Performance of a CEBAF Production Cavity after High-Temperature Heat Treatment*

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Abstract

CEBAF's production cavities are tested in a vertical configuration after appropriate chemical surface treatment prior to installation into the accelerator. The performance of these cavities is excellent, often exceeding the specifications of E_{acc}=5 MV/m at 2 K by factors of 2 to 3. In such cases the cavities are often limited by thermal-magnetic breakdown. A cavity that exhibited a limiting gradient of $E_{acc} \leq 16.4$ MV/m has been heat-treated at 1400°C for 6 hours in the presence of titanium as a solid state gettering material to improve the thermal stabilty of the niobium. After the heat treatment a gradient of E_{acc}=20.5 MV/m corresponding to a peak surface electric field of E_{peak}=52 MV/m has been measured. In addition to the cavity results, data on thermal conductivity and tensile properties of samples which have undergone the same treatments as the cavity are reported.

I. INTRODUCTION

Superconducting niobium cavities for accelerator application are presently limited in their high-gradient performance by either field emission loading or thermal-magnetic breakdown.

CEBAF's 5-cell production cavities—even though they perform excellent and exceed the design gradient of $E_{acc} \geq$ 5 MV/m on the average by a factor of ≈ 2—are in 20% of the cases limited by quenches, more often by strong field emission loading [1].

It is generally accepted that field emission loading is caused by artificial contamination of the sensitive cavity surfaces due to handling and assembly procedures or by intrinsic emitters embedded in the surface. In several cases it has been shown that the severity of the field emission can successfully be reduced by improved cavity handling and cleaning techniques like e. g. "closed chemistry" [2], high-pressure rinsing with ultra-pure water [3], high-temperature heat treatment or high-peak-power processing [4]. Nevertheless, cavities made from presently commercially available high-purity niobium of RRR ≈ 250 to 300 become thermally unstable if a signifant amount of rf heating is generated at microscopic defects. Such defects as foreign material inclusions, weld imperfections, chemical residue from surface treatments, surface irregularities or dust and debris on the surface limit quench fields to ≤ 90 mT corresponding in a typical accelerating cavity to ≤ 20 MV/m. Improvement of the thermal conductivity of the wall material, which can be achieved by high-temperature heat treatment in an ultrahigh vacuum in the presence of a solid state gettering material like titanium [5], will significantly improve the thermal stability of such cavities, and gradients can possibly be shifted towards higher values [6].

In the following sections we report about experiments on a 5-cell CEBAF production cavity, which had been post-purified after initial testing.

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II. EXPERIMENTAL

A. Cavity Processing

For the investigations reported here, production cavity IA080 manufactured from high-purity niobium with RRR ≥ 250 was used. For the baseline test the cavity received the standard removal of a surface layer of ≈ 60 μm by buffered chemical polishing followed by an ultrapure water rinsing combined with ultrasonic agitation over a period of 1 hour with several water changes in between. Assembly of the external cavity parts like rf window, gate valve at one beam-pipe end, blank-off plates and rf coupling ports took place in the class 100 production clean room after a threefold rinsing of the cavity with reagent-grade methanol.

In preparation for the heat treatment in the KfK-furnace,* the cavity was again slightly chemically polished (≈ 5 μm of material removal) and then enclosed in a Ti/Nb foil assembly with a titanium foil arrangement on the inside of the cavity as indicated in Figure 1. Stiffening bars of niobium on the cells were used to avoid cell deformations, and spacer pieces of niobium at the beam-pipe ends were used as a precaution to avoid direct contact between the inside titanium foil and the cavity surface. This assembly was heat-treated at 1400°C for 6 hours in an ultrahigh vacuum; after 4 hours at this temperature, the vacuum had improved to 3×10^{-9} torr.

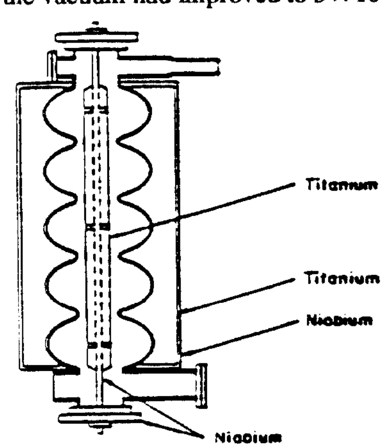

Figure 1. Experimental setup for post-purification of the 5-cell niobium cavity with titanium.

