Losses in SRF Cavities

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Abstract

There is evidence that the rapid degradation of Q_0 observed at high fields in superconducting RF cavities can be assuaged by gently baking the cavity. Baking at 100–120 °C seems to be most beneficial, while 150 °C actually decreases the Q_0. Preliminary tests carried out here at Cornell indicate baking removes some of the lossey areas and leaves others unaffected [4]. Thermometry can monitor how individual areas of the cavity respond to baking at various temperatures. The cavity could be cut open and the inner surface examined to correlate attributes of its material with losses and responses to baking. The first cavity chosen for baking was found after baking at 100 °C to have developed a band of lossy material about the equator and was no longer useable. The replacement cavity prepared was also rendered unuseable by contamination.

Introduction

The primary application of RF cavities is in accelerators, where the alternations of the strong electric fields produced in the cavity are coordinated with the progress of the charged particles to give them a boost as they pass through. The average electric field experienced by a particle traveling through an RF cavity is called the accelerating field, E_{acc}. The maximum electric field in the cavity is called the peak field, E_{pk}. The two fields are proportional, with the constant depending on the physical attributes of the cavity[2]. For this paper, it is sufficient to assume

$$\frac{E_{pk}}{E_{acc}} = 2 \tag{1}$$

The benefit of using superconducting RF cavities over copper cavities is the relatively small amount of power dissipated in the cavity wall. This decreases the power necessary to create a given electric field and minimizes heating. A convenient way of expressing the losses of the whole cavity is with the quality factor, Q_0, which is defined as

$$Q_0 = \frac{\omega U}{P_d} \tag{2}$$

where ω is the angular frequency, U is the energy stored in the cavity, and P_d is the power dissipated in the cavity wall[1]. A high Q_0 ($\sim 10^{10}$) can be obtained by using high-purity niobium, etching the cavity in a buffered chemical bath, rinsing it with high-pressure (1000psi) distilled water, and carefully mounting it in a clean room. Even with clean, pure niobium, the cavities show rapid Q_0 degradation at high fields. Gently baking the cavity at ~ 100 °C has been known to improve the Q_0 at high fields, as shown in Fig. 1 [3].

Studying Losses

The quality factor measures the losses of the whole cavity, but the data that can be gleaned from it is limited. Cornell uses a temperature mapping system consisting of 756

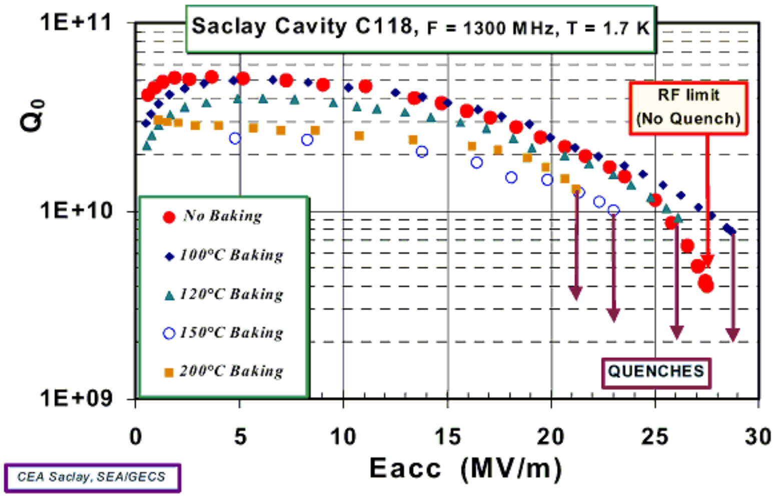

FIGURE 1. Q vs E curves for a cavity baked at various temperatures [3]

resistors in thermal contact with the cavity to monitor losses locally, that is, show where and at what field the losses are ocurring.

