INVESTIGATION OF "HOT-SPOTS" AS A FUNCTION OF MATERIAL REMOVAL IN A LARGE-GRAIN NIOBIUM CAVITY*

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Abstract

The performance of a single-cell cavity made of RRR > 200 large-grain niobium has been investigated as a function of material removal by buffered chemical polishing. Temperature maps of the cavity surface at 1.7 and 2.0 K were taken for each step of chemical etching and revealed several "hot-spots", which contribute to the degradation of the cavity quality factor as a function of the RF surface field, mostly at high field levels. It was found that the number of "hot-spots" decreased for larger material removal. Interestingly, the losses of the "hot-spots" at different locations evolved differently for successive material removal. The cavity achieved peak surface magnetic fields of about of 130 mT and was limited mostly by thermal quench. By measuring the temperature dependence of the surface resistance at low field between 4.2 K and 1.7 K, the variation of niobium material parameters as a function of material removal could also be investigated. This contribution shows the results of the RF tests along with the temperature maps and the analysis of the losses caused by the "hot-spots".

INTRODUCTION

Recently, it became possible to fabricate niobium cavities made from large-grain (with area of the order of few cm^2) niobium sheet directly sliced from a niobium ingot [1]. This new technology has the potentials of cost-savings, smooth surfaces by buffered chemical polishing (BCP) alone and reduced risk of foreign material inclusions, introduced during the manufacturing process, compared to the standard "fine grain" (ASTM grain size > 6) niobium. Preliminary results on single-cell cavities were very promising both in terms of high accelerating fields and high quality factors [1]. A very powerful tool to identify the losses in a superconducting cavity consists of a thermometry system which provides a "thermal map" of the cavity as a function of the RF field in superfluid helium. This allows to localize lossy areas and to follow their evolution for different surface treatments. We used such a temperature mapping system to investigate the performance of a large grain single-cell niobium cavity as a function of material removal by chemical etching to evaluate whether large grain cavities have a thinner "damaged" layer than fine grain ones.

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CAVITY FABRICATION AND SURFACE PREPARATION

Two 3.175 mm thick niobium sheets for the fabrication of the single-cell cavity were saw cut from an ingot provided by CBMM [2]. The material is characterized by a RRR of ~280, the main impurity being tantalum (≈800 ppm). The sheets followed the standard fabrication technique of niobium cavities, which consists of forming two half-cells by deep drawing, electron beam welding (EBW) cylindrical beam tubes onto half-cells and final EBW at the cell's equator, after mechanical polishing of the half-cells to remove visible imperfections. The center cell shape of the CEBAF cavities is used for this single cell cavity. It resonates at 1.47 GHz in the TM_{010} mode.

The surface treatment and preparation for an RF test in superfluid helium consist of

- Degreasing in a soap/water solution with ultrasonic agitation for 30 min.
- BCP with a 1:1:2 mixture of HF, HNO_3 and H_3PO_4 manually stirred at room temperature, removing typically 25 μm of material (removal rate ~ 1 μm/min)
- High pressure (≈ 80 bar) rinsing with ultra-pure water for 30 min to remove the surface contamination by dust particles.
- The cavity is dried overnight in a class 10 clean room and it is sealed with niobium disks which have feedthroughs with pick-up and input antenna. The input antenna disk has also a pump-out port that is connected to the vacuum system installed on the cryostat insert. Indium wire gaskets are used for vacuum seals.. The cavity is evacuated to about 10^{-8}-10^{-7} mbar using a combination of scroll and turbomolecular pumps.
- The thermometry system, consisting of 576 100 Ω Allen-Bradley carbon resistors (1/8 Watt) divided into 36 printed circuit boards spaced azimuthally by 10°, is installed on the cavity with fixed orientation; Apiezon N grease is used as a "bonding agent". Details on the temperature mapping system can be found in Ref. [3]. The position of the thermometers on the cavity are identified by two numbers: the first indicates the angular position in degrees from the reference mark on the cavity, while the second one is the vertical position, 1 to 16, 1 being the thermometer on the top beam tube near the cavity iris.

