

Reduction of the surface resistance in superconducting cavities due to gas discharge *

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Abstract

Thermometric studies of the surface resistance of superconducting niobium cavities have revealed that the residual resistance can be reduced by ion and/or electron bombardment of the rf surface. We have demonstrated that the surface resistance of cavities can be increased by intentionally adsorbing gases on the rf surface. Subsequently the original low resistance state was recovered following what appears to be a gas discharge event. Frequently, we also observed a local reduction of the surface resistance following thermal breakdown events or multipacting, even if the cavity had not been previously contaminated with gas. In these cases, too, we suspect that gas discharge is responsible for the improvements.

1 Introduction

Measurements on niobium show that the radiofrequency (rf) surface resistance (R_s) can be well approximated by

$$R_s = A_s \frac{\omega^2}{T} \exp\left(-\frac{T}{T_c}\right) + R_0 = R_{\text{BCS}}(T) + R_0. \quad (1)$$

Here A_s and ω are material dependent constants and ω is the rf frequency.

The first term (R_{BCS}) is known as the BCS resistance, which is well understood from the theory of superconductivity. [1] It is related to the number of unpaired electrons that remain below the critical temperature, and it drops exponentially with decreasing temperature. [2]

At sufficiently low temperatures, R_{BCS} becomes insignificant and the second term, the temperature independent residual resistance, dominates. For this reason, it is of practical importance that an understanding of R_0 be gained. The residual resistance cannot be explained by the theory of superconductivity. However, it has been established that it is affected by, for example, impurities, trapped flux, adsorbed gases, and microscopic particles. [2, 3] Well prepared niobium has a residual resistance of about 5 n Ω .

Recently, a high-speed, high-sensitivity thermometry system was developed to study 1.5-GHz niobium cavities. [3, 4] One of the system's strengths lies in the fact that it is able to measure changes in the surface resistance down to a few nanohms, close to typical values of R_0 .

Experiments with this system were performed at 1.6 K, where $R_{\text{BCS}} < R_0$. They have revealed that the low field surface resistance can change locally during the course of a cavity test. Both increases [3, 5] and reductions were observed. In this paper, we report on reductions observed following short-term breakdown events. We believe, that these reductions are due to gas discharge events triggered by multipacting or field emission electrons. The bombardment of the rf surface by electrons and ions from this discharge then removes surface contaminants and adsorbates, resulting in an improved surface resistance. One experiment, in particular, demonstrated that gases, which had been adsorbed intentionally on the rf surface, could be removed by a discharge event.

2 Experimental setup

The experimental setup to study 1.5-GHz (L-band) cavities has been described in a number of papers [3, 4, 6] and will not be repeated here in detail. The main diagnostic tool is a fixed-array thermometry system comprising 756 thermometers attached to the cavity exterior. The array is capable of mapping the cavity temperature

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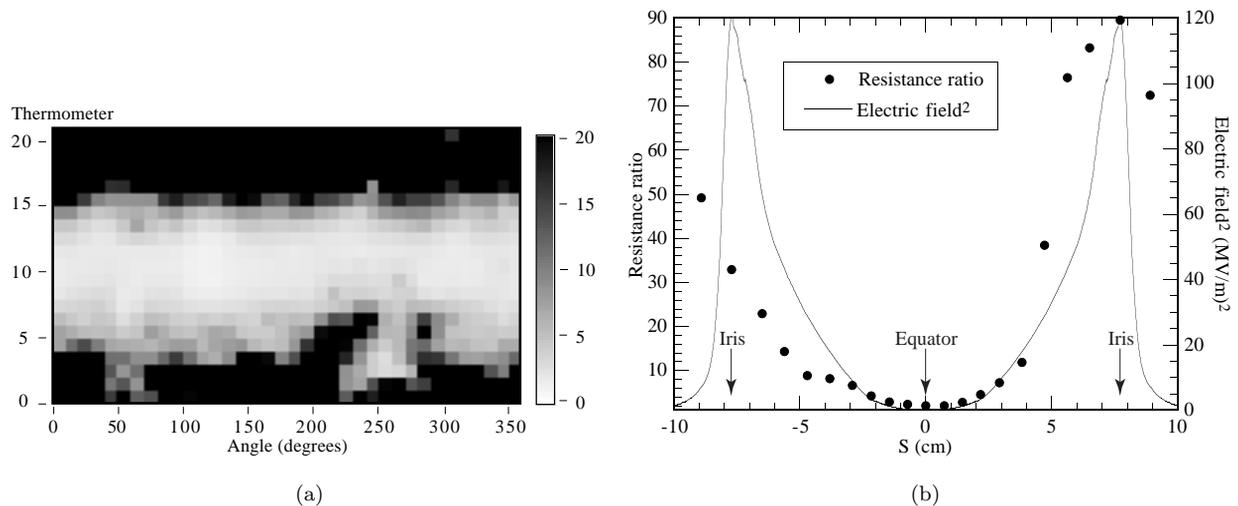


