PERFORMANCES OF HIGH-PURITY NIOBIUM CAVITIES WITH DIFFERENT GRAIN SIZES*

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Abstract

Grain boundaries have for some time been suspected of influencing the performance of RF cavities made from high purity niobium by limiting the temperature dependent BCS surface resistance to a residual resistance because of impurity segregation and by causing field limitations due to flux penetration. We have carried out a comparative study of the RF behavior of 2.2 GHz TM_{010} cavities of identical shape, fabricated from single crystal niobium, niobium of grain sizes of the order of several cm^2 and standard poly-crystalline material. All the cavities were treated with buffered chemical polishing (BCP), post-purified at 1250 °C and "in-situ" baked at 120 °C. This contribution reports about the results of the measurements of the temperature dependence of the surface resistance $R_s(T)$ and the Q_0 vs. E_{acc} behavior at 2 K. From the analysis of the $R_s(T)$ data at low RF fields material parameters such as gap value, mean free path and residual resistance could be extracted. The dependence of the Q-value on RF field was analyzed with respect to the medium field Q-slope, "Q-drop" at high fields and the "quench" fields. The best performance resulted in a breakdown field of ~ 165 mT, corresponding to an accelerating gradient of E_{acc} ~ 38 MV/m.

INTRODUCTION

In 2004 it was decided to adopt RF superconductivity as the technology of choice to build the International Linear Collider (ILC), which is the next high-energy physics accelerator to be built in the next decade. The superconducting cavities for ILC are required to operate at accelerating gradient close to the magnetic limit of niobium, the superconductor of choice for RF applications. Since grain boundaries are "weak" areas in a niobium surface that can easily be contaminated by segregated impurities and form "weak links", they are a prime candidate for causing a degradation of the performance of the material. In 2005 it became possible to fabricate RF cavities from large (cm^2 area) grain and single crystal RRR > 200 niobium [1] and the results from the first tests were promising. In this contribution we present the results from a study on the performance of 4 single-cell cavities of the same shape. Two were built from large-grain Nb provided by Wah Chang [2], one made of single crystal Nb from CBMM and one made of standard fine-grain material (ASTM grain size ≥ 6), also from Wah Chang. The TM_{010} mode resonates at 2.2 GHz and the shape is based on the "High Gradient" shape considered for the CEBAF Upgrade [3] scaled to this higher frequency. The main electromagnetic parameters of the cavity shape are given in Table 1.

Table 1: Electromagnetic Parameters of the Cavity Shape used for this Study

Frequency (MHz)	2256
R/Q (Ω)	113
G (Ω)	270
E_p/E_{acc}	1.67
B_p/E_{acc} [mT/(MV/m)]	4.29

CAVITY FABRICATION AND SURFACE PREPARATION

The single crystal cavity, described in Ref. [1], was made from RRR ~ 280 (800 ppm Ta content) sheets, sliced from a Nb ingot by wire-EDM. The two large-grain cavities were made from RRR > 300 Nb (< 500 ppm Ta) from sheets which were cut from the ingot by wire-EDM on one side and saw cut on the other side. The fine grain cavity was made from RRR > 300 Nb standard rolled sheets. All the half-cells were deep drawn and they were joined by electron beam welding along with the beam tubes. The cavities were etched by buffered chemical polishing (BCP) with a 1:1:1 solution of HF, HNO_3 and H_3PO_4 at room temperature, removing approximately 70-100 µm of material. The cavities were heat-treated in a vacuum furnace at 600 °C for 10 h (the single crystal one was heated at 800 °C for 2 h) to degas hydrogen introduced by the wire-EDM and the chemical etching. Afterwards, additional 50-70 µm were removed by BCP 1:1:1. The cavities were high-pressure rinsed for about 1 h, dried in a class 10 clean room, assembled with input and pick-up antenna and pump-out port, evacuated on a vertical stand to a pressure of about 10^{-8} mbar prior to the RF test at 2 K.