EXPERIMENTAL RESULTS

For the first test about 70 µm were removed from the inner surface of the cavity after fabrication by BCP, and the results from the high-power RF tests are shown in Fig. 1. A strong medium field Q-slope characterizes the Q_0 vs. B_p curve. Field emission started at about B_p = 90 mT. The temperature map at 1.7 K at the highest field showed a broad heating of the surface with the strongest "hot-spots" in the equator region, where the magnetic field is maximum (Fig. 2a). Figure 2b shows the temperature increase as a function of the logarithm of B_p for some "hot-spots" obtained from temperature maps at 1.7 K. In the presence of ohmic-type losses, for which R_s is independent of B_p, for small ΔT, ΔT is proportional to B_p^2. It is interesting to notice that some regions have an approximately constant slope of log(ΔT) vs. log(B_p) in the whole range of values of B_p (for example thermometer 270-8 in Fig. 2b) while some others shows a higher slope starting at about B_p = 115 mT (for example thermometer 280-7 in Fig. 2b). This sharp increase of heating has been recognized as a signature of the high-field Q-drop [4]. By visually inspecting the location of the "hot-spots" on the cavity surface, it was found that the areas with increased heating at high field were on grain boundaries.

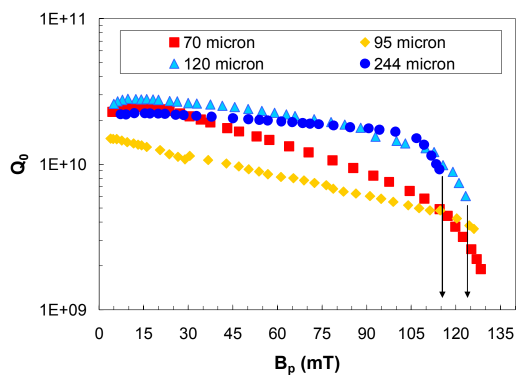

Figure 1: Q_0 vs. B_p at 1.7 K as a function of the total material removal.

The cavity received a new surface preparation, removing an additional 25 µm. The cavity achieved B_p = 126 mT without field emission (see Fig. 1) and the test was limited by the available RF power. As can be seen from the temperature map at 1.7 K, shown in Fig. 3a, the number of "hot-spots" decreased from the previous test and ΔT rises uniformly at increasing RF field (Fig. 3b); simultaneously, the Q-drop is reduced. Similar results were obtained from the temperature maps at 2.0 K.

The cavity was prepared for another RF test, after etching an additional 25 µm by BCP. The tests at 1.7 K and 2.0 K were limited by quench at B_p = 123 mT. There was no field emission but the quality factor dropped sharply starting at about 110 mT. The temperature maps showed a sharp increase of the slope in the plot of log(ΔT) vs. log(B_p), starting at about B_p = 110 mT, for several thermometers, causing the Q-drop.

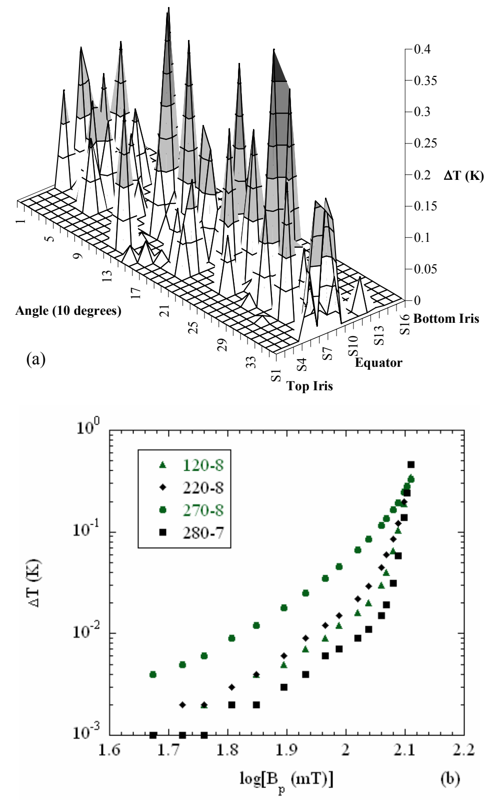

Figure 2: (a) Temperature map of the cavity surface at 1.7 K and B_p = 128 mT after 70 µm of material removal and (b) ΔT vs. log(B_p) for few "hot-spots".