Figure 1: Ratio of the surface resistance at 11 MV/m after and before several torr of helium were administered to cavity LE1-31. (a) Ratio map of the entire cavity. The lower and upper iris are at thermometer 1 and 19, respectively, while the equator is at thermometer 10. (b) Same data as in (a) but summed over all thermometer boards at each latitude (constant latitude is equivalent to constant thermometer number). The square of the surface electric field is included to illustrate that the losses are mainly dielectric in nature.

distribution in superfluid helium at 1.6 K. Especially important to the study of residual loss mechanisms in cavities is the system's high resolution (as good as $30 \mu\text{K}$), allowing us to witness R_s changes on the nanohm scale. An automated Q_0 versus E_{pk}^1 measurement system operates in conjunction with the thermometry system, to provide information on the integrated cavity losses.

Single-cell cavities of the CEBAF shape [7] were made with $\text{RRR} = 250$ niobium. The cavity preparation prior to testing consisted of a standard chemical treatment [3, 8] (one hour in nitric acid to remove any remaining indium and then about five minutes in buffered chemical polish (BCP 1:1:2)). A rinse with deionized water for one hour followed the chemical etch, before drying the cavity with hot, filtered nitrogen gas and mounting the cavity on the test stand.

3 Removal of intentionally adsorbed gases

In one experiment we demonstrated the ability of a discharge to remove adsorbates by using the following procedure: First we adsorbed gases on the cold rf surface by letting several torr of filtered helium gas rush into the cavity while (at 1.6 K). The test stand was then evacuated again to less than 10^{-4} torr. Temperature data taken before and after this procedure was used to extract a surface resistance map of the cavity. A convenient way of comparing the two data sets, is to take the ratio. An example is shown in Figure 1(a). It confirms that the surface resistance had increased substantially following the admission of helium gas. Correspondingly, the measured Q_0 also dropped by a factor of 10 (from $\approx 3 \times 10^{10}$ to 3×10^9).

Most increases were observed in the high electric field regions of the cavity (near the irises), so they are likely to be dielectric in nature. Figure 1(b) shows that the increased losses roughly follow the square of the electric field. The quadratic nature of these losses was also demonstrated by a field independent Q_0 . We suspect that the losses are caused primarily by impurity gases in the helium rather than the helium itself, because no R_s changes were observed when helium was administered very slowly, giving the impurity gases a chance to condense before they ever reach the cold cavity. A thermal cycle with another cavity treated in the same manner reduced this type of losses back to original levels, thereby proving that the increases are *not* due to particles.

At higher electric field emission activity, characterized by a line of heat at constant azimuth [2, 3, 6], was detected at 190° (Figure 2(a)). Then, at $E_{\text{pk}} = 25.3 \text{ MV/m}$, the fields in the cavity suddenly collapsed. Low field ($\approx 10 \text{ MV/m}$) surface resistance data taken immediately after the breakdown demonstrated that a large area of the cavity near the azimuth of the field emitter had reduced its surface resistance (Figure 2(b)).

¹ E_{pk} is the peak electric field.

