SUPERCONDUCTING NIOBIUM CAVITIES WITH HIGH GRADIENTS*

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Abstract

Present accelerator projects making use of superconducting cavity technology are constructed with design accelerating gradients E_{acc} ranging between 5 MV/m and 8 MV/m and Q-values of several 10^9. Future plans for upgrades of existing accelerators or for linear colliders call for gradients > 15 MV/m corresponding to peak surface electric fields > 30MV/m. These demands challenge state-of-the-art production technology and require improvements in processing and handling of these cavities to overcome the major performance limitation of field emission loading. This paper reports on efforts to improve the performance of cavities made from niobium of different suppliers by using improved cleaning techniques after processing and ultrahigh vacuum annealing at temperatures of 1400°C. In single cell L-band cavities peak surface electric fields as high as 50 MV/m have been measured without significant field emission loading.

Introduction

In recent years rf-superconductivity has become an important technology in the design and construction of particle accelerators in High Energy and Nuclear Physics. Presently several projects are under construction or have been completed employing more than 300 m of SRF cavities with design accelerating gradients of 5 to 8 MV/m and Q-values of several 10^9. This renewed and increasing interest in superconducting radio frequency technology reflects the significant progress which has been made in the last few years in understanding limitations and implementing techniques and cures to eliminate these limits. Notably, the improvements in the thermal conductivity of the cavity material stabilized the cavities against microscopic defects, which had been identified through improved diagnostic techniques as the cause of early quenches [1]; the implementation of extensive QA-procedures during the fabrication process as well as contamination control measures during processing and assembly of these cavities shifted the dominant performance limitations of field emission loading to higher surface electric fields. Along with substantial performance improvements came increased reliability; e.g. at CEBAF production cavities exhibit on the average twice the design gradients [2].

For future application of SRF-technology in High Energy Accelerators or FEL's, higher gradients than the present design gradients are needed, and in several cases it has been demonstrated that by applying processing techniques like ultrahigh vacuum firing and high peak power processing accelerating gradients of 15 to 20 MV/m can be reached in laboratory tests [3]. To transfer this cavity performance into a full scale production project with beam is the challenge for the future and a collaborative proposal for such a test facility has been developed at DESY [4]. Precursors to such ambitious proposals have to be developments on smaller assemblies.

In the following we report on an experimental program with single cell L-band niobium cavities of the CEBAF geometry aimed at investigating niobium material of four different suppliers as well as the effect on cavity performance of "conventional" processing techniques like chemical polishing, electro-polishing, anodic oxidation and high temperature heat treatment.

Cavity Fabrication and Processing Techniques

Cavity Fabrication

The cavities under investigation were fabricated from high purity niobium of RRR > 220 of four different suppliers: Teledyne Wah Chang, Fansteel Corp., W. C. Heraeus and Tokyo Denkai. After initial material inspection for imperfections, the half cells were formed from 236 mm diameter sheets of 3.2 mm thickness with dies made from Al 7075; the forming pressure was 100 tons and the irises were coined with a pressure of 25 tons. In a next step, the half cells were machined to the final dimension with a 1.6 mm interlocking weld step at the beam-pipe and the equator. Any surface imperfections like scratches or dents introduced by the forming and trimming steps were mechanically removed with an abrasive wheel (3M Company). Prior to electron beam welding the beam-pipe/flanges to the half cells with interpenetrating welds from inside and outside, the parts were chemically cleaned in buffered chemical solution for a few seconds. The final weld at the equator was carried out in a vacuum $\leq 10^{-4}$ torr after an additional careful inspection of the previous welds and removal of visible weld or surface imperfections of the previous step.

Surface Treatments

After fabrication and degreasing in a caustic solution combined with ultrasonic agitation, several different surface treatments were applied to the cavities:

a). Buffered Chemical Polishing (BCP) was carried out with a solution of equal parts of hydrofluoric (49%), nitric (69%) and phosphoric (85%) acids at room-temperature with a removal of $\geq$ 50 μm from the surface.

b). Electropolishing was done in a mixture of sulfuric (95%) and hydrofluoric (49%) acids in a ratio of 10:1 at

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a temperature of 32°C. A voltage of 11.5 V was continuously applied, resulting in a current density of 50 mA/cm^2 and a removal rate of 0.5 μm/min. A total of 120 μm was removed. The next processing step consisted of an annealing at 710°C for three hours at a pressure $\leq 10^{-4}$ torr to remove the dissolved hydrogen from the niobium. During this step the cavities were surrounded by a Ti-box. Subsequently an additional 5 μm was removed by electropolishing [5].

c). In several cases the niobium surfaces were anodically oxidized immediately after a BCP-treatment in a solution of (10%) ammonium-hydroxide at 100 V resulting in a green niobium-pentoxide layer of 2000 Å.

d). Heat treatments at 1400°C for a few hours were applied to several cavities in a cryo-pumped horizontal furnace. During these treatments the cavities were surrounded by a Ti-box, which acted as a solid state getter material and resulted in a homogenization of the material and an improvement of the thermal conductivity [6].

