EFFECTS OF ELECTRIC AND MAGNETIC FIELDS ON THE PERFORMANCE OF A SUPERCONDUCTING CAVITY*

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Abstract

A special two-cell cavity was designed to obtain surface field distributions suitable for investigation of electric and magnetic field effects on cavity performance. The cavity design and preliminary results were presented in a previous contribution.

The bulk niobium cavity was heat-treated in a vacuum furnace at 1250 °C to improve thermal conductivity. Three seamless hydroformed Nb/Cu cavities of the same design were fabricated to investigate the role of the electron beam welds located in high field areas.

This paper will present RF test results at 2 K for the bulk niobium and one of the seamless cavities.

INTRODUCTION

Superconducting cavities made from high purity niobium with RRR > 200 are often limited by a sharp decrease of the quality factor (so-called *Q*-drop) at high rf fields ($B_p \approx 100$ mT), in absence of field emission.

Several models have been proposed over the last few years to explain the origin of these "anomalous losses". A model by Halbritter [1] describes the *Q*-drop as due to an interface tunnel exchange process occurring between conduction electrons from the metals and electrons trapped in localized states in the surface oxide. This phenomenon is supposed to be driven by an intense electric field.

A model proposed by Knobloch *et al.* [2] considers the *Q*-drop as due to a geometric magnetic field enhancement at rough areas of the cavity surface causing localized quenches. In particular, the equator weld area is considerably rougher than the rest of the cavity surface [3] and might contribute to the *Q*-drop. Furthermore, defective equatorial welds have been already identified as limiting factors towards achieving higher accelerating gradients [4].

A two-cell cavity was designed to investigate the origin of the *Q*-drop and the role of the welds. The electromagnetic parameters and the surface field distributions of the TM_{010}-0 and TM_{010}-π modes were given in a previous article [5]. The major difference consists in the peak surface electric field being about a factor of 3.9 higher in the TM_{010}-π than in the TM_{010}-0, for the same stored energy and peak surface magnetic field.

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NIOBIUM CAVITY PREPARATION AND TEST RESULT

A cavity made of niobium RRR > 200 had been fabricated and the results from rf tests at 2 K were reported in Ref. [5]. The Q vs. B_p curves were identical, within the errors, in both modes and the cavity was limited by a "mild" *Q*-drop, in absence of field emission, to B_p = 100 mT. "In situ" baking did not improve the performance.

In order to increase the maximum field, the niobium cavity was post-purified by heat treatment at 1250 °C in a vacuum furnace. The cavity was placed inside a titanium box which acts as solid state getter for niobium interstitial impurities such as oxygen, nitrogen and carbon.

The post-purification procedure followed the one developed in Ref. [6]. The temperature was raised to 1250 °C in about 4 h and remained there for 12 h, allowing the titanium to sublimate and deposit on the niobium cavity. The temperature is then lowered to 1000 °C at a rate of -0.2 °C/min. The cool-down to room temperature took about 9 h. The maximum pressure was about 10^{-5} mbar at 1250 °C, decreasing to about 10^{-7} mbar before cool-down.

The RRR of a niobium samples treated with the cavity increased from 390 to 720, proving the effectiveness of the process.

The outer surface of the cavity was etched with Buffered Chemical Polishing (BCP) in ratio 1:1:1 for about 5 min, while the inside surface was etched with BCP 1:1:2 removing about 70 µm of niobium. The cavity was high pressure rinsed (HPR) for 2 h and dried overnight in a class 10 clean room.

The results of the high power rf test at 2 K are shown in Fig. 1. Both the low-field quality factor and maximum B_p achieved were about 50 % lower in the TM_{010}-0 than in the TM_{010}-π mode. The magnetic field distribution in those modes is similar, except for the 0-mode being close to the peak value in the iris region between the two cells, while the π-mode has a node at that location. Therefore we suspect additional losses to be located in that area. The performance of the cavity was limited by the *Q*-drop, without field emission, to B_p = 85 mT in the 0-mode and B_p = 125 mT in the π-mode.

