatment improves the RRR further to values of 600-700 by reducing the amount of interstitially dissolved impurities like carbon, nitrogen and oxygen. The higher RRR allows to thermally stabilize larger inclusions in the niobium material (for details on high temperature heat treatments see [4]).

Preparation of Niobium Surfaces

After welding typically 100-200 µm of damage layer need to be removed to obtain a sufficiently defect-free surface. For historic reasons, etching using a mixture of HF, HNO_3 and H_3PO_4 is still the most commonly used method [3,4]. Unfortunately this leads to undesirable effects like grain boundary etching and rather rough surfaces. Typical maximum surface magnetic fields are in the order of 100 mT at 2 K. More recently, electropolishing – due to the impressive results at KEK on single-cells – becomes more and more popular [8-12]. Using this process, glossy surfaces can be obtained. It turned out that electropolishing allows much higher peak magnetic surface fields in the order of more than 140mT at 2 K, which has been recently demonstrated in multi-cell cavities (see below).

One major limitation of cavities is still field emission: Therefore high pressure rinsing with ultrapure water is a necessity as well as the dust-free assembly with quality control [13].

Operational Issues / Auxiliaries

A multi-cell cavity needs several interfaces to the outside. Several boundary conditions have to be met to fulfill reliable operation at specified gradient. All these components need careful design.

- He Tanks, mechanical stiffness
- RF Couplers for cavities are critical elements because power handling capability, need for low heat conductivity etc.
- HOM dampers to guarantee beam quality
- Tuners for frequency adjustment and active elements counteracting e.g. Lorentz force detuning

A full description would go beyond the limit of this paper (for more details see [4]). These issues have been covered elsewhere during the workshop, so that this paper will illustrate one issue related to active tuning (see below). In the next section an overview of results on multi-cell cavities from several different projects is given.

PROTON CAVITIES

SNS

The SNS project relies on two types of 805 MHz cavities. The so-called medium beta (β=0.61) and the high beta cavities (β=0.81).

The basic preparation includes a 600°C firing and etching. The vertical test results of the medium beta cavities show that the design goal of 10 MV/m is routinely reached with some safety margin (best 17MV/m).

Currently the first medium beta modules are under high power test and show good performance: 15 MV/m. The high beta cavities have reached up to 20 MV/m after standard etch. An electropolished cavity performed at 22 MV/m with higher Q (figure 2). Due to this success the gradient specification has been increased from 12.5 to 15.5 MV/m [14].

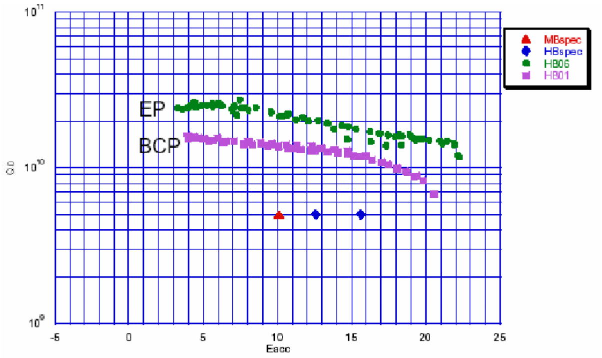

Figure 2: The electropolished SNS high beta cavity improved its performance as compared to the test after etching [14].

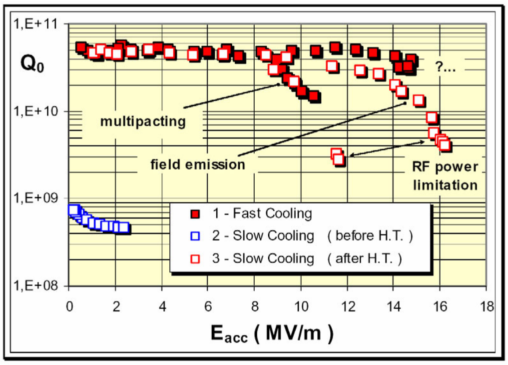

Figure 3: 700 Hz, five-cell for XADS/EURISOlL [15].

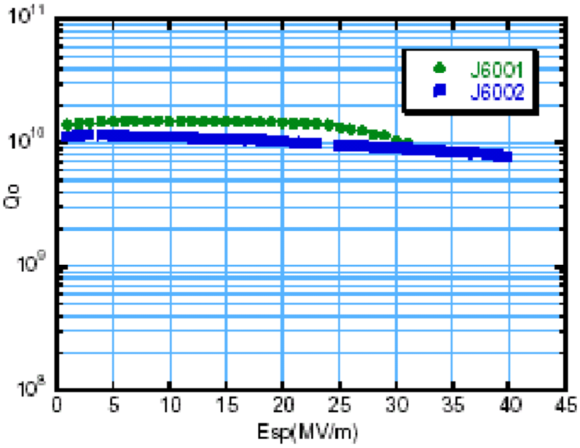

Figure 4: Achieved peak electrical surface field for the 600 MHz five-cell cavities of the KEK/JAERI joint project [16].