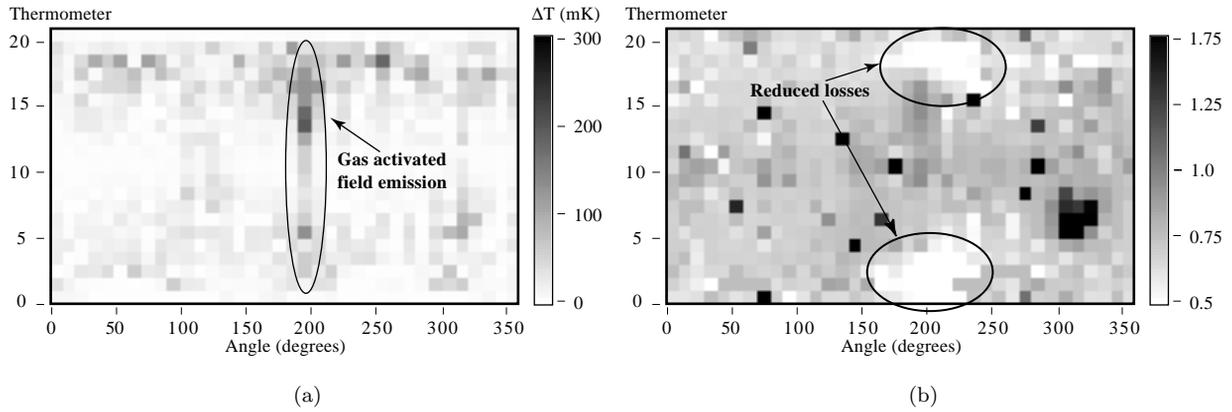


Figure 2: Temperature map of cavity LE1-31 at 25 MV/m showing weak field emission activity after several torr of helium gas were administered to the cavity. (b) Ratio of the surface resistance after and before a discharge event at 25.3 MV/m. (Ratio taken at $E_{pk} = 8$ MV/m.)

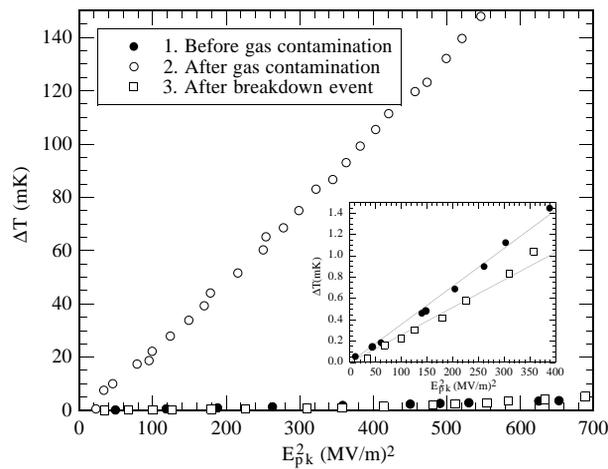


Figure 3: Temperature data recorded by resistor 18 at 220° before and after cavity LE1-31 was “contaminated” with helium. Following a breakdown event, the temperature signals reduced to below pre-helium levels (see inset).

In most places, the surface resistance reduced to levels between those measured before the helium was administered and those measured just before the collapse of the fields. In some cases, though, the surface resistance reduced to values lower than those achieved at any time previously in the cavity test (see Figure 3).

It is likely that we witnessed a discharge fueled by helium remaining in the cavity and/or gases desorbing from the rf surface by field emission electron bombardment. It appears that the field emitter was directly responsible for initiating the discharge. In particular, we see, that a discharge is very effective at removing lossy surface adsorbates, even those that were not artificially introduced.

4 Removal of naturally occurring adsorbates

Although in the previous example mostly intentionally introduced adsorbates were removed by a discharge, we also observed the removal of naturally occurring adsorbates, albeit on a more limited scale. In these cases, discharge was either initiated during multipacting activity or during thermal breakdown. The following are examples of such events.