The cavity was baked at 120 °C for 48 h. In the subsequent rf test at 2 K the low-field quality factor increased by about 50 %, consistently with the reduction of the BCS surface resistance measured in previous studies of the baking effect [7]. There was not a significant increase in the residual resistance, as the surface resistance at low field was only about 10 nΩ at 2 K and 1.4 GHz. After baking, the maximum field improved to about B_p = 167 mT in the π-mode and B_p = 152 mT in the 0-mode, in both cases limited by quench. Some residual *Q*-drop is present above 135 mT. The value of B_p achieved in the TM_{010}-π mode is among the highest ever achieved and would correspond to an accelerating field of about 42 MV/m in a standard speed-of-light elliptical cavity [$B_p/E_{acc} \cong 4$ mT/(MV/m)]. The rf test results after baking are also shown in Fig. 1.

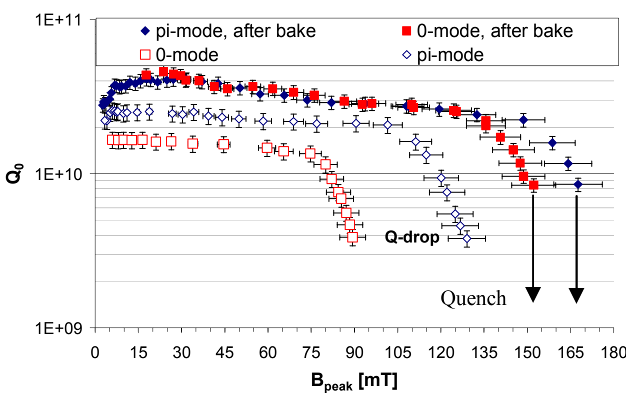

Figure 1: Q_0 vs. B_p for the two-cell cavity measured at 2 K before and after baking at 120 °C for 48 h.

Fig. 2 shows the quality factor as function of the peak surface electric field in both modes, before and after baking. E_p in the TM_{010}-π mode reached values approximately six time higher than in the 0-mode, with no additional losses. These results are consistent with the ones obtained in the tests before post-purification and with the results from a study in Ref. [8] and suggest that the *Q*-drop is related to a magnetic field effect.

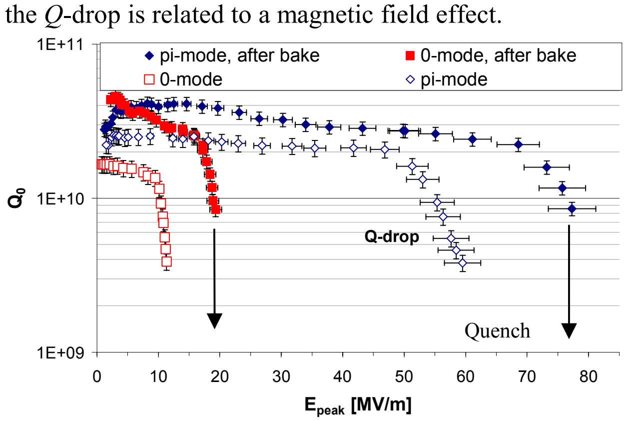

Figure 2: Q_0 vs. E_p for the two-cell cavity measured at 2 K before and after baking at 120 °C for 48 h.

Thermal Feedback Model Comparison

The data from the rf tests have been compared with a thermal feedback model developed by Gurevich [9]. According to the model, the surface resistance increases at higher rf field due to two contributions:

- Heating of the rf surface due to the thermal resistance to the helium bath
- Intrinsic quadratic dependence of the BCS surface resistance from rf magnetic field.

The following expression of the low-field surface resistance has been used [10]:

$$R_s = \frac{A}{T}\left(\frac{f}{1.5}\right)^2 e^{-18.5/T} + R_{res} \qquad (1)$$

where f is the frequency in GHz, R_{res} is the residual resistance and A is a constant which depends on material parameters. The thermal conductivity of niobium RRR 700 is taken from Ref. [11] and is 30 W/m K at 2 K, while the Kapitza conductance is from Ref. [12] and is equal to 9450 W/m^2 K at 2 K.