RF TEST RESULTS

The RF tests of the cavities consisted of measuring the surface resistance between 4.2K and 2K and the dependence of the Q-value on accelerating gradient (Q_0 vs. E_{acc}) at 2K. Figure 1 shows the Q_0 vs. E_{acc} data for cavities made from large-grain, single crystal and fine-

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grain Nb. The performances of the two large grain cavities were always very consistent with respect to each other and only one of them is shown in Fig. 1 for clarity. The large grain cavities had the lowest Q_0 and onset of the high-field Q-drop, without field emission. The cavities were "in-situ" baked at 120 °C for 12 h for the large grain ones and at 120 °C for 48 h for the single crystal and fine-grain ones. The Q_0 vs. E_{acc} curves at 2.0 K after baking are shown in Fig. 2: while the fine grain and single crystal cavities show comparable performance, the large grain ones had both lower Q_0 (higher residual resistance) and quench field. The Q-drop was still limiting the performance of the fine grain cavity while field emission was the limit in the single crystal one.

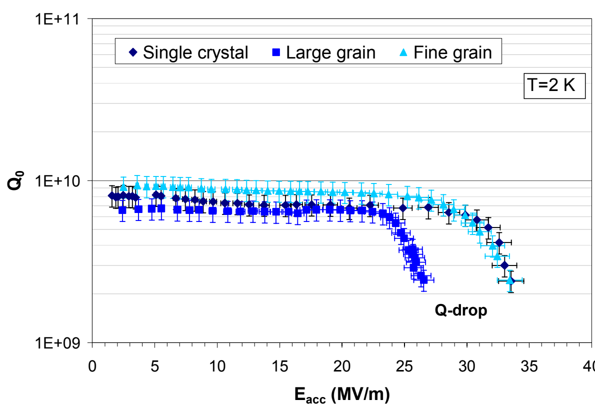

Figure 1: Q_0 vs. E_{acc} for the cavities made of niobium with different grain size after hydrogen degassing and chemical etching.

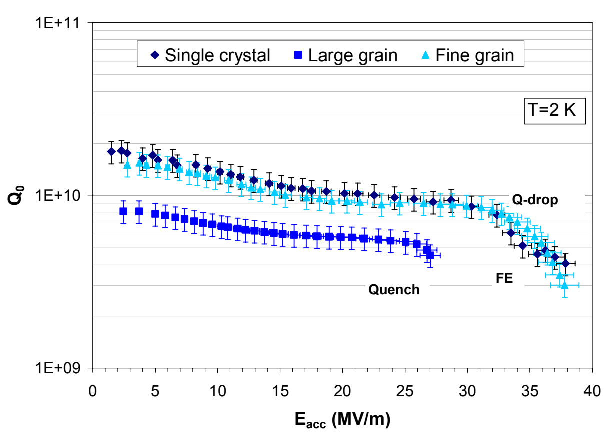

Figure 2: Q_0 vs. E_{acc} for the cavities made of niobium with different grain size after 120 °C "in-situ" baking.

In order to improve the thermal conductivity of the niobium, the cavities were post-purified in a Ti box inside a vacuum furnace, heated at 1250 °C for 12 h. Approximately 50 µm of Nb were subsequently removed by BCP 1:1:1. Figure 3 shows the Q_0 vs. E_{acc} data after post-purification: the performance of the fine-grain cavity degraded, the large-grain ones did not change significantly, while the single crystal one slightly improved. In all cases, the limitation is represented by the Q-drop without field emission. The cavities were "in-situ" baked at 120 ° for 12 h (45 h for the single crystal one) and their performance is shown in Fig. 4: all the cavities had similar behavior, in all cases the Q_0 increased, the Q-drop was eliminated and the cavities were limited by quench. The single crystal cavity quenched at the highest field (E_{acc} = 36 MV/m, B_p = 154 mT).

