Microscopic Examination of Field Emission Areas in Superconducting Nb Cavities*

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Abstract

We have developed a new type of superconducting cavity in which it is possible to expose a small region of the cavity, called the "dimple", to very high surface RF electric fields. In a break-apart version of this cavity, the dimple is part of a demountable niobium end-plate which fits into our SEM/EDS system. Surface RF electric fields between 50 and 70 MV/m have been supported by the dimple in several tests. On subsequent SEM examination of the end-plates, many new and interesting features associated with emission were discovered. Each emission site is located at the center of a "starburst" shaped region of reduced secondary emission coefficient. At the center of these sites we have often found craters of molten niobium. Sometimes the sites contain features which look like nodules or ripples on the niobium surface. A rudimentary DC field emission apparatus was assembled to supplement these RF field emission studies.

I. INTRODUCTION

Limiting the area of a cavity exposed to high surface electric fields reduces the area one must examine when looking for field emission sites. Within this area we may encounter naturally occurring emitters and be able to study the effect of their exposure to high electric fields. This has not previously been accomplished for the case of RF fields, although there have been extensive studies of emitters in DC fields [1-3]. Such information may help track down the source of emitters in niobium cavities and lead to ways of eliminating them. We may also place an emitter at a controlled location or treat the high field region in special ways in order to study the influence of such treatments on emission.

The basic design of our cavities is that of an accelerating cavity half-cell closed at the equator with a plate. An extensive discussion of the design and testing of copper models of this cavity is given elsewhere [4,5]. The end-plate of the cavity is attached with an indium seal. A choke joint was added to reduce joint losses. The electric field pattern of the TM_{020} mode, as calculated by URMEL [6], is shown in Figure 1. The electric field at the dimple is ~4.4 times higher than anywhere else on the surface. The total area exposed to fields within 50% of the maximum is $80 mm^2$.

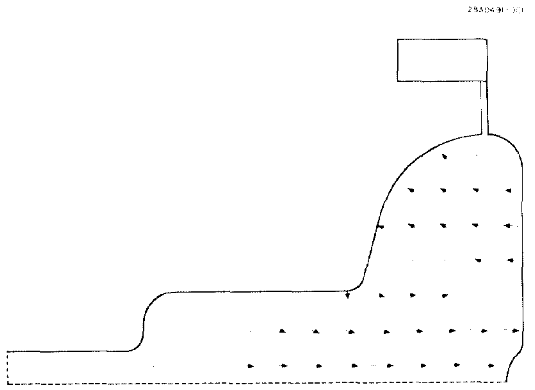

Figure 1. Electric field pattern of the TM_{020} mode.

Calculations show that an electrode facing the dimple can detect primary electrons emitted from emitters at the exact center of the dimple and secondary electrons from emitters on the sides of the dimple. Primary electrons from other regions of the cavity do not terminate on the electrode.

II. RF TEST RESULTS

In the following discussions, all field values quoted refer to the field at the center of the dimple.

Q_o vs E_{peak} curves for several tests of the cavity are shown in Figure 2. The low field Q_o values of $7\text{-}9 \times 10^9$ proved the effectiveness of the choke joint. Unfortunately, this joint also caused two-point multipacting at peak fields of 2-3 MV/m. Application of 20-100 watts of RF power processed this away, enabling the field to jump to ~15 MV/m, but causing the low power Q_o to degrade to $\sim 2\text{-}3 \times 10^9$.

In one of our first tests the emission current jumped to 2.5 μA at 50 MV/m. The feature shown in Figure 3 was discovered half-way down the dimple, where the field was ~35 MV/m. It appears that an explosion formed several craters and droplets of molten niobium. Closer examination reveals that this feature is surrounded by concentric rings extending for several tens of microns. The entire region is free of elements other than niobium (our windowless EDS system is sensitive to elements as light as carbon).