The results from the comparison between the model and the experimental data before and after baking are shown in Figs. 3 and 4 respectively.

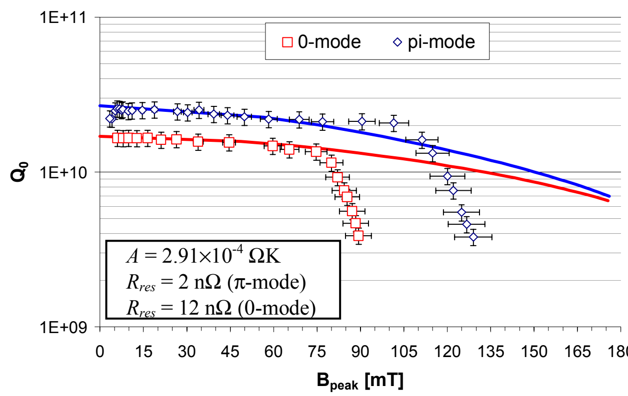

Figure 3: Q_0 vs. B_p data before baking compared with the thermal feedback model (solid lines).

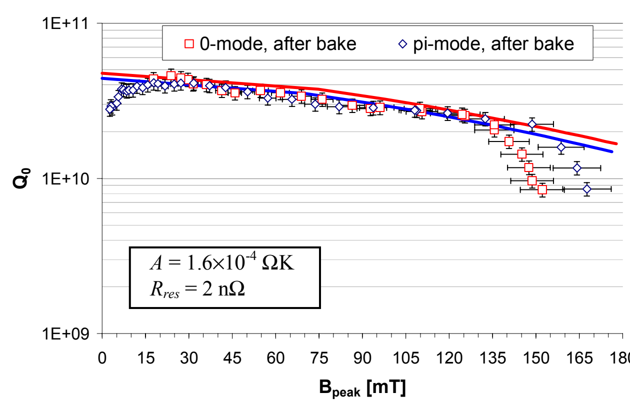

Figure 4: Q_0 vs. B_p data after baking compared with the thermal feedback model (solid lines).

The surface resistance vs. B_p dependence is well described by the model up to the onset of the high field *Q*-drop.

Nb/Cu CAVITY FABRICATION AND PRELIMINARY TEST RESULT

In order to eliminate the contribution to the *Q*-drop from electron beam welds (EBW) at high rf fields, three seamless cavities of the two-cell's shape were fabricated at DESY. A niobium cylinder about 1 mm thick was

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explosively bonded to a copper tube, 3 mm thick. The cavities were made by hydroforming the Nb/Cu tube [13]. Niobium beam pipes needed to be welded at the ends of the cavity and in the first attempt, the welds in all three cavities were not leak tight. It was found that copper contaminated the welds. One cavity was repaired by cutting the weld, machining the copper about half inch back from the weld area and re-welding the beam pipe through two adapting rings. A schematic of the cavity/beam pipe transition is shown in Fig. 5 and a picture of the cavity is shown in Fig. 6.

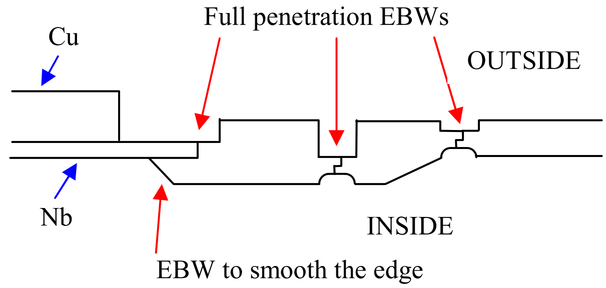

Figure 5: Schematic of adaptive rings used to join the cavity to the niobium beam pipes.

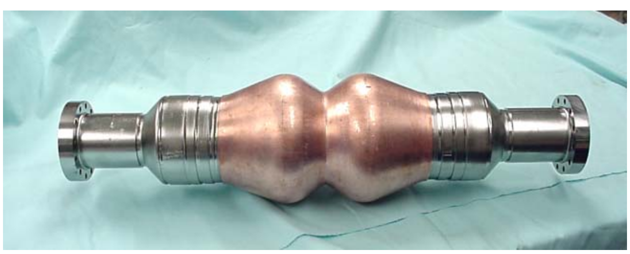

Figure 6: Picture of the completed Nb/Cu cavity.

