EFFECT OF MILD BAKING ON HIGH FIELD Q-DROP OF BCP CAVITY

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Abstract

Previous measurements have shown that mild baking has a significant effect on the high field Q-drop of electropolished cavities. But for BCP (112) cavities, the improvement is not as substantial. Recently we tested a RRR = 500 cavity without high temperature (1350° C) titanium purification, nor 800° C baking. As a result we have a small grain size very high RRR cavity. To our surprise a mild baking (110° C, 48 hours) increased the onset field of the Q-slope by 40%. At 10^{10}Q the field increased from Eacc = 18 to Eacc = 27 MV/m. At a Q = $2{\cdot}10^9$ the field improved from Eacc = 24 to 32 MV/m. A light BCP re-established the stronger Q-slope. A second baking at 140° C had little effect on the Q-slope. Results from other cavities show Q-slope degradation for higher temperature bakes. All tests are accompanied by temperature mapping which show interesting features.

INTRODUCTION

Current technology of cavity preparation enables to avoid various defects that limited cavity performance in the past. With proper chemical etching, high pressure rinsing and assembling in the clean room it is possible to avoid defects and field emission sites in the cavity. Even so, Q's drop sharply at fields about twice as low as the theoretical limit for niobium. Usually at high field, the Q of the cavity drops without any X-rays. The key to the future increase of cavity performance is in understanding the strong high field Q drop.

Previous measurements showed that mild baking had a strong effect on the high field Q drop of electro polished cavities[1-2]. For BCP cavities the improvement due to baking is less[3]. Using the existing thermometry system in our lab it is possible to recognize a cavity without field emission sites and major defects[4]. Then we can study the effect of mild baking on the cavity performance for different baking temperatures.

EXPERIMENT

For this experiment we chose a high RRR (residual resistance ratio) cavity. The cavity was fabricated in Russia. The cavity has RRR about 500 without purifying hence a small grain size. We finally made standard BCP ($HF : HNO_3 : H_3PO_4$ = 1:1:2) etching for about 100 μm at temperature less than 20° C to avoid Q disease. The following is the treatment and test history:

- The cavity was rinsed with high purity de-ionized water under about 100 bar pressure to remove possible dust from inner surface of the cavity.
- It was assembled to the 1.5 Ghz test stand in the class 100 clean room to avoid dust contamination.
- The cavity was tested at bath temperature about 1.6° K.
- The cavity was baked at 110° C for 48 hours.
- The cavity was tested at bath temperature about 1.6° K.
- The cavity was tested at several different bath temperatures up to 2.1° K.
- The cavity was removed from the test stand and it was etched for about 20 μm at temperature less than 20° C.
- It was rinsed and assembled to the test stand in the class 100 clean room.
- The cavity was tested at bath temperature about 1.6° K.
- The cavity was baked at 140° C for 48 hours.
- The cavity was tested at bath temperature about 1.6° K.

For all tests the cavity was fast cooled to LHe temperature in a couple of hours.

RESULTS

The first time we tested the cavity it had a good performance for BCP cavity, reaching almost 50 MV/m peak surface field. At low fields the Q was about $1.8{\cdot}10^{10}$ at Epk = 4 MV/m and it decreases slowly to $1.0{\cdot}10^{10}$ at Epk = 40 MV/m. We call this change the medium Q slope. At higher fields the Q of the cavity rapidly dropped to $2.0{\cdot}10^9$ at Epk = 48 MV/m. The cavity did not quench and we were restricted by the lack of power(see Fig.1). There were no X-rays. As it was revealed with thermometry there were no field emission or defect sites in the cavity. Even so there were four distinguishable hot spots, the heating happened over a large regions of the surface in the high magnetic field regions(see Fig.2). Thermometry data showed that for low fields the power dissipated was almost quadratic with field. At some field, which was almost the same for all thermometers in high magnetic field region, there was a switch to stronger slope(see Fig.3). Q data also showed that some switch in Nb surface resistance took place at high field.

Then we baked this cavity at about 110° C. The baking was not uniform and there was temperature distribution in the vertical direction along the cavity surface. After 110° C baking the cavity performance improved significantly. The peak electric field reached almost 65 MV/m (see Fig.1).

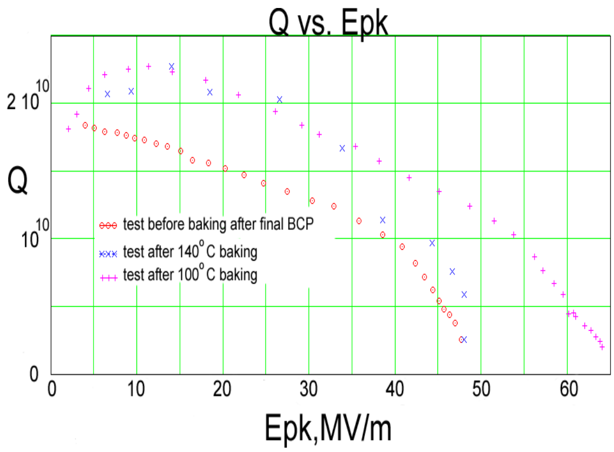

Figure 1: Q versus peak electric field results showing the medium Q-slope and strong Q-slope regions.