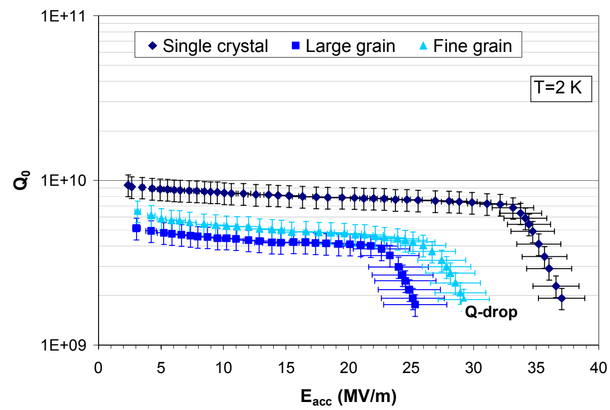

Figure 3: Q_0 vs. E_{acc} for the cavities made of niobium with different grain size after post-purification and chemical etching.

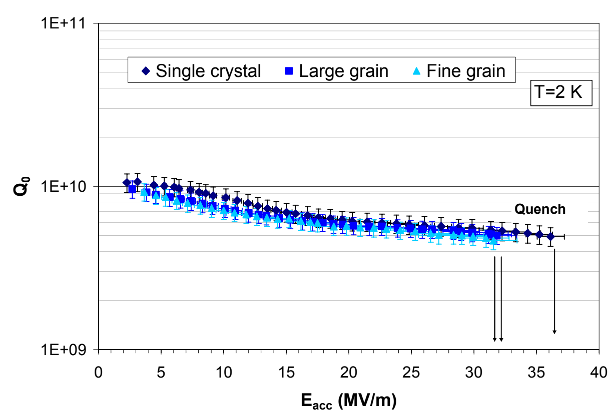

Figure 4: Q_0 vs. E_{acc} for the cavities made of niobium with different grain size after post-purification and 120 °C "in-situ" baking.

DATA ANALYSIS

The R_s vs. T data have been fitted with the BCS theory with the addition of the residual resistance (R_{res}). The critical temperature (T_c=9.25 K), the penetration depth at 0 K (λ=32 nm) and the coherence length (ξ_0=39 nm) are considered fixed material constants. The fit parameters energy gap (Δ/kT_c) and residual resistance R_{res} for different treatments of the fine-grain, large-grain and single-crystal cavities are shown in Figs. 5 and 6, respectively. The values for the large-grain case are average of the results from the two large-grain cavities. The energy gap increased by baking about 3-9% in both fine-grain and single crystal cavities while it didn't change significantly on the large grain ones. The residual resistance is lowest in the single crystal cavity, while it does not differ significantly between the fine-grain and the large grain cavities. R_{res} either did not change or increased by few nΩ by baking.

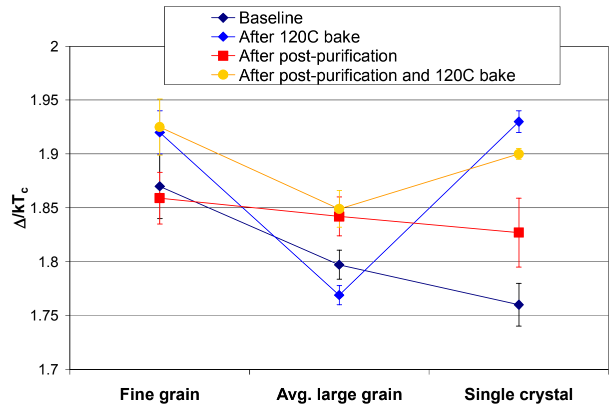

Figure 5: Δ/kT_c for cavities with different grain size and for various treatments.

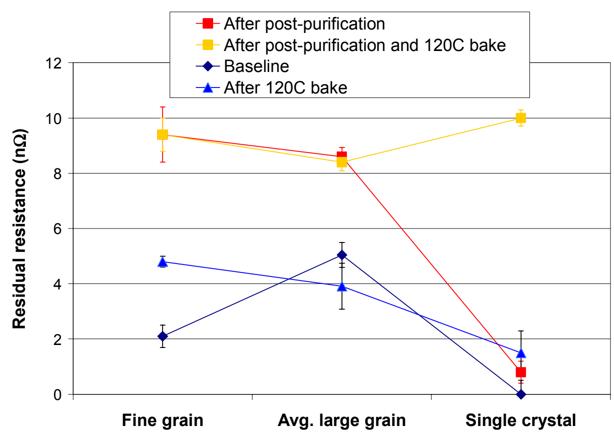

Figure 6: R_{res} for cavities with different grain size and for various treatments.

