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Microscopic examination of defects located by thermometry in 1.5 GHz superconducting niobium cavities*

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Abstract

A new high resolution, high speed thermometry system has been built at Cornell to permit the study of anomalous loss regions in 1.5 GHz superconducting Nb cavities in superfluid He. Following a cavity test, the cavity is dissected for examination of these regions in an electron microscope. Presented is a survey of the topographical and elemental characteristics of various defects found so far. Included are field emitters which were known to be active at the end of a cavity test, as well as those which processed.

I. INTRODUCTION

In present day Nb cavities the surface magnetic fields achieved still fall far short of those theoretically attainable. The maximum field possible is believed to be the superheating rf field (2300 Oe @ 1.6 K) [1]. In practice, though, one finds that the cavity Quality (Q) already begins to drop between 300 and 1000 Oe.

Several mechanisms responsible for anomalous power dissipation at these fields have been identified. Presently, the most common ones are dielectric/magnetic losses (thermal defects) [2] and field emission (FE) [3]. Both mechanisms can be attributed to microscopic defects present on the inner cavity wall.

To better understand the nature of the defects we have begun to search for these, using thermometry [2] as a guide. We catalogue their heating characteristics and after cavity tests dissect the cavities to undertake a microscopic and elemental examination of the defects.

II. EXPERIMENTAL SETUP

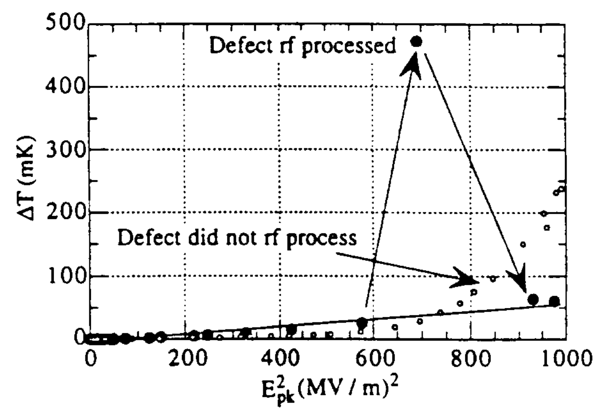
To facilitate the search a new thermometry system was developed, whose details have been discussed elsewhere [4]. It is designed for L-Band cavities operating in superfluid He at 1.6 K. Its essence is an array of 756 specially prepared carbon thermometers pressed against the outer cavity wall. A map at a resolution of 0.25 mK takes about 1/10 s to acquire. Increasing the acquisition time to 2.5 s permits us to resolve 30 μK signals. This is a marked improvement over previous systems which either were very slow, requiring several tens of minutes for an acquisition, or were unable to detect signals below 5 mK.

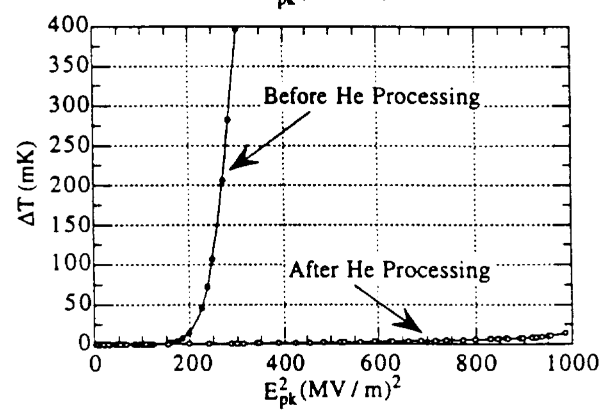
After the tests, cavities that have interesting sites are cut apart. During the cutting process the interior of the cavity is pressurized with filtered N_2 gas, thereby minimizing dust contamination. Cuts are made along the beam tubes (~ 2.5 cm from the iris) and along the equator using two sizes of conventional pipe cutters. The entire cutting process is carried out in a class 100 clean room.

The chamber of an electron microscope (SEM) has been enlarged to permit the examination of the half cells. We have been able to show that thermometry data is a useful guide to locating defects in the SEM. The defects' elemental composition is also studied by energy dispersive x-ray analysis.

The heating due to thermal defects occurs directly at the defect site. On the other hand, field emitters are more difficult to pinpoint. Generally one detects the power deposited by accelerated FE electrons impacting with other parts of the cavity wall. In that case we revert to trajectory calculations using the program "MULTIP" to determine the emitter location [5].