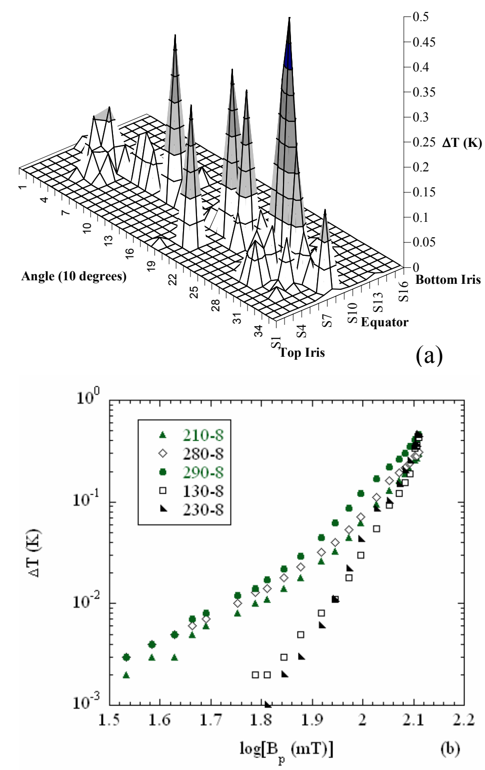

Figure 3: (a) Temperature map of the cavity surface at 1.7 K and B_p = 126 mT after 95 µm of total material removal and (b) ΔT vs. log(B_p) for few "hot-spots".

The cavity was heat treated at 600 °C for 15 h in a vacuum furnace and subsequently 11 μm were etched by BCP. The RF tests at 2 K showed strong multipacting at B_p ~ 50 mT. It was found that a valve on the test stand had a leak, causing contamination of the vacuum system. The valve was replaced and the cavity was chemically treated additionally resulting in a total material removal of about 244 μm. The subsequent RF test at 1.7 K and 2.0 K were limited by a quench at B_p = 115 mT with the Q-drop starting at 105 mT. The temperature maps showed again a change in the slope of log(ΔT) vs. log(B_p) for several thermometers as the Q-drop begins.

ANALYSIS OF RESULTS

The residual resistance was obtained by subtracting the BCS component to the surface resistance vs. temperature data. The results are shown in Fig. 4, as a function of total material removal, and they are compared with a previous study [5] done on a standard fine-grain Nb cavity. Figure 5 shows the maximum B_p achieved as a function of total material removal, along with the data from Ref. [4] for a fine-grain Nb cavity which was limited in all cases by quenches, without field emission. The quench field in the fine-grain cavity increased with more material removal, suggesting the presence of defects or foreign inclusions in the Nb as the cavity limitation while in this study, the highest surface magnetic field was already achieved after only 70 μm of material removal.

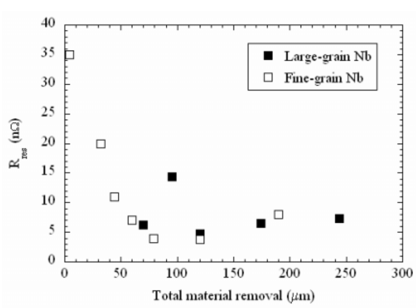

Figure 4: Residual resistance as a function of material removal measured on a fine grain [5] and on a large grain Nb cavity at 1.5 GHz.

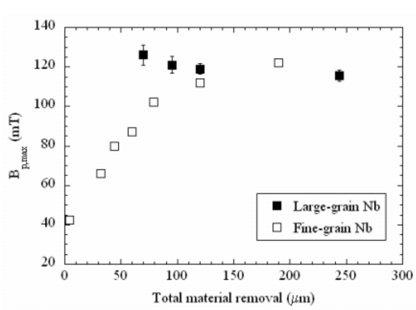

Figure 5: Maximum value of B_p at 2 K as a function of material removal for the large grain single cell used for this study compared with the results from a previous study [5] done on a fine grain cavity.

CONCLUSIONS

Measurements of the quality factor as a function of the peak surface magnetic field were carried out on a cavity made of large grain niobium for different amounts of material removal by BCP. A thermometry system was used as an additional tool to identify the location of the RF losses and their field dependence. The results showed that the removal of 70 μm of niobium after fabrication is sufficient to obtain the best performance of the cavity in terms of both high surface field (B_p > 120 mT) and low residual resistance (R_{res} ≈ 6 nΩ). A similar study [5] on a fine-grain niobium cavity showed that a removal of about 120 – 180 μm was necessary to achieve a similar performance. On the other hand, after 70 μm of etching there is still a significant area of the cavity near the equator which exhibit anomalous losses, characterized by a strong slope in the plot of Q_0 vs. B_p in the medium field range. Our results show that these losses are significantly reduced after about 120 μm of BCP and it is possible that they could be due to foreign inclusions/insufficient cleaning of the EBW area. Therefore we are planning a repeat the test sequence with a new cavity, which has undergone much more material removal in the equator area prior to electron beam welding both half cells together.

The majority of the grain boundaries and the weld seam are located at the cavity equator but we did not succeed in finding in all cases a clear correlation between those features and the hot-spots locations.

In conclusion, the use of large-grain, high RRR niobium directly sliced from an ingot has the potential of high RF performances with lower amount of chemical etching than required for standard fine-grain niobium sheet, allowing some cost-savings.

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