When studying loss mechanisms, it is useful to know the relationship between the losses and the electric field. This can be found by plotting, for each resistor individually, $log\Delta T$ vs $logE_{pk}$. The slope of a line fitted to the data points is then the exponent in the relationship, that is, n in $T \propto E^n$. There is always some rf resistance in the cavity. When a direct current is applied to a superconductor, the paired electrons, which move without generating losses, carry the current and shield the unpaired electrons from the electric field. An RF cavity uses an alternating current, which means forces must be present to change the direction of motion of the electrons. These forces act on the unpaired electrons, which are always present for $T > 0$K, causing them to move, which generates losses. The power dissipated is proportional to the internal electric field and the current, which is itself proportional to the electric field[2]. For ordinary losses in a cavity, therefore, the slope as defined above is equal to two. An example of ordinary losses is shown in Fig. 2.

Notice that, at high fields, the slope changes dramatically. This is an example of the anomalous losses occurring at high fields that we hoped to decrease by baking the cavity.

Baking and Testing the Cavity

When testing a cavity, the cavity is installed on a test rack. A copper antenna coupled to the cavity at the bottom inputs the RF signal, automatically adjusted to remain at the resonant frequency. A small antenna at the other end of the cavity picks up the power transmitted through the cavity which is key to calculating the field in the cavity. The inside of the cavity is kept under a high vacuum. For the test proper, the cavity and the test rack are inserted into a cryogenics pit. Liquid Helium is used to cool the pit initially, then pumped down through the superfluid stage so that the tests can be conducted at 2 K.

For this test, a 1.5 GHz bulk niobium cavity, LE1-31 by name, was chosen. Its last test had shown it to have an average Q_0 of 1.4 10^{10} at low $E_{\rm acc}$ fields (see Fig. 3). The cavity

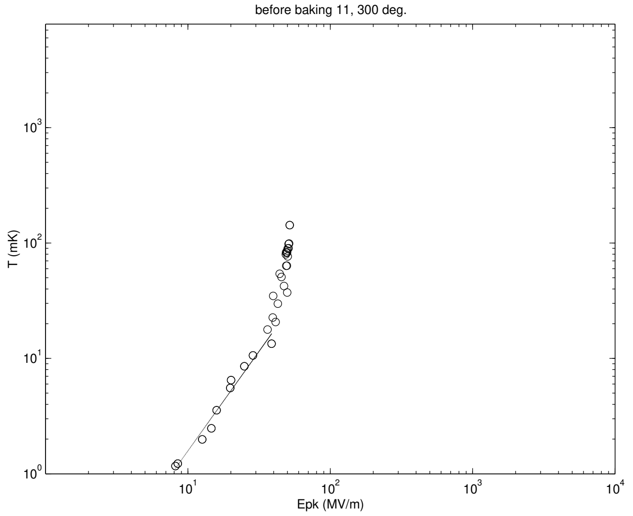

FIGURE 2. The relative temperature vs. the E_{pk} field for a resistor on the equator of LE1-31. The line fitted to the lower part of the plot has a slope of 2.

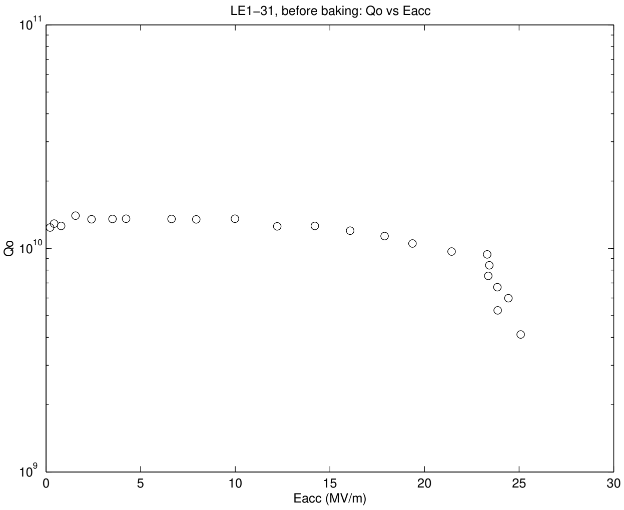

FIGURE 3. A Q_0 vs E plot for LE1-31. Notice the sharp Q-slope at high fields.

showed anomalous losses starting at a peak field of about 44 MV/m. As the temperature map in Fig. 4 shows, the losses occurred throughout the region that attained high magnetic fields.