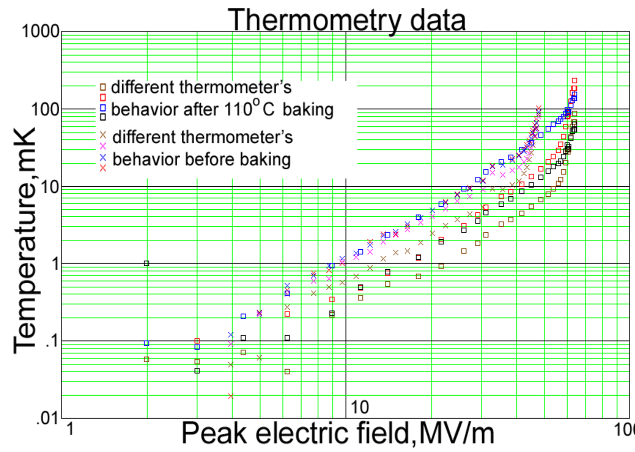

Figure 3: Thermometers data.

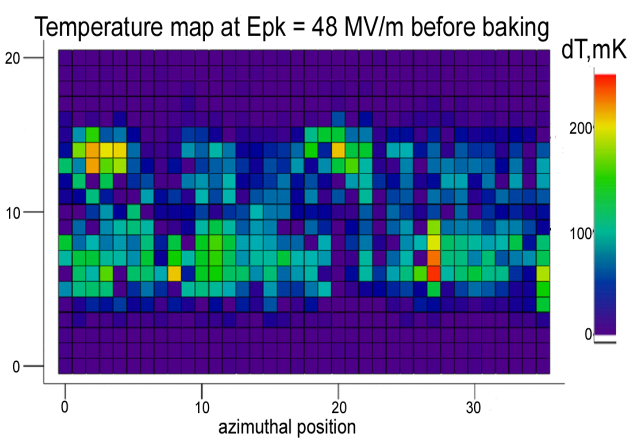

Figure 2: Thermometry map before baking.

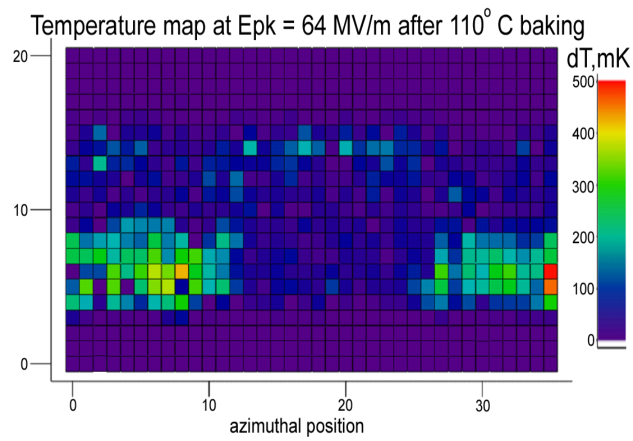

Figure 4: Thermometry map after 110° C baking.

The low field Q was about $2.3{\cdot}10^{10}$ at Epk = 10 MV/m and it decreases slowly to $1.0{\cdot}10^{10}$ at Epk = 54 MV/m. Above this field the Q of the cavity rapidly dropped to $2.0{\cdot}10^{9}$ at Epk = 64 MV/m. There was no quench and we were restricted by our power supply. But the cavity behavior was in some sense the same as it was before baking: there was steady drop of Q at medium fields, that means slightly non - quadratic RF losses in Nb surface and then switch to strongly non - quadratic RF losses at high fields. However the field at which the switch took place became higher after 110° C baking(see Fig.1). After 110° C baking the temperature map of the cavity wasn't as uniform as it was before baking: top of the cavity was less lossy than the bottom. This may be because of the non-uniform temperature distribution during baking(see Fig.4).

The thermometry data was also similar to that before baking - slightly non-quadratic losses at low field, then switch to strongly non-quadratic losses at some field which was almost the same for all thermometers(see Fig.3). After such a good result we made Q measurements of this cavity for the different LHe bath temperatures.

By varying He gas pumping speed in the cryostat we adjusted the temperature of LHe bath. At the average fields the Q of the cavity dropped with the LHe bath temperature in correspondence with BCS losses. But the Q was almost the same at high fields for different LHe bath temperatures that ranged from about 1.6° K to 2.1° K (see Fig.5). This result suggests strong magnetic field dependence of Nb surface resistance rather than temperature dependence at high fields. The experiment showed that all data points laid on two lines for different LHe bath temperatures. The jump from one line to another happened when the initial LHe bath temperature was about 1.8° K.