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Unfortunately, the cavity tilted at the high temperature because of improper support in the furnace, and portions of the inner titanium foil got in contact with the two lowest irises of the cavity. This caused some problems as discussed in the next section and made it necessary to heavily chemically treat the cavity.

B. Cavity Testing

Before fast cooldown within ≈ 1 hour the cavity was evacuated to a pressure of $< 6 \times 10^{-7}$ torr after the assembly; the external static magnetic field in the vicinity of the cavity was shielded to better than 10 mGauss by an active compensation coil and a μ- metal layer.

During the experiments the temperature dependence of the surface resistance was measured between 4.2 K and 2 K and data for the dependence of the Q-value on the cavity fields were taken.

III. RESULTS AND DISCUSSION

A. Measurements on Samples

Niobium samples for tensile testing and for thermal conductivity measurements were placed inside the cavity during the heat treatment. For the thermal conductivity two different thicknesses for the test samples were chosen, simulating the material thickness of a cavity cell (3.2 mm) and of a weld (1.6 mm). Figure 2 shows the thermal conductivity of both samples: at 4.2 K the values are 294 W/mK for the thin sample and 214 W/mK for the thicker sample. These values represent an improvement of a factor of 3 to 4 over the starting material.

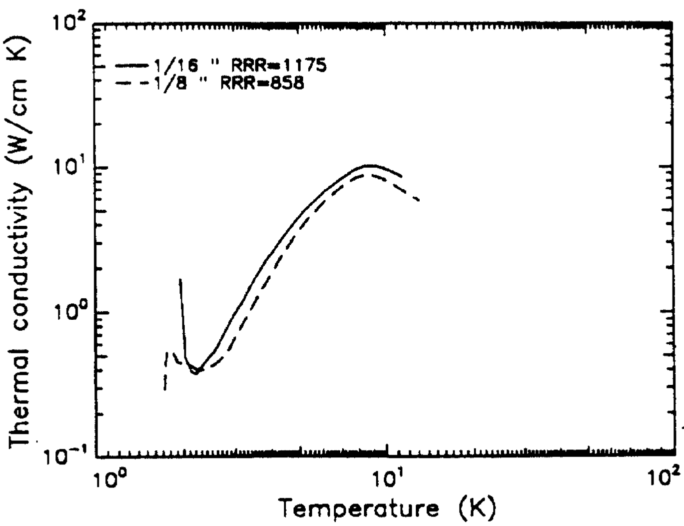

Figure 2. Thermal conductivity of post-purified niobium.

Table 1 summarizes the results of the tensile measurements carried out with a cross-head speed of ≈0.13 mm/min. The sample at 293 K showed a ductile fracture, whereas at 4.2 K a brittle fracture occurred. Nevertheless, the heat treated sample showed a dramatic increase in the elongation to 21.8% in comparison to the non-heat-treated material, which fractured at < 2% [7].

Table 1
Tensile Properties of Post-Purified Niobium at 293 K and 4.2 K.
[YS = yield strength , TS = tensile strength]

T [K]	As received			Heat treated		
	YS [ksi]	TS [ksi]	$\Delta l/l$	YS [ksi]	TS [ksi]	$\Delta l/l$
293	14.5	23	42%	5.9	14	48%
4.2	130	131	<1	—*	102.8	21.8%

*Serrations started before reaching 0. 2 offset yield

B. Q-Value and Gradient Measurements

In the baseline test of the non-heat-treated cavity a Q-value of $Q_0 \approx 1.7 \times 10^{10}$ was measured at 2 K. From the temperature dependence of the Q-value a residual resistance of 6 nΩ was calculated; field emission loading started in this test at $E_{acc} \approx 9$ MV/m after some processing at lower field levels had taken place. A maximum gradient of E_{acc}=15 MV/m was measured limited by a Q-degradation at a dissipated power level of ≈ 60 W. In the 4π/5-mode magnetic breakdown was observed at a stored energy in the end-cell, which would be equivalent to 16.4 MV/m in the π-mode.