Eurisol/XADS

A generic 700 MHz, β=0.65, five-cell prototype cavity for proton acceleration has been tested for the EURISOL/XADS projects [15]. So far the cavity does not feature stiffening and coupler ports. The stainless flanges are copper brazed to the niobium. The cavity was etched only on the inner side and achieved an accelerating gradient of 16 MV/m (figure 3).

KEK/JAERI

The old cavity design for the KEK/JAERI joint project uses 600 MHz cavities with five-cells [16]. A maximum peak electric surface field of 40 MV/m was achieved, which corresponds to ~11MV/m E_{acc} (figure 4). The new ADS cavity design will use 972 MHz and is under design and manufacturing at the moment. The β=0.81 nine-cell cavities have a gradient goal of E_{peak}=30 MV/m and E_{acc}=10MV/m, respectively.

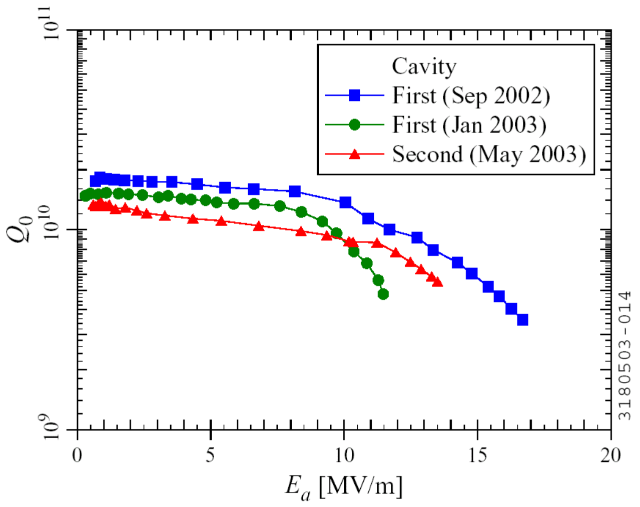

Figure 5: Results for RIA 805 MHz, β=0,47. six-cell cavities [17].

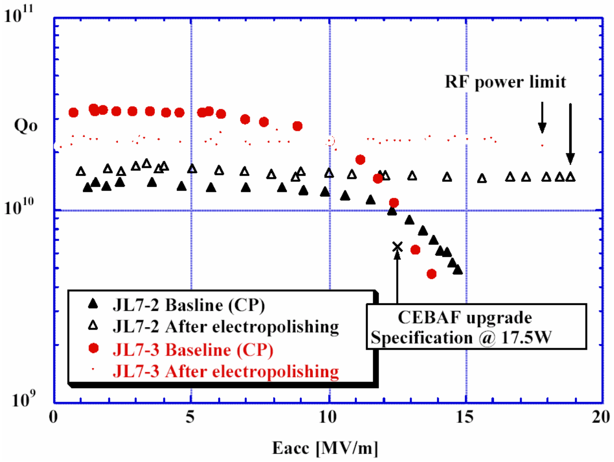

Figure 6: Results for the 1.5 GHz CEBAF upgrade seven-cell cavities.

ION CAVITIES

RIA/MSU

Only very recently the velocity range of elliptical cavities was explored down to β=0.47. For RIA 805 MHz six-cell cavities have been built. So far the first prototype does not feature stiffening rings nor coupler ports. The preparation was chemical etching and a high temperature heat treatment at 600°C for 10 hours. A second prototype was etched but was not treated in a furnace yet [17].

CAVITIES FOR ELECTRON ACCELERATION

JLAB

At Jlab several new cavity shapes are explored including changes in individual cell shapes optimised for high gradient or for low-loss operation [18] and also superstructures especially for the high power FEL [21]. For a energy upgrade version of the CEBAF machine electropolishing was used as a surface preparation for the 1.5 GHz seven-cell cavities. This yielded very good results in a low power test. An example is shown in figure 6.

TESLA

Etched Cavities

For TESLA etching and 1400° C postpurification for RRR values in the order 600-700 is the standard procedure [7]. The results for the last production series are very reproducible as illustrated in figure 7. Gradients of more than 25 MV/m are reliably obtained.