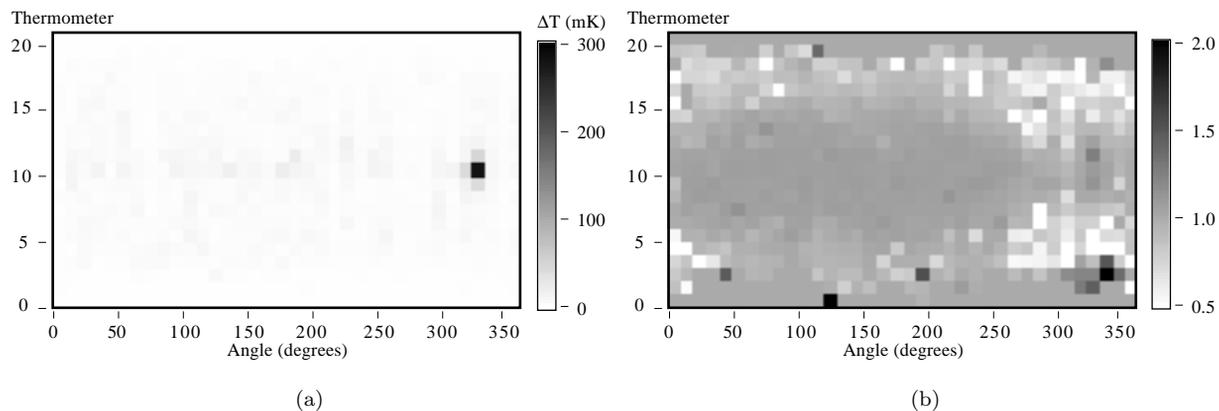


Figure 4: (a) Temperature map of cavity LE1-23 at $E_{pk} = 26.5$ MV/m before any breakdown events. A hot defect is observed on the equator at 320° . (b) Surface resistance ratio map at 30 MV/m after and before a single breakdown event at 30 MV/m. Light areas indicate reductions in R_s .

4.1 Multipacting induced discharge

Our thermometric studies have revealed the presence of short-lived two-point multipacting along the cavity equator, starting at 30 MV/m. [3, 7] Simulations confirm the multipacting, and demonstrate that intense electron bombardment occurs with less than a millimeter of the equator, leading to a quench. In several cases these events are also associated with the creation and trapping of magnetic flux along the cavity equator. Consequently an increased residual resistance is observed in this region. [5] However, in many instances local reductions of the surfaces resistance were also observed.

A striking example is the following cavity, named LE1-23: It had a hot magnetic² defect on the equator at 320° (Figure 4(a)). Even at $E_{pk} = 30$ MV/m x rays were not detected outside the cryostat, indicating that no field emission was active. At this field the cavity quenched once, and large areas at intermediate latitudes, centered in azimuth on the hotspot, reduced their surface resistance by as much as a factor of 1/8 (see Figure 4(b)). At the same time, a short burst of x rays was recorded, indicating that electronic activity took place in the cavity. On average, the affected region reduced its surface resistance from 17 n Ω to 12 n Ω .

This event is reminiscent of the one described in the previous section. Since the breakdown occurred at 30 MV/m (the onset field for multipacting) we assume that it is also multipacting related. At a slightly higher field (31 MV/m), another breakdown event was recorded, and R_s increases as well as reductions were observed between 230° and 50° along the cavity equator, confirming that multipacting was indeed active (see References [3, 7] for more details). Thermal cycling to room temperature restored all the original losses.

If the low loss regions, centered (in azimuth) on the equator defect, were created by ion bombardment during gas discharge, one possible mechanism is that gases evolving from the hot defect were ionized by a short burst of multipacting current. [9] The newly created ions and electrons subsequently spread and impacted the cavity wall, desorbing further gases and reducing the surface resistance. The thermal cycle to room temperature then redistributes the gases in the cavity and restores the original surface resistance.

More common in our cavities were multipacting related quenches that led to increased losses along the equator, this being due to flux trapping. [3, 5] However in a few places along the equator, a reduced residual resistance was observed. An example is given in Figure 5, where a drastic reduction of the surface resistance is apparent.

Again, we believe that charged particles bombarding the rf surface are responsible for the reduced surface resistance. Desorption of adsorbates due to the intense multipacting electron bombardment of the equator is likely, this being confirmed by the fact that the multipacting activity is very short lived. [7]³ Possibly, ionization of these gases by the multipacting current also leads to discharge and further removal of surface adsorbates. A reduced surface resistance results.