Each emission feature on the dimple is surrounded by an area of reduced secondary emission coefficient (i.e. in the SEM these appear dark). These dark regions are ~50-100 μm in diameter and thus make it much easier to find the emission features. It is extremely important to minimize the time of exposure of the end-plate to the atmosphere; the contrast of

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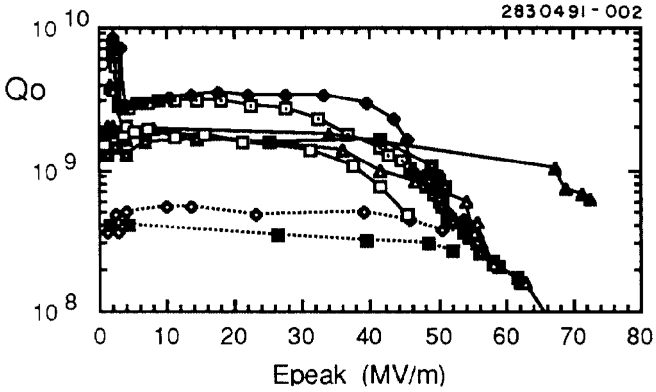

Figure 2. Q_o vs E_{peak} curves for several cavity tests.

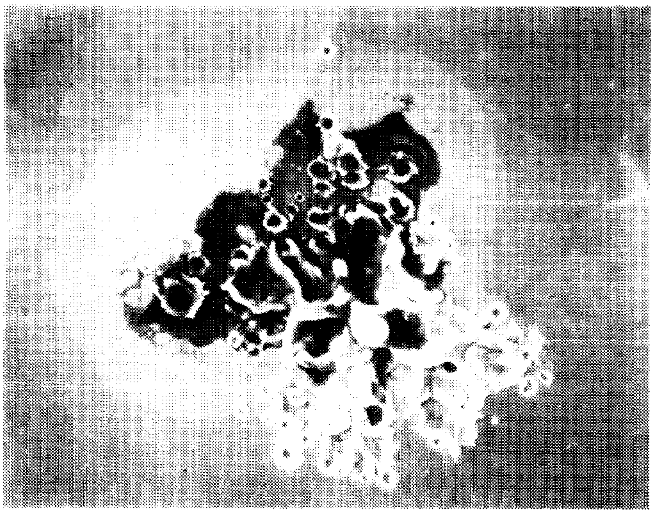

Figure 3. SEM micrograph of the molten and cratered niobium dimple surface. The electric field at this feature was ~35 MV/m.

these regions is greatly reduced after an atmospheric exposure of only 1-2 hours. Typically, a dimple will contain ~10-30 such dark regions. Figure 4 is a low magnification micrograph showing a cluster of dark regions.

Close examination of the dark regions reveals a multitude of features. The typical region is ~100 μm in diameter and has a "starburst" appearance, Figure 5, although some regions are "spider-like" rather than circular in outline. At the center of each is usually a cluster of molten niobium craters. The craters are sometimes separated, but usually overlap one another as shown in Figure 3. As previously mentioned, the craters are often surrounded by several uniquely created series of concentric rings, Figure 6, which give the overall appearance of a fingerprint.

The central crater region usually contains only niobium. Occasionally, submicron to micron size fragments detected near craters contain foreign elements such as titanium, indium, aluminum, calcium, chromium and oxygen. A singular case of a 5 μm sphere of stainless steel was also observed. Though the detection of any foreign element is very rare, titanium appears more frequently than the others.

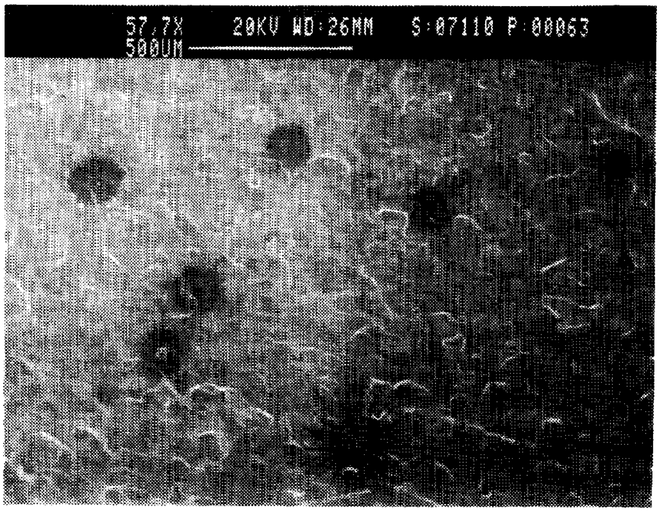

Figure 4. SEM micrograph showing a cluster of dark regions. The peak electric field was 66 MV/m.