The cavity was wrapped in heat tape and baked for 50 hours with a temperature between 95 ° and 105 °C. The pressure was closely monitored, as were the temperatures of the flanges to make sure the integrity of the seals was not compromised. The bake was completed satisfactorily and the cavity tested again. The Q_0 at low fields was now found to be 1.6 10^{10}, but at higher fields the Q_0 degredation was even more rapid than before the bake (see Fig. 5). The temperature map in Fig. 6 shows that a band of very lossy material had developed along the equator. Fig. 7 is of a typical resistor on the equator. Note that even at low fields, the slope is greater than 2. This indicates contamination of the niobium at that point. The most likely culprit is hydrogen [1].

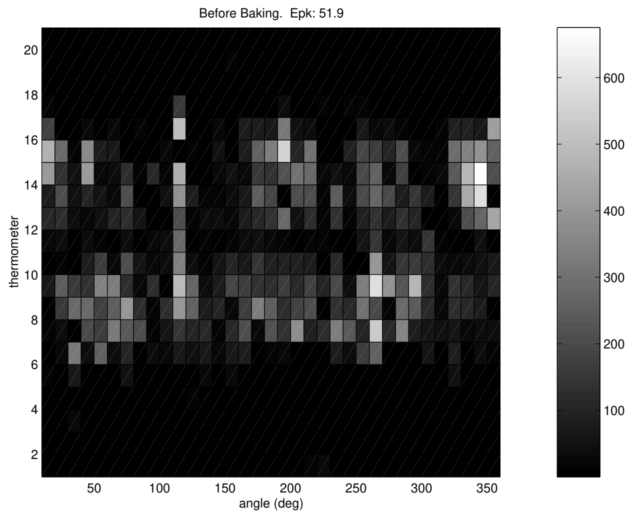

FIGURE 4. A temperature map of cavity LE1-31. The shading shows the change in temperature in milliKelvin.

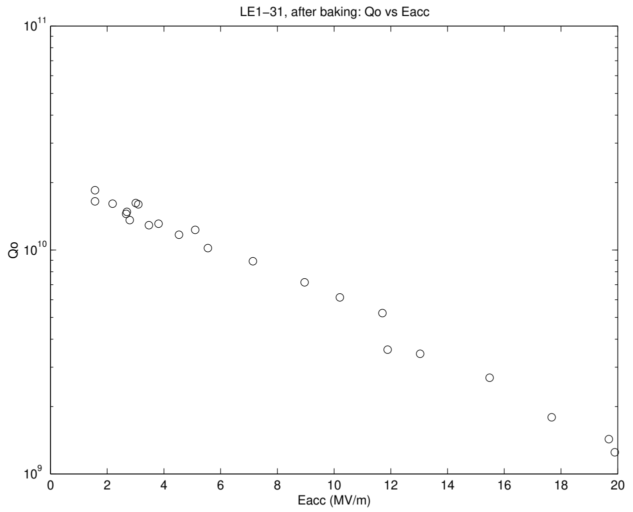

FIGURE 5. A Q_0 vs E plot for LE1-31. The sharp break at $\sim$ 12 MV/m is a result of increasing the coupling strength.

There is always some hydrogen present in the niobium. The bulk of it, however, is acquired during chemical etching when the cavity is treated with acid. In the case of LE1-31, hydrogen from the etching process could have become trapped in the grain boundaries along the weld. The baking process would have encouraged it to diffuse into the bulk of the niobium, where it could form niobium hydride precipitates as the cavity cooled. These precipitates cause a large residual surface resistance. No conclusions about the affects of baking the cavity can be made in areas contaminated with hydrogen[2].