As mentioned earlier, during the heat treatment of the cavity the inside titanium foil got attached to the two irises closest to the higher-order-mode coupling waveguides due to deformation of the cavity. Therefore—after the cavity had mechanically been straightened out and the frequency, field profile and Q_{ext} of the fundamental power coupler had been readjusted—the suspicious areas of the defective surface were mechanically ground. Subsequently, 50 μm of material were chemically removed from the surface prior to the first test after the heat treatment. The result of this experiment was quite disappointing: The Q-value at 2 K was only ≈ 4×10^9 and the cavity quenched at E_{acc}=6.5 MV/m. In the next two tests additonal mechanical grinding was done and niobium was chemically removed in steps of 25 μm. Each time some improvement in the cavity performance was observed. Because of an uncontrolled exposure of the cavity surface to air after initial evacuation, rather strong field emission loading was observed in test #3a starting at $E_{acc} \approx 7.5$ MV/m. The cavity was taken apart and only rinsed with a high-pressure jet of ultrapure water, resulting in an improvement of the obtainable gradient to $E_{acc} \approx 14$ MV/m. No radiation was observed even at this gradient; the degradation of the Q-value seemed to be caused by heating of some areas on the surface, presumably some spots of titanium or NbTi as a result of the contact between cavity surface and Ti foil. The effectiveness of the high-pressure rinsing had been demonstrated prior to this experiment on several tests with a single-cell cavity, which consistently resulted in peak surface fields of E_{peak} > 50 MV/m without any signs of field emission loading [8].

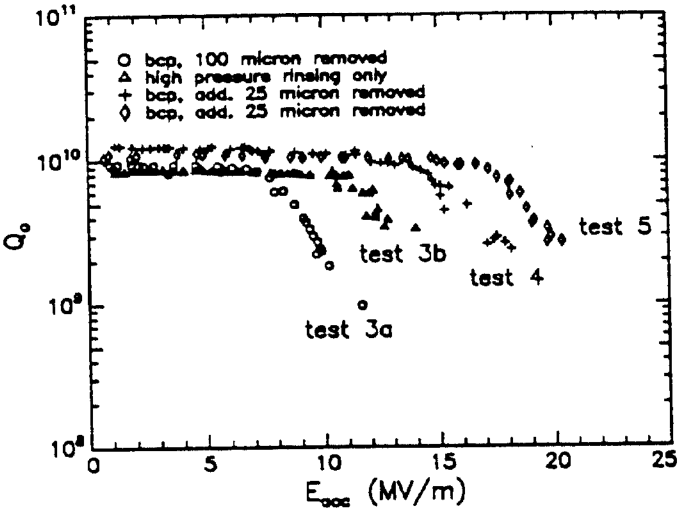

Figure 3. Summary of test results on heat-treated cavity after subsequent chemical surface treatments (bcp=buffered chemical polishing).

In two subsequent tests additonal material (25 μm each time) was removed followed by 1 hour of high-pressure rinsing at 8.3 MPa. These tests are labeled as #4 and #5 in Figure 4. Each time the gradient improved and no or very little field emission loading occurred. The decrease of the Q-value beyond 16 MV/m in test #5 is proportional to the square of the cavity field and hints again to some heating, probably occurring at remaining spots of Ti contamination. Even at the maximum gradient of E_{acc}=20.5 MV/m, corresponding to a peak surface field of $E_{peak} \approx 52$ MV/m, the highest field ever achieved in this type of cavity, only very little X-radiation was observed. At this field level the cavity could tolerate ≥ 100 W without thermal instability. In the 4 π/5-mode the end cells of the cavity could tolerate a stored energy equivalent to 28 MV/m in the π-mode.

B. Additional Measurements

Prior to the post-purification, the pressure sensitivity of the cavity between 760 torr and 23 torr was measured to be 68.8 Hz/torr. In the first test after the heat treatment, this value had increased to 77.4 Hz/torr. This change can be attributed to the thinning of the wall material due to the additional chemical treatment after the post-purification.

The response of the cavity frequency to the static radiation pressure was measured in the range 5 MV/m $\leq E_{acc}$ < 20 MV/m and resulted in a value of $\Delta f/E^2$=3.1 Hz/[MV/m]^2.

IV. CONCLUSIONS

Post-purification of the presently commercially available high-purity niobium with a solid state getter material like titanium can improve the thermal stability of accelerator cavities significantly. This might be necessary for future high-gradient applications, even though very good cavity performances have been achieved with non-heat-treated material. But the quench fields in these cases vary over a wide range of values as experienced at CEBAF [1]. Chemical treatment after post-purification in combination with high-pressure pure water rinsing seems to be a very useful method to reduce field emission loading up to peak surface fields of $E_{peak} \approx 50$ MV/m. In optimized cavity geometries with a ratio of $E_{peak}/E_{acc} \approx 2$, such fields correspond to gradients of $E_{acc} \approx 25$ MV/m, which are needed for future linear collider projects.

V. ACKNOWLEDGEMENTS

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