After additional BCP we baked the cavity at 140° C. We changed the baking procedure so that the baking temperature distribution was more uniform. The test showed that 140° C baking had minor(compared to 100° C baking) effect on the cavity behavior(see Fig.1). The low field Q was almost the same as after 100° C, but then a switch to stronger slope took place at Epk = 40 MV/m. The temperature map showed that heating wasn't as uniform as before, but took place over a large areas of high magnetic field region(see Fig.6). Previous experiments have shown

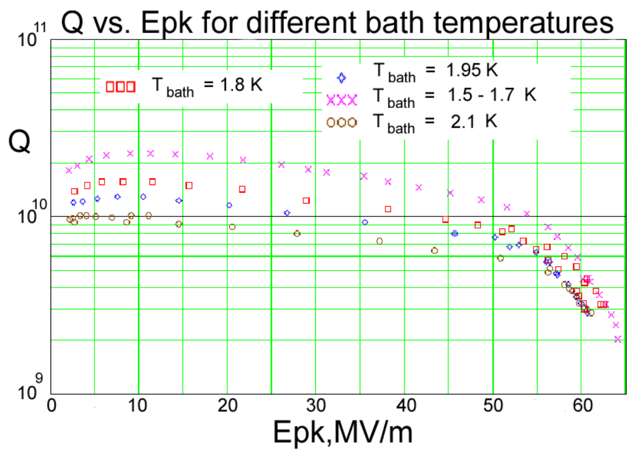

Figure 5: Test result for different LHe bath temperatures.

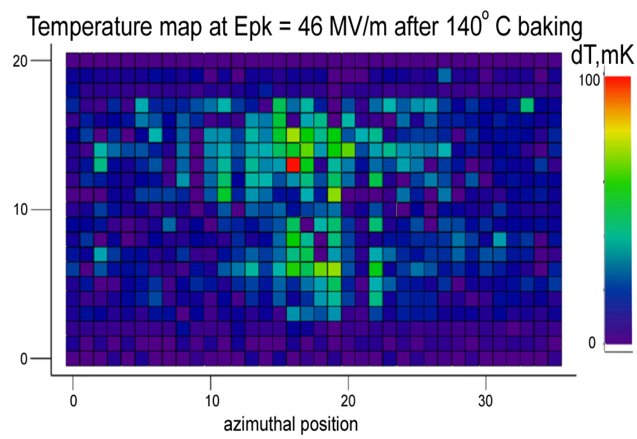

Figure 6: The temperature distribution at high fields after 140° C baking.

that baking at 140° C and higher temperatures leaves the Q-slope unchanged or makes the Q-slope stronger[5-6].

DISCUSSION

The high field Q-slope showed strong field and baking temperature dependence. To make some simple calculations of cavity performance we took BCS resistance as $R_0 + \frac{2\cdot 10^{-4}}{T}\cdot exp(\frac{-17.67\cdot K}{T})\cdot\Omega\cdot K$ [6]. We used the SLANS code to calculate field distribution along the inner surface of our cavity and the HEAT code (developed in our lab) to calculate temperature of the inner and outer surfaces of the cavity versus applied power. During this calculation we assumed the LHe bath temperature to be constant and used calculated thermal conductivity of our cavity(RRR = 500, grain size = 50 μm). The total power dissipation in the cavity and its distribution along the cavity surface gave us a new temperature of Nb surface which in turn yields a new surface resistance. After several iterations we derived the cavity behavior versus field. We didn't received neither "medium Q-slope" nor a switch to a strong high field Q-slope.

The strong Q-slope can be understood under certain assumptions about Nb surface resistance. 1) From the fact that heating happens over the large regions of surface one can conclude that the cavity performance was not governed by a localized defect but rather by the properties of the whole Nb surface. This is also supported by the absence of quench. 2) One possible important effect of mild baking is diffusing of oxygen from the Nb surface into the bulk. Another possible effect is modifying of the Nb oxide layer on the cavity inner surface. 3) After the switch both Q and thermometry data showed strong non - quadratic field losses at high fields, which means the field dependent surface resistance. This strong field dependence of the surface resistance was seen to be independent on LHe bath temperature. 4) Superconducting properties of Nb depend on the concentration of oxygen dissolved in the bulk. One possible conclusion that can be drawn from the strong Q-slope is that the magnetic field starts to penetrate into Nb surface at fields higher than Hc_1. This magnetic field in the Nb surface is a cause of additional RF losses. And the critical magnetic field depends on oxygen concentration, so that even relatively slight changes in oxygen concentration due to baking can cause changes in critical magnetic field[7]. Because of these two processes that happen in Nb surface of the cavity (diffusion of oxygen, which decreases oxygen concentration, and modification of Nb oxide, which increases oxygen concentration) the oxygen concentration depends on the baking temperature and so does Hc_1.