Examining the relationship between the E fields and losses for the second test shows the location of the contamination. After cutting out the noisiest signals and the broken resistors, the average slope along the equator (that is, the middle four rows of resistors) of LE1-31 after baking is $4.02 \pm .04$. The average slope off the equator is $2.12 \pm .13$. The contamination is restricted to the equator. Fig. 8 gives the uncut data. The large amount of noise in

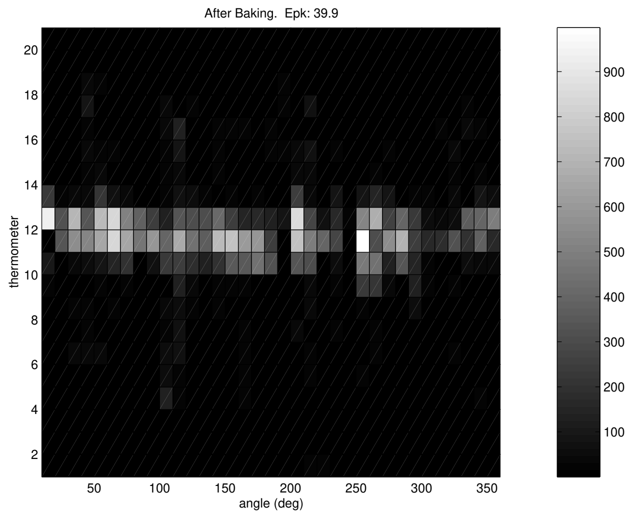

FIGURE 6. A temperature map of cavity LE1-31. The shading shows the change in temperature in milliKelvin.

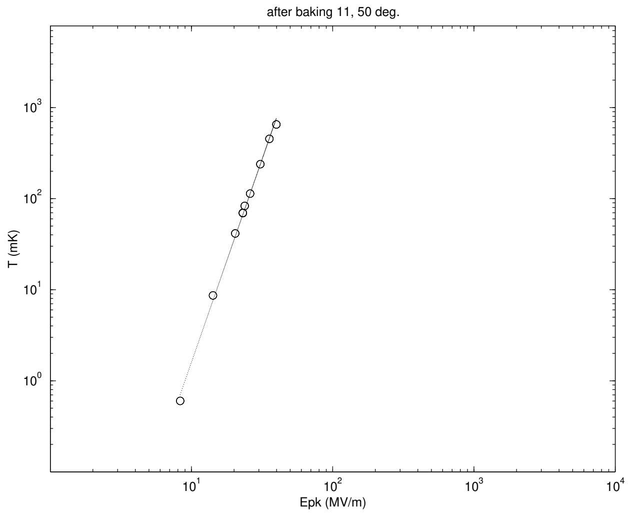

FIGURE 7. The relative temperature vs. the E_{pk} field for a resistor on the equator during the second test. The line fitted to the plot has a slope of about 4.5.

the first part of the plot is probably due to the inclusion of the resistors near the flanges, which experienced so little heating that their readings are just noise. Since the larger part of the cavity is uncontaminated, it would be possible to study the effects of baking on the uncontaminated part. However, the anomalous losses to be studied began at an E_{pk} field of 44 MV/m. The top E_{pk} field from the second test was 39.9 MV/m. This cavity could not show how baking could decrease losses.

2-17-M16/2-18-F16

A new cavity, 2-17-M16/2-18-F16, to be referred to as 2000C, was chosen. In 1987, the cavity was baked for two hours at 2000 °C, as a result of which it had very large grains all over. It was later baked for 10 hours with titanium getter. After sitting in the clean room for

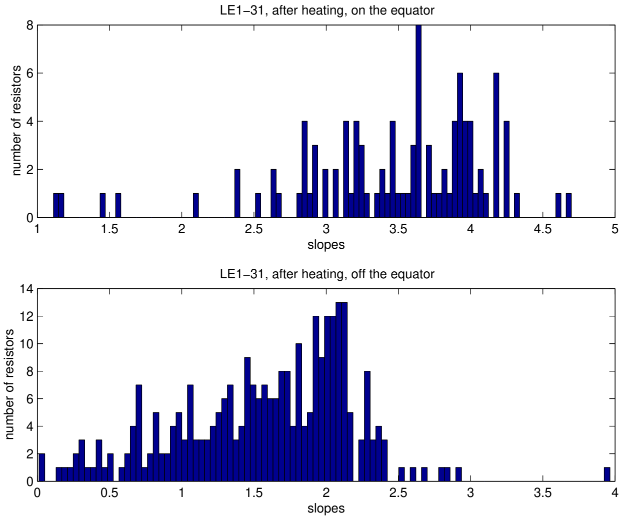

FIGURE 8. The exponential relationship between the losses and the E field in LE1-31

15 years, it was cleaned according to the standard procedure: etched in chilled acid, rinsed with high-pressure distilled water, and inserted into the test stand in a class 100 clean room.