After each surface treatment, the cavities were thoroughly rinsed with ultrapure water. Both flush rinsing with 200 gallons of water through internal spray nozzles in the cavity and "static" rinsing combined with ultrasonic agitation at 20°C and 50°C for a total of 1 hour with several exchanges of water were tried. A final threefold rinsing with reagent grade methanol was carried out in CEBAF's class 100 production clean room, where the assembly of the rf-probes to the cavities took place. Subsequently the cavities were attached to a cryogenic test station and evacuated; within 30 min a pressure of 10^{-6} torr was reached at the ion-pump of the test station. After 12 hours the vacuum had usually improved to the low 10^{-7} torr range before fast cooldown to 4.2 K was started.

Experimental Results and Discussion

A total of nine different cavities have been built from the materials mentioned above and have been tested with a variety of surface treatments to explore the most successful combination. The results can be summarized as following:

a). In a series of tests surface electric peak fields above 40 MV/m were measured. In Figure 1, the best results are shown for cavities of different materials. Whereas the highest fields were measured after a heat treatment at 1400°C and subsequent BCP with the cavities made from Fansteel and Tokyo Denkai niobium, the cavities from Teledyne and Heraeus material were not heat treated. Both heat treated cavities did not quench at the highest obtained fields, but were terminated by radiation safety interlocks at the test location. The Teledyne cavity quenched at $E_p = 50.6$ MV/m and the Heraeus cavity was limited by available rf-power because of the lower Q-value.

b). In all four cases shown in Figure 1 field emission loading was absent at peak fields below 35 MV/m, even though the final surface preparations had been done by "wet" chemical methods. We believe that this reproducible behaviour reflects the high quality of CEBAF's pure water system for rinsing the cavities after the surface treatment and the efficiency of the rinsing and assembly methods. On the insert in Figure 1 the experimental data for peak surface fields beyond the onset of field emission loading have been plotted in the form of a modified Fowler-Nordheim Plot and the "Field-enhancement-factor β" has been extracted. In three of the four examples, β is extremely low with values $\leq$ Å, indicating that surface contamination apparently can be controlled very well with standard chemical methods.

c). Several cavities were electropolished at KEK and sent back to CEBAF under vacuum. Prior to testing they were rinsed with reagent grade methanol. Peak surface fields of 32 MV/m to 38 MV/m were measured. Even though the statistics are limited, the data seem to show a tendency towards slightly higher gradients compared to only chemically treated surfaces, possibly the result of less chemical surface residue due to a smoother surface finish.

d). Anodizing seems to suppress to some extent field emission on surfaces treated by BCP only, resulting in sometimes higher field levels. But at the same time a decrease in Q-value was observed frequently. Anodic layers are on the other hand quite effective in reducing Q-degradations, which occur when high purity niobium cavities are held at temperatures around 100 K and are believed to be caused by precipitation of niobium-hydride phases [7]. The anodization process certainly seems to be helpful and deserves some more investigation.

e). The most important cavity rinsing process after the chemical surface treatment is believed to be ultrasonic agitation at a temperature of 50°C with several exchanges of the ultrapure water. This procedure resulted in the best and most reproducible cavity performances. A high pressure water rinsing system as successfully used at CERN [8] will be available soon for our ongoing experiments and we hope to be successful in pushing the field emission onset to higher gradients.

Conclusion

The presently commercially available high purity niobium is of high quality. In six of the nine cavities which were investigated, peak surface electric fields greater than 37 MV/m up to 52 MV/m were measured after applying wet chemical surface treatment methods, and in several cases field emission loading was not observed below 35 MV/m. For future accelerating cavities with a ratio of $E_{peak}/E_{acc} = 2$, such values correspond to accelerating gradients of 18 MV/m to 26 MV/m, well within the future needs. Whether such cavity performance can be achieved in a production environment with the more complex multi-cell cavities needs to be seen; nevertheless the combination of annealing and wet surface treatments potentially provide the technology to achieve the future goals.