Electropolished Cavities in Low Power Tests

For an energy upgrade of TESLA to center-of-mass energy of 800 GeV (TESLA-800) a gradient of 35 MV/m at a Q0 of $5*10^9$ is needed. The results on electro-polishing at KEK triggered a collaboration on multi-cell cavities. 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.

Out of the 9 cavities from the last production series of TTF cavities four cavities achieved the TESLA-800 specification (figure 8) and six cavities more than 30 MV/m. Two cavities were strongly loaded with field emission and will be reprocessed in the EP system recently brought into operation at DESY [19].

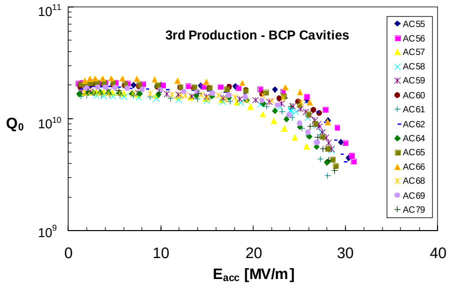

Figure 7: Etched TESLA nine-cells post-purified at 1400°C with titanium getter.

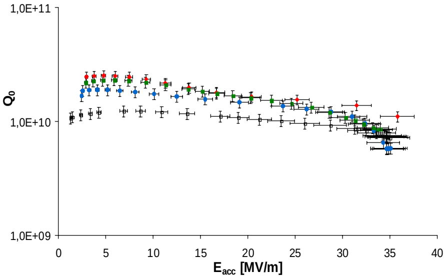

Figure 8: TESLA nine-cell cavities electropolished at KEK/Nomura Plating.

Electropolished Cavities High Power Tests

So far, two of the cavities (AC72, AC73) shown in figure 8 have been prepared for a high power test. The cavities were equipped with a liquid helium tank, a high power coupler and a tuning mechanism. The tests have been carried out in a horizontal cryostat at the TESLA Test Facility (CHECHIA). After being cooled to 2 K the dependence of the quality factor on the accelerating has been measured. Due to the strong coupling in the high power test $Q_{ext}=3*10^6$ the quality factor of the cavity is calculated from the measured dynamic heat losses into the Helium bath.

Several measurements at nominal pulse length (500 µs, filling time, 800µs flat-top) at a repetition rate of 1-10 Hz have been performed, all confirming the very good performance of the cavities in the vertical test (for example of one of the cavities see figure 9). The quality factor of about $7*10^9$ at a gradient of 35MV/m is larger than required for TESLA-800 in both cases. Warm-ups of the cavity to 300 K and 150 K respectively did not change the cavity behaviour.

The cavity AC73 has been operated for more than 1100 hours at 35 MV/m showing no sign of degradation. Neither the quality factor of the cavity nor the coupler performance degraded. Thermal breakdowns (quenches) of the cavity induced during the setup of the LLRF (Low-level RF system) were not influencing the quality factor either. This is a well-known behaviour for superconducting cavities. Breakdowns in the coupler also caused during setup of the LLRF were not detrimental to the coupler performance.

In addition during the high power test, the compensation of the Lorentz force detuning could be demonstrated. The pulsed operation leads to a time-dependent frequency shift of the 9-cell cavities which is proportional to E_{acc}^2. The stiffening rings joining neighbouring cells are adequate to keep this Lorentz-force detuning within tolerable limits up to the nominal TESLA-500 gradient of 23.4 MV/m.

To allow for higher gradients the stiffening must be improved, or alternatively, the cavity deformation must be compensated. The latter approach has been successfully demonstrated using a piezoelectric tuner at 23.4 MV/m in a previous test reducing the Lorentz-force detuning by about 200 Hz [20]. More recently, while operating at 35 MV/m a compensation of more than 500 Hz over the full pulse length was achieved (see figure 10). The result indicates that the present stiffening rings augmented by a piezoelectric tuning system will permit efficient cavity operation at the TESLA-800 gradient of 35 MV/m.

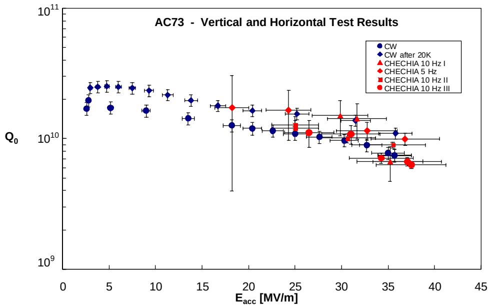

Figure 9: High power test of an electropolished TESLA nine-cells.