The cavity was treated with BCP 1:1:2, removing about 100 µm of niobium from the inner surface, and high pressure rinsed for 3 h. Upon drying overnight in a class 10 clean room, niobium flanges with pump-out port and coupling antennas were assembled to the cavity and sealed with $AlMg_3$ gaskets.

The result of the first test at 2 K showed a strong multipacting at all field levels, and a strong *Q*-slope starting at about B_p = 15 mT (Q = 1.2×10^{10}) and up to 50 mT (Q = 1×10^9) in both modes. Although multipacting was encountered in the tests of the bulk niobium cavity, it was quickly overcome by rf processing.

The degradation of the quality factor at low field was previously observed in seamless cavities [14] and was moved to progressively higher levels by successive chemical treatments. A damaged layer of niobium, obtained as a result of the forming process, is suspected as the cause for the additional losses.

The presence of steps in the beam pipe region, as shown in Fig. 6, needs to be evaluated with respect of the strong multipacting observed experimentally.

SUMMARY

A two-cell cavity designed to investigate the role of electric and magnetic field losses at high rf fields achieved a peak surface magnetic field of 167 mT after post-purification (the critical field for niobium is about 190 mT at 2 K). It also provided evidence for the *Q*-drop as being caused by an intense magnetic, rather than electric field, and not by a “global” heating of the rf surface. Tests of a Nb/Cu seamless cavity, built to evaluate the influence of the welds on the *Q*-drop, are underway.

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REFERENCES

[1] J. Halbritter *et al.* IEEE Trans. Appl. Supercond. 11 (2001) 1864.
[2] J. Knobloch *et al.*, “High Field Q Slope in Superconducting Cavities due to Magnetic Field Enhancement at Grain Boundaries”, Proc. 9h RF Supercond. Workshop, Santa Fe, USA, 1999, p. 77.
[3] R. L. Geng *et al.*, “Micro-Structures of RF Surfaces in the Electron-Beam-Weld Regions of Niobium”, (Ref. [2]), p. 238.
[4] A. Brinkmann *et al.*, “Performance Degradation in Several TESLA 9-Cell Cavities Due to Weld Imperfections”, Proc. 8th Supercond. Workshop, Abano Terme, Italy, 1997, p. 452.
[5] G. Ciovati *et al.*, “Preliminary Studies of Electric and Magnetic Field Effects in Superconducting Niobium Cavities”, PAC’03, Portland, OG, May 2003, p. 1374.
[6] H. Safa *et al.*, “Nb Purification by Ti Gettering”, Proc. of the 7th Supercond. Workshop, Gif sur Yvette, France, 1995, p. 649.
[7] G. Ciovati, J. Appl. Phys. 96 (2004) 1591.
[8] G. Ciovati and P. Kneisel, “Measurements of the High Field Q-Drop in TE_{011}/TM_{010} Mode in a Single Cell Cavity”, Proc. Workshop on Pushing the Limits of RF Supercond., Argonne, IL, September 2004, p. 74.
[9] A. Gurevich, “Thermal RF Breakdown of Superconducting Niobium Cavities”, (Ref. [8]), p. 17.
[10] H. Padamsee, J. Knobloch and T. Hays, “RF Superconductivity for Accelerators” (Wiley&Sons, New York, 1998).
[11] P. Bauer *et al.*, FNAL Technical Report TD-05-020 (2005).
[12] J. Amrit *et al.*, Cryogenics 47 (2002) 499.
[13] W. Singer *et al.*, “Hydroforming of Superconducting TESLA Cavities”, Proc. 10th RF Supercond. Workshop, Tsukuba, Japan, 2001, p.170.
[14] P. Kneisel and V. Palmieri, “Development of Seamless Niobium Cavities for Accelerator Applications”, PAC’99, March 1999, p. 943.