When tested, the cavity showed a remarkably high Q_0 at low fields, i.e., 6.5 10^{10}. Using an alternate definition of Q_0

$$Q_0 = \frac{G}{R_s} \tag{3}$$

where G, the geometry constant, depends only on the cavity's shape and is here 257Ω and R_s is the surface resistance. The test pit is shielded from the earth's magnetic field, but not perfectly: the field inside the shielding is about 30 mOe. The resistance due to an external magnetic field is

$$R_{mag} = .3(\mathrm{n}\Omega)\sqrt{f}(\mathrm{GHz})H_{ext}(\mathrm{mOe}) \tag{4}$$

Substituting in H_{ext} = 30 mOe, we find R_{mag} = 11nΩ. Using this for R_s yeilds a Q_0 of 2.3 10^{10}, considerably lower than the Q_0 observed in 2000C. If the contamination is due to titanium, magnetic flux pinning by the titanium-niobium alloy could account for the high Q_0. The Q_0 decreased *exponentially* as the field increased (see Fig. 9). The temperature map shown in Fig. 10 reveals heating across essentially the entire surface of the cavity. Considering the cavity's history, titanium in the grain boundaries may be to blame. In any case, it is contaminated (see Fig. 11) and the contamination is widespread (see Fig. 12). This cavity cannot be used to test the effects of baking.

Conclusions

The Q_0 of LE1-31 showed additional degredation, even at low fields, after baking, probably due to hydrogen contamination (see Fig. 13). The effects of baking on the anomalous losses at high fields could not be determined. The second cavity (see Fig. 9) showed general contamination, possibly titanium. Of interest is the Q_0 at low fields, which actually increased

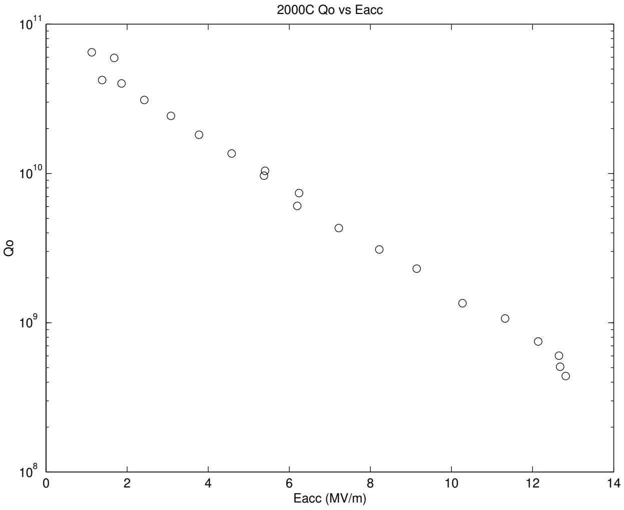

FIGURE 9. A Q vs E slope for 2000C. The breaks in the straight line of the plot are where the coupling strength was changed.

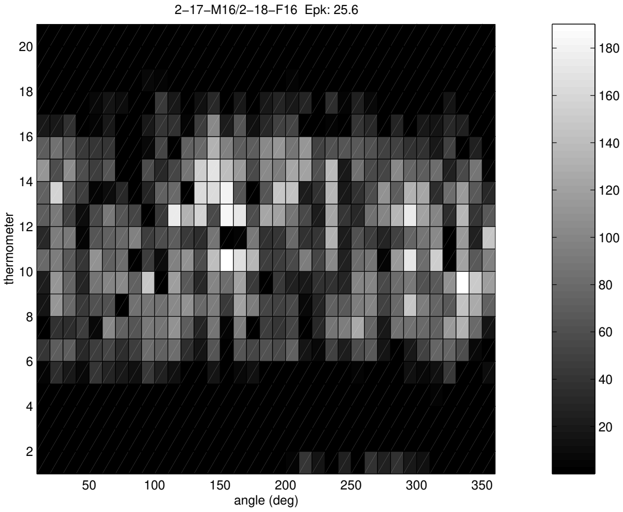

FIGURE 10. A temperature map of cavity 2-17-M16/2-18-F16. The shading shows the change in temperature in milliKelvin

with the contamination. This cavity was not suitable for testing the effects of baking.