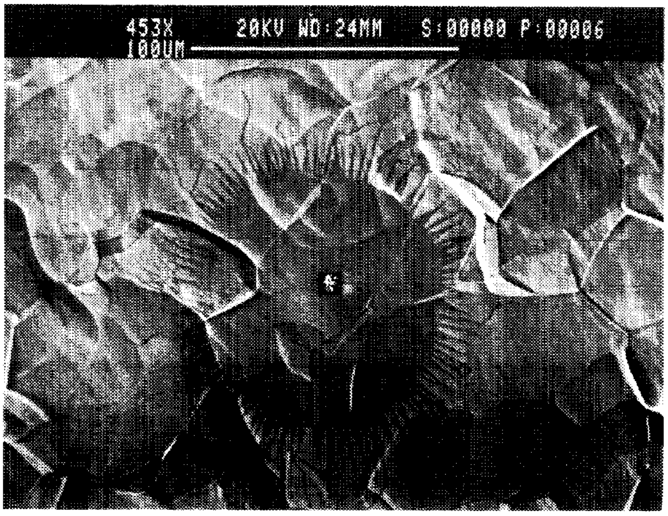

Figure 5. SEM micrograph showing details of one of the dark regions. The peak electric field was 54 MV/m.

It was important to verify that the features observed on the dimple revealed the location of emission activity. Carbon from a pencil has been shown to be a reliable source of emission [1]. A fine-tipped pencil was lightly touched to the end-plate about half way down the side of the dimple. Unfortunately, it was not possible to produce a single carbon flake, but rather hundreds of flakes were deposited over a ~200 μm diameter area. This end-plate was then tested and examined several times, the peak field increasing with each successive test.

It was found that RF processing led to the gradual disappearance of the emission source. As the peak field was increased, the number of carbon flakes remaining on the surface diminshed dramatically and the number of molten niobium crater clusters increased. It was interesting to find that the craters were carbon-free.

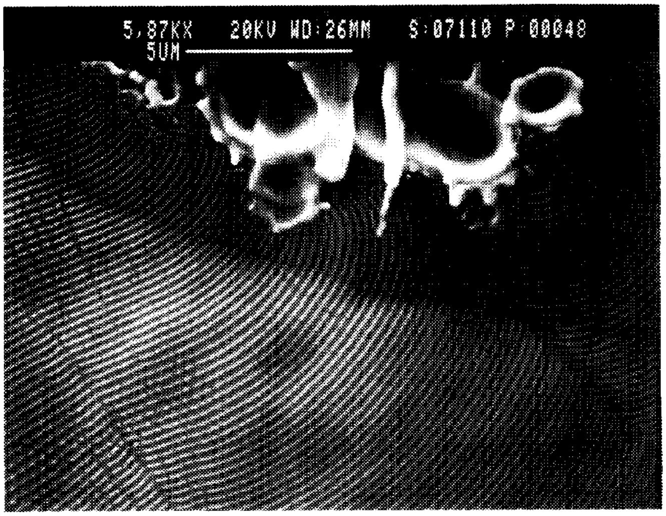

Figure 6. SEM micrograph showing the concentric rings. The peak electric field was 66 MV/m.