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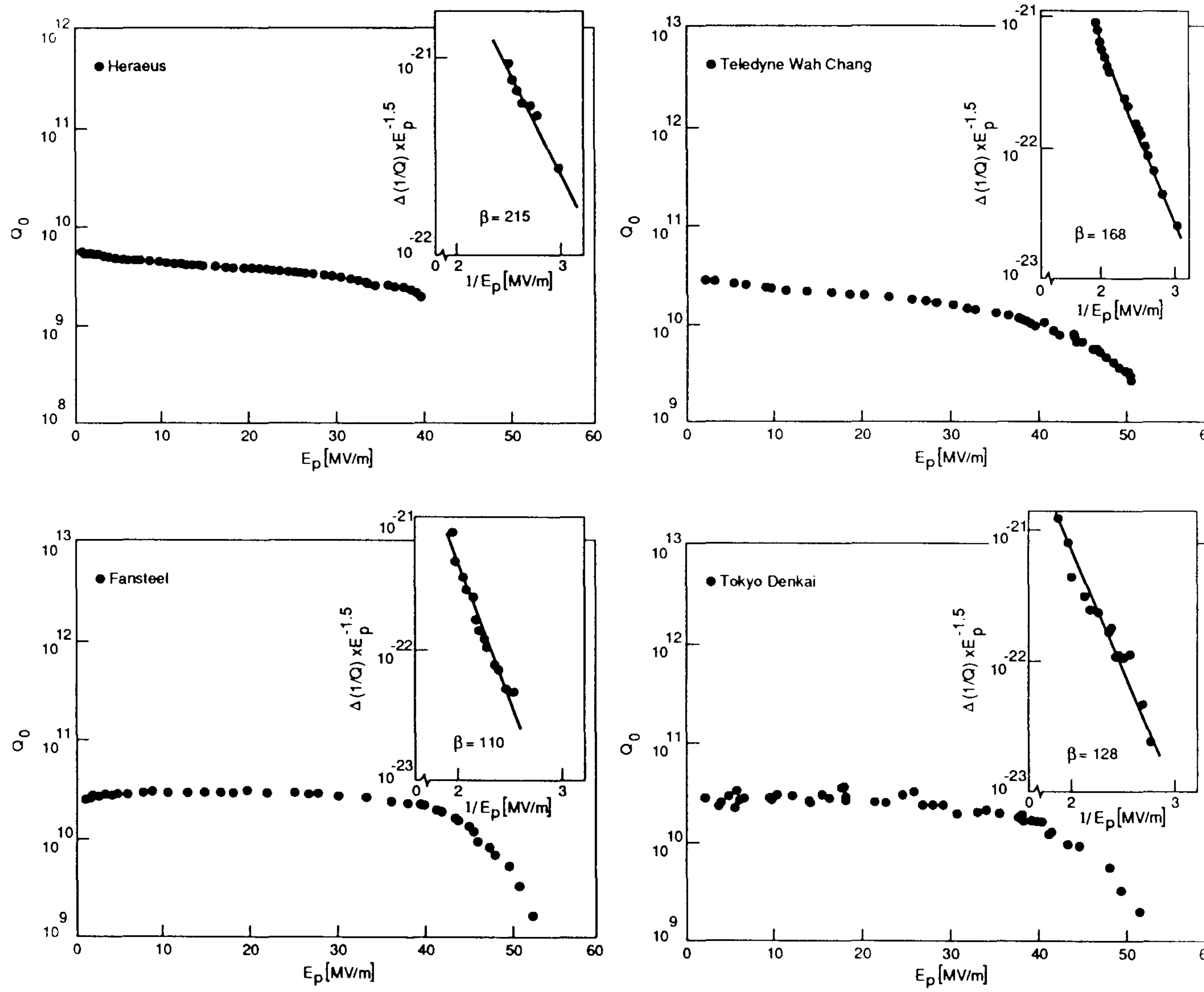

Figure 1: Q_0 vs. E_{peak} for single cell L-band cavities of CEBAF-geometry at $T \leq 1.8$ K. The insert in each plot shows field emission in the form of a modified Fowler-Nordheim plot (β = field enhancement factor) ($E_p/E_{acc} = 1.81$).