Thermal cycles of a cavity that had reduced its surface resistance in this manner revealed that a cycle to

²The term magnetic in this case refers to the fact that the heating increased quadratically with the magnetic field in the cavity the heating was not field emission related.

³Multipacting depends critically on the first few monolayers covering the wall. Hence, the fact that multipacting easily processed away, suggests that the surface condition is changing under the electron bombardment.

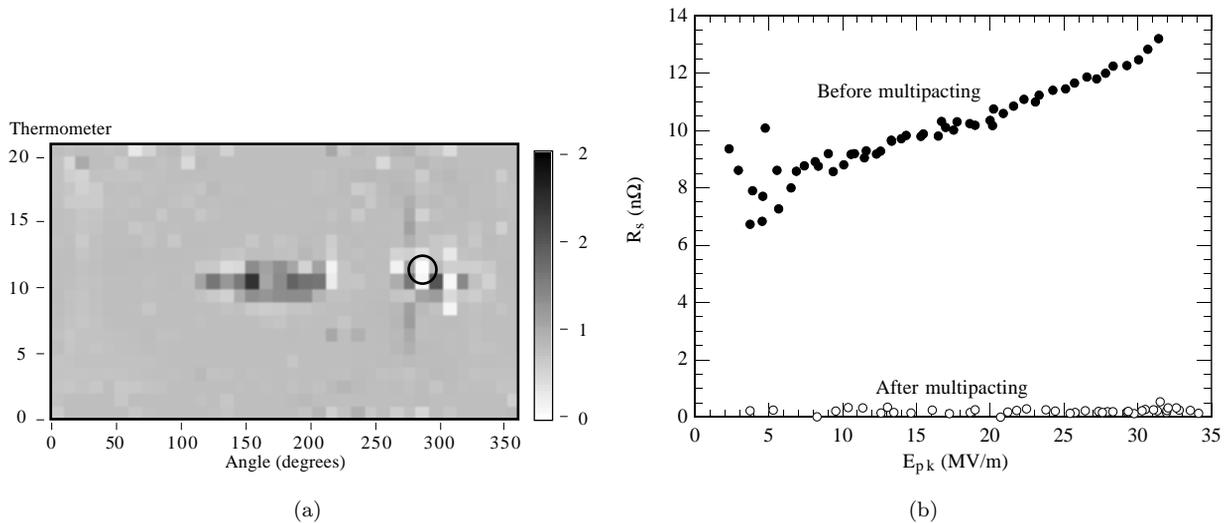


Figure 5: (a) Ratio of the surface resistance after and before multipacting related breakdown in cavity LE1-17. Dark regions indicate an increase in R_s and are due to flux trapping. [5] Light regions denote regions that reduced their surface resistance during the multipacting activity. (b) Surface resistance at the circled site as a function of the peak electric field.

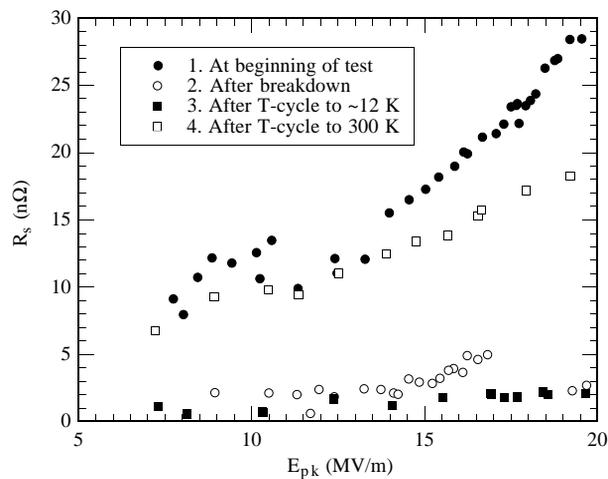


Figure 6: Surface resistance as a function of E_{pk} of a site in cavity LE1-20, that had reduced its surface resistance during multipacting. A complete thermal cycle to room temperature was required to restore the surface resistance to its initial value.

12 K is insufficient to restore the original surface resistance (see Figure 6). In similar cases, even cycling to temperatures on the order of 200 K proved ineffective at restoring the original R_s . However, a cycle to 300 K restored the original losses. This observation underscores the fact that adsorbed gases play an important role in governing the residual resistance.