A plot of the maximum value of B_p (for $Q_0 = 2\times10^9$ before bake) for cavities with different grain size is shown in Fig. 7 for various surface treatments. The performance of the fine-grain cavity degraded significantly after the post-purification, where the quench field decreased by about 18%. Possible causes might be not sufficient material removal or a contamination due to a power outage in the vacuum furnace while the cavity was being heat-treated at 1250 °C.

The R_s vs. B_p dependence in the range 20-80 mT (medium field Q-slope) was fitted with a second order polynomial, as described in [4], with coefficients of the linear term R_{res}^1 and of the quadratic term γ^* as fit parameters. The data showed that the linear term is dominant and that R_{res}^1 increases by baking. This increase was approximately independent of the cavity grain size before post-purification, while it becomes greater for larger grain size after post-purification (Fig. 8). By one theoretical model [4] R_{res}^1 is related to "weak-link" losses across grain boundaries.

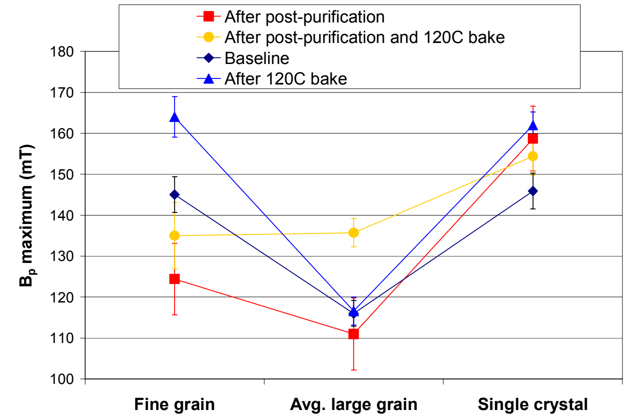

Figure 7: Highest B_p achieved on cavities with different grain size and for various treatments.

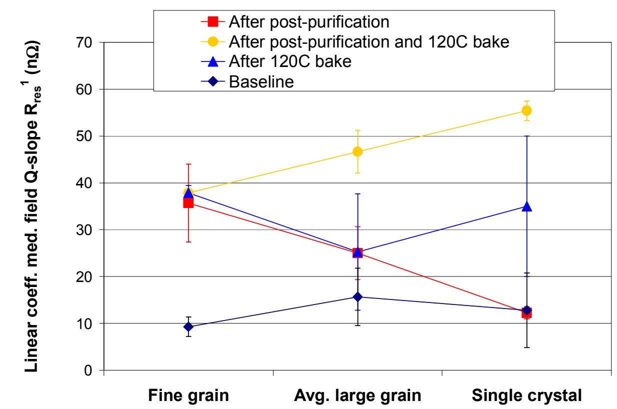

Figure 8: Linear coefficient of the medium field Q-slope, R_{res}^1, on cavities with different grain size and for various treatments.

CONCLUSIONS

Cavities of the same shape made of RRR>200 Nb of different grain size were fabricated and tested to evaluate the influence of grain boundaries on the RF performance. Different treatments such as "in-situ" baking and post-purification were equally applied to the cavities. The results showed no clear dependence of residual resistance, medium field Q-slope and maximum surface magnetic field on the density of grain boundaries. This result seem to indicate that grain boundaries are not the main limitation towards achieving the highest cavity performance, which might be more strongly influenced by other parameters such as the distribution of the impurities and the presence of defects in the Nb.

REFERENCES

[1] P. Kneisel et al., Proc. of the 2005 PAC, Knoxville, TN, 2005, p. 3991.
[2] Courtesy of R. Graham.
[3] P. Kneisel et al., JLab Technical Note, TN-01-015, 2001.
[4] G. Ciovati and J. Halbritter, Physica C 441 (2006) 57.