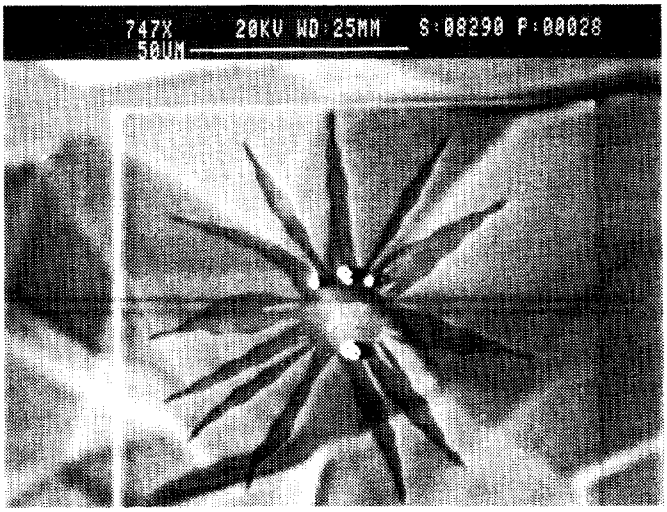

Figure 7. SEM micrograph of the cathode from a DC field emission test.

III. DC TEST RESULTS

We hypothesized that each dark region was created after a spark discharge which had been initiated by field emission activity in that region. To verify this, we used a simple DC field emission apparatus consisting of a niobium anode with a 1.6 mm radius tip and a 1.9 cm diameter niobium cathode. The gap between the electrodes was adjusted by lightly touching them and then setting their separation. The vacuum in the system was $<10^{-8}$ torr and the electrodes were cleaned using standard cavity techniques.

Several locations were tested for emission activity at fields as high as 120 MV/m. Emission currents were measured at many points, with two locations showing strong emission. However, only those points at which a spark occurred showed features similar to those seen on the RF cavity end-plates. These are shown in Figure 7.

IV. DISCUSSION

Studies of craters caused by DC arcs [2,3] reveal many similarities to the results presented here. From these studies the following model of arc formation has emerged. The emission area heats up by Joule heating from the emission current, assisted by ion bombardment from the residual gas. As temperatures approach the melting point of niobium the resulting vapor provides the plasma for a spark. Photographs from DC studies show this plasma and subsequent examination of the cathode reveals molten, eroded craters. The plasma cloud is probably responsible for the dark regions surrounding the craters while pressure from this cloud acts on the molten cathode causing crater excavation and droplet ejection.

As the plasma dissipates the field can rise until another emitter heats up and explodes. The new emission may take place from the sharpened edge of the previous crater, leading to a chaotic track of overlapping craters. This effect has been observed on a clean molybdenum cathode [2]. An oxidized molybdenum cathode produced crater clusters [2].

V. SUMMARY

A break-apart RF cavity has been made and successfully tested at high fields with high Q_o's. The choke joint was crucial to this success. Microscopic examination of spots where emission has occurred reveals that RF sparking is a mechanism whereby emitters in superconducting cavities are processed. In a few cases, foreign elements have been detected in the vicinity of the craters formed during sparking. The origin of some of these can be traced to our assembly procedures, emphasizing the need for extreme cleanliness. The presence of other elements suggest that inclusions in the raw material must be reduced.

Recently, an S-band accelerating cavity was cut in half at the equator and examined. The same features shown in the preceeding figures were observed at emission sites.

VI. REFERENCES

[1] P. Niedermann, "Experiments on Enhanced Field Emission", Université de Genève, Genève, Suisse, PhD dissertation, 1986.

[2] B. Jüttner, "On the Variety of Cathode Craters of Vacuum Arcs, and the Influence of the Cathode Temperature", Physica, vol. 114C, pg. 255-261, 1982

[3] B. Jüttner, "Characterization of the Cathode Spot", IEEE Trans Plasma Science, vol. PS-15(5), pg. 474-480, October 1987

[4] D.L. Moffat, et al., "Superconducting Niobium RF Cavities Designed to Attain High Surface Electric Fields", in *Proceedings of the 4th Workshop on RF Superconductivity*, KEK, Tsukuba, Japan, August 1989, pg. 445-465. Also distributed as Internal Report CLNS 89-934, 1989

[5] D.L. Moffat, et al., "Studies of Superconducting Niobium in High RF Surface Electric Fields – An Update", Internal Report CLNS 90-991, 1990

[6] URMEL and URMELT were written by U. Lauströer, U. van Rienen and T. Weiland