4.2 Surface resistance reduction during thermal breakdown

We should briefly mention that, similar to multipacting, thermal breakdown due to cavity defects occasionally also led to a reduction of the surface resistance. Figure 7(a) demonstrates this fact by depicting the ratio of a cavity's surface resistance after and before thermal breakdown due to a defect. The surface resistance of the circled thermometer, as shown in Figure 7(b), reduced. Note that the increased losses elsewhere are due to flux trapping during the quench, which is discussed in References [3, 5].

Again, a discharge is a possible explanation for the reduced losses. In the example in Figure 7, field emission electron bombardment occurred very close to the breakdown center, on the side where reductions are observed

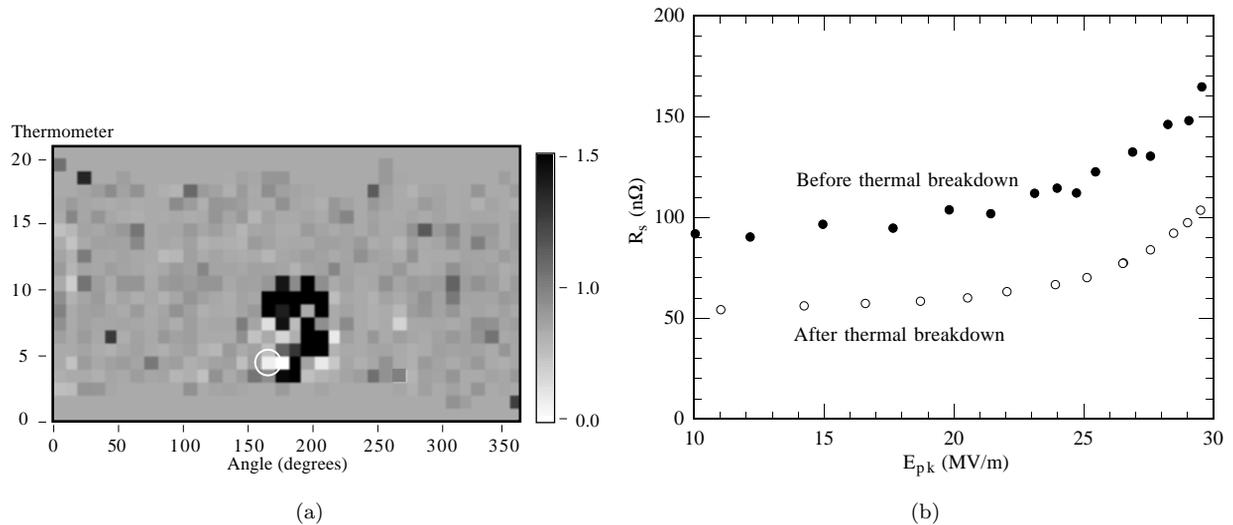


Figure 7: Changes of R_s following thermal breakdown in cavity LE1-34 at 37 MV/m. (a) Ratio of R_s at 12 MV/m after and before thermal breakdown, showing that both increases as well as reductions in R_s occurred. (b) R_s versus E_{pk} of the circled site in (a) showing that the surface resistance reduced following thermal breakdown.

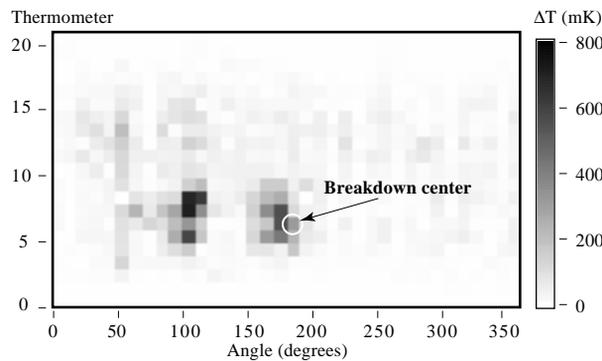


Figure 8: High field Temperature map of cavity LE1-34, taken just before thermal breakdown.

(see Figure 8). Gases such as hydrogen, evolving during the thermal breakdown, may be ionized by the emission electrons. A discharge and the subsequent “cleaning” of the rf surface then ensues.