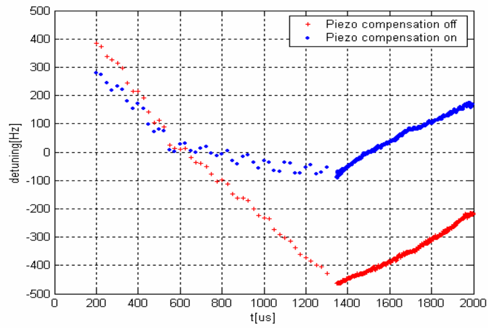

Figure 10: Compensation of Lorentz-forces using piezoelectric tuners.

SUMMARY

An overview of the maximum E_{acc}, $E_{peak,surf}$ and $B_{peak,surf}$ achieved in niobium bulk elliptical multi-cell cavities is given in figure 11. Since the 1980s the maximum fields achievable at frequencies in the range of 1 GHz has increased significantly because several limitations have been overcome (material defects, multipacting, improvement of assembly procedures and surface preparation). Magnetic surface fields in the order of 100 mT have been demonstrated at many projects including those who are using drift tube cavities (see figure 12 for comparison). The first results on electropolished TESLA nine-cell cavities indicate that even 140 mT are achievable.

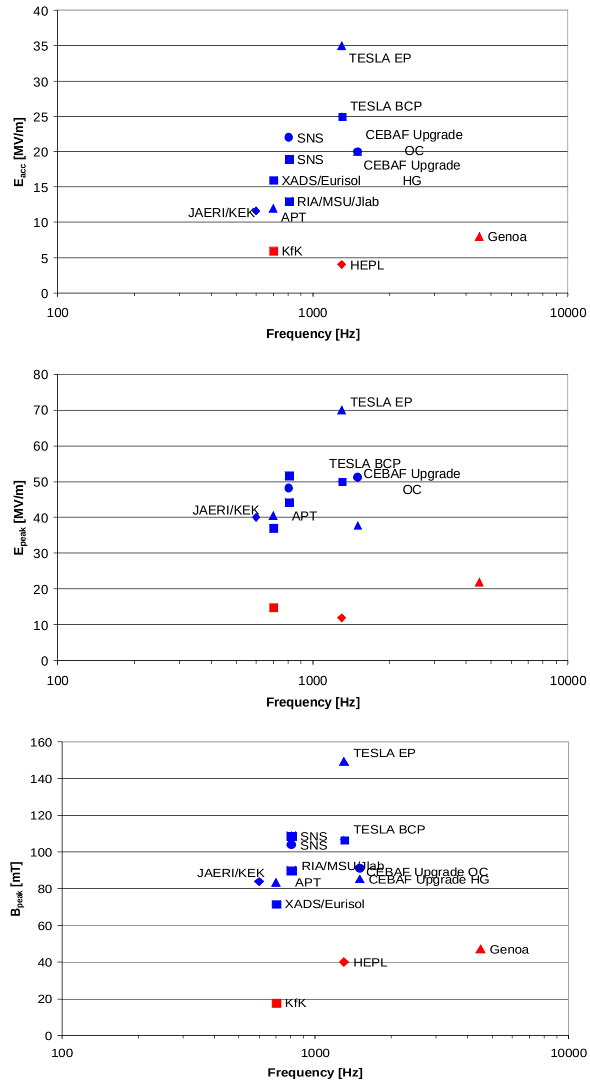

Figure 11: Maximum peak electric and peak magnetic fields in elliptical niobium bulk cavities.

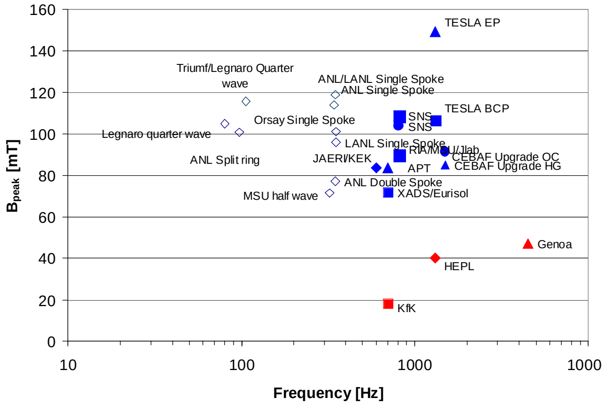

Figure 12: Maximum B_{peak} with compared between drift tube and elliptical cavities. Open symbols:Drift tube cavities, closed symbols: elliptical cavities. (Drift tube data is courtesy of Mike Kelly (ANL).)

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