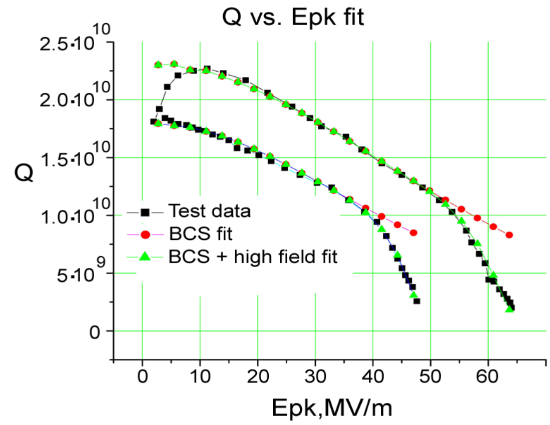

Figure 7: Calculated cavity performance based on temperature dependent BCS resistance. The black points are experimental data, the red points are fit for "medium Q-slope", the green points are fit for "medium Q-slope" and high field Q-slope.

Another possibility is a roughness of Nb surface[7]. If we have some distribution of field enhancement factor versus number of edges, so that for most edges of the cavity inner surface the field enchantment factor is β_0, then at field $\frac{Hcrit}{\beta_0}$ most edges go normal conducting, and this additional amount of normal conducting areas creates the switch to the high field Q slope.

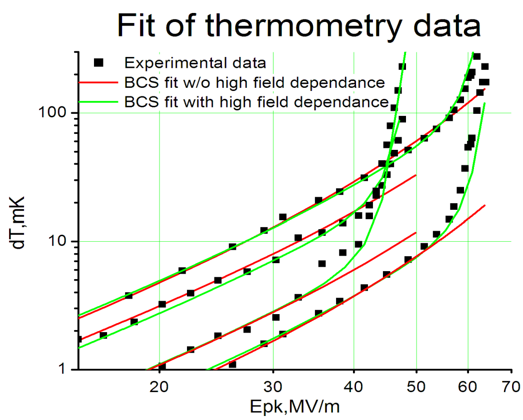

Figure 8: Fit of thermometry data before and after $110°$ C baking.

We tried to simulate cavity behavior by inserting field dependence into Nb resistance. To fit medium field Q drop we took $R_{residual} = R_0 \cdot (1+\alpha \cdot H^{2.2})$ and to fit high field Q drop we took $R_{BCS} = \frac{2 \cdot 10^{-4}}{T} \cdot exp[-\frac{\Delta_0}{T} \cdot [1 - \frac{(H-Hc_1)^2}{(Hc_2-Hc_1)^2}]]$ for H higher than Hc_1. The results showed that Q behavior as well as thermometry data can be approximated by such surface resistance field dependence with reasonable values of $Hc_1 \simeq$ 1000 Oe and $Hc_2 \simeq$ 2000 Oe(see Fig.7 and Fig.8).

CONCLUSION

This experiment shows the possibility to achieve 32 MV/m accelerating field gradient even for BCP cavities. The strong Q slope of this cavity seems to be caused by transition in niobium surface resistance at some field, which is dependent on the baking temperature. The $100°$ C baking increases the onset field. The $140°$ C baking has minor effect on this transition field.

ACKNOWLEDGMENT

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BIBLIOGRAPHY

[1]K.Saito et al., ”Superiority of electropolishing over chemical polishing on high gradients”, 8^{th} Workshop on RF Superconductivity, 1997.

[2]E.Kako et al., ”Improvement of cavity performance in the Cornell/Saclay/DESY’s sc cavities”, 9^{th} Workshop on RF Superconductivity,1999.

[3]B.Visentin at al., ”Cavity Baking: A cure for the high accelerator field Q drop”, 9^{th} Workshop on RF Superconductivity,1999.

[4]J.Knobloch, ”Advanced Thermometry Studies Of Superconducting RF cavities, PhD Thesis, Cornell University”, 1997, Laboratory Of Nuclear Studies thesis CLNS 97-3.

[5]H.Safa, ”High Gradients in SCRF Cavities”, C.E.Saclay, DSM/DAPNIA/SEA, 91191 Gif/Yvette, France.

[6]H.Padamsee,J.Knobloch, and T.Hays. ”RF Superconductivity for Accelerators ”, Wiley and Sons, New York, 1998.

[7]J.Knobloch,R.L.Geng,M.Liepe and H.Padamsee, ”High Field Q-slope in superconducting cavities due to magnetic field enhancement at grain boundaries”, 9^{th} Workshop on RF Superconductivity, (1999)77.