5 Potential Q_0 improvements

The fact that a discharge or multipacting is able to reduce the surface resistance substantially is interesting because it demonstrates that the Q_0 values of 2×10^{10} , that we routinely achieve with niobium cavities, can be improved upon significantly. Although flux trapping of an insufficiently shielded terrestrial magnetic field contributes to the surface resistance [2, 10], it appears that adsorbed materials are responsible for a substantial part of the residual surface resistance in our cavities.⁴

Consider, for example, the event described in Figure 4 that led to reduced losses. On average, the affected region reduced its losses from 17 nΩ to 12 nΩ. Individual thermometers registered much greater reductions from a factor of 1/2 to even a factor of 1/8. The low field Q_0 of this cavity was 1.5×10^{10} . If the R_s reductions observed in this test could be achieved with the entire cavity surface, then Q_0 values in excess of $5 \times 10^{10} - 10^{11}$ should be possible, provided adequate magnetic shielding is used.⁵

⁴Note that R_s losses at 1.6 K are about 2.5 nΩ for RRR = 250 niobium at 1.5 GHz. Hence Q_0 values in excess of 10^{11} should be possible with our cavities.

⁵The best Q_0 values we can hope to achieve with the shielding in our cryostat are one the order of $5 - 7 \times 10^{10}$.

6 Summary

The observation of a gas discharge initiated by multipacting demonstrated that ion and/or electron bombardment can remove adsorbates from the rf surface, which are responsible for a sizable fraction of the residual losses. In one case, an average improvement of the residual resistance by 30 % was recorded in the affected region. Locally, the residual resistance reduced to values as low as 1/8 of the original surface resistance. If such improvements could be achieved throughout the entire cavity, then Q_0 values of 10^{11} should be possible.

Experiments, where gases are intentionally adsorbed on the cold rf surface, have also demonstrated that renewed desorption of these gases is possible following a discharge. The original surface resistance can be recovered in this manner.

Similar discharge cleaning was recorded during thermal breakdown (in limited cases), where field emission electrons may serve to initiate a discharge in gases evolving during the quench. Investigations into the use of gas discharge to “clean” the rf surface are therefore appropriate and may point the way to improved cavity performance.

References

- [1] D. C. Mattis and J. Bardeen, *Physical Review* **111**, 412 (1958).
- [2] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators*, Wiley and Sons, New York, 1998, To be published.
- [3] J. Knobloch, *Advanced Thermometry Studies of Superconducting RF Cavities*, PhD thesis, Cornell University, 1997, Laboratory of Nuclear Studies thesis CLNS 97-3.
- [4] J. Knobloch, H. Muller, and H. Padamsee, *Review of Scientific Instruments* **65**, 3521 (1994).
- [5] J. Knobloch and H. Padamsee, Flux trapping in niobium cavities during breakdown events, in *Proceedings of the 8th Workshop on RF Superconductivity*, Padua, Italy, 1997.
- [6] J. Knobloch and H. Padamsee, *Particle Accelerators* **53**, 53 (1996), Also published in the Proceedings of the 7th Workshop on RF Superconductivity, Gif-sur-Yvette, France, pp. 95–103 (1995).
- [7] J. Knobloch and H. Padamsee, Multipacting in 1.5-GHz superconducting niobium cavities of the CEBAF shape, in *Proceedings of the 8th Workshop on RF Superconductivity*, Padua, Italy, 1997.
- [8] P. Kneisel, Surface preparation of niobium, in *Proceedings of the Workshop on RF Superconductivity*, edited by M. Kuntze, pages 27–40, Karlsruhe, 1980, Proceedings also published as internal Kernforschungszentrum Karlsruhe report KFK-3019.
- [9] F. Llewellyn-Jones, *Ionization and Breakdown in Gases*, Wiley, New York, 1957.
- [10] C. Vallet et al., Flux trapping in superconducting cavities, in *Proceedings of the 1992 European Particle Accelerator Conference*, edited by H. Henke, H. Homeyer, and C. Petit-Jean-Genaz, pages 1295–1297, Berlin, Germany, 1992.