Acknowledgments

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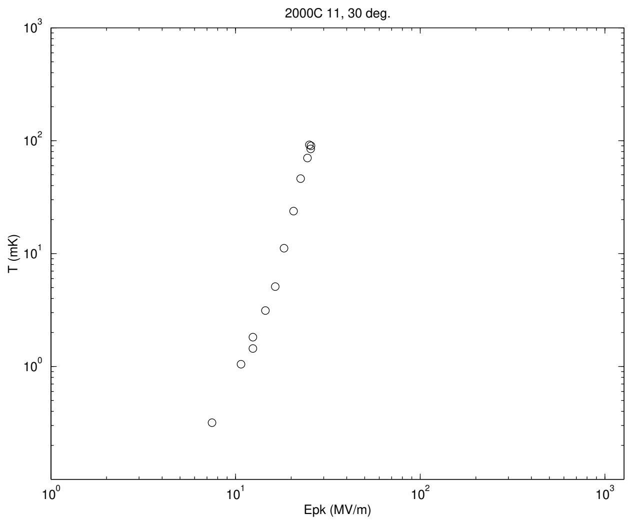

FIGURE 11. The relative temperature vs. the E_{pk} field for a resistor during the third test. The slope even at low fields is greater than 3.

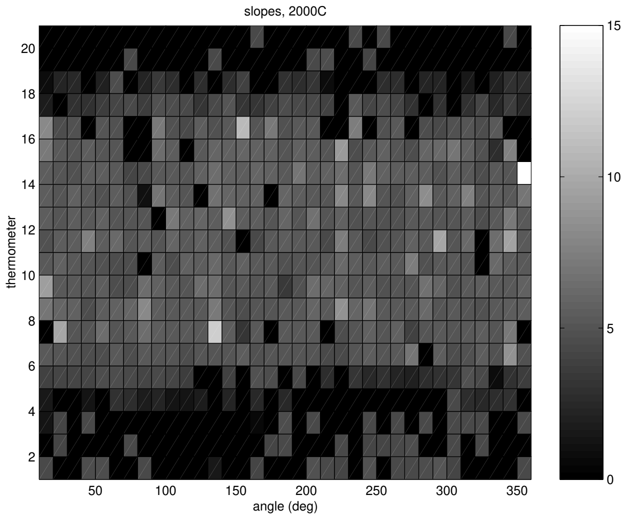

FIGURE 12. Uncut data from the third test. The shading is the exponential index of the temperature vs. E_{pk} plot for each resistor

Footnotes and References

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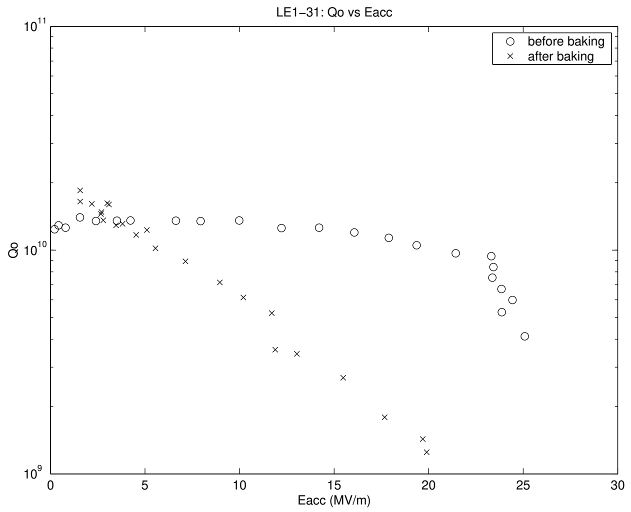
LE1−31: Qo vs Eacc
before baking
after baking
Qo
10^{11}
10^{10}
10^{9}
0
5
10
15
20
25
30
Eacc (MV/m)

FIGURE 13.