III. MEASUREMENTS





Figures 1a & 1b: FE heating measured for sites which a) didn't process (shown in fig. 2b), b) processed in the rf field (shown in fig. 2c) and c) He processed (shown in fig. 2d). The heating is plotted vs. the electric field squared so that background heating in the absence of FE is linear.

All of the cavities discussed here had been tested in the past. For the most recent test all but one (LE1-Hereaus) were

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chemically etched with BCP 1:1:2 for 3 minutes. This was followed by rinsing the cavity with continuous flow deionized water for at least 2 hours prior to drying with warm filtered N_2 gas. LE1-Hereaus was only cleaned with DI water in conjunction with ultrasonic agitation.

During the tests the cavity fields were increased while measuring the cavity Q and temperature distributions at regular intervals. In one case an emitter *rf processed* [6], that is, upon raising the field beyond a threshold, the emitter's heating was permanently extinguished. (see fig. 1a).

In another case, the maximum power dissipated in the cavity was 8 W, most of which was absorbed by a single emitter. Subsequently *He processing* [7] was successfully performed on the cavity resulting in the elimination of the emitter (fig. 1b).

IV. RESULTS & DISCUSSION

On average we found the temperature signals of two or three FE sites in each cavity. LE1-Hereaus, which had far more, was the exception. This was not surprising, considering this cavity had not been etched prior to the test.

Of the nine FE sites studied in greater detail, six were located in the bottom halves of the cavities. This observation supports the notion that emitters are primarily caused by foreign particles, accumulating at the bottom due to gravity.

In two cases a microscopic search of an area ±1 cm and ±10° centered on the predicted emitter location failed to turn up any defects that were indicative of FE (discussed later).

In the remaining seven cases we found defects displaying definite signs of FE within at most a 2-3 mm radius of the predicted emitter location. Table 1 summarizes these. Frequently we also searched the surrounding area. Although occasionally we did find micron sized particles, these did not show any signs that FE had occurred and could easily be removed by high pressure N_2 gas, whereas the FE sites remained anchored to the cavity surface.

Table 1: Summary of the emission sites for which microscopic defects could be correlated with the thermometry signals.

#	Melting/Craters Present ?	Starburst?	Processed?	Contaminants	Fig.
1	Minimal Melt.	No	No	Fe, Cr	2a
2	Melting	No	No	In, Al	None
3	Minimal Cratering	No	No	C,O,Fe,Ni, Cr,Ti,Ca,Br	None
4	Min. Cratering	Yes	No	None	None
5	Severe Melting	Yes	No	C,O,Cl, Ti	2b
6	Significant	Yes	Yes	C	2c
7	Very Severe	Yes	w/ He	None	2d

Cataloging field emitters

The defects listed above can be categorized as follows:

A) Three unprocessed FE sites (entries 1-3) consisted of foreign particles a few 10's of μm in size which had been partially melted. Fig. 2a shows an example of such a defect. Note the molten region which is magnified in the inset.

B) In two unprocessed cases (entries 4 & 5) we found regions of limited cratering surrounded by a large area (diameter = 500 μm) of reduced secondary electron emission coefficient. This feature has been observed in the past [3],[8] and is known as a starburst because of its dark star shaped appearance in the SEM. In the case of entry 5, we also found a large (70 μm) foreign particle which had melted to a large extent (see fig. 2b)

C) At the location of the rf processed emitter (entry 6) we found an irregularly shaped starburst surrounding a region of significant cratering and melting (see fig. 2c) Some remnants of a foreign particle (carbon) existed as well.

D) The helium processed emitter (entry 7) had a very regularly shaped starburst (see fig. 2d). No foreign elements were detected at the center which consisted entirely of severely molten Nb surrounded by some cratering.

Progression of field emission:

These results suggest the following scenario for the progression of FE:

1. At sufficiently low current densities the FE process is insufficient to alter the appearance of the emitter. This explains why we were unable to find some field emitters in the microscope.

2. As the electric field is increased, the FE current density rises locally to values sufficient to melt parts of the site (fig. 2a). FE may perhaps occur at several points on the defect simultaneously, so that the melting process doesn't noticeably affect the defect's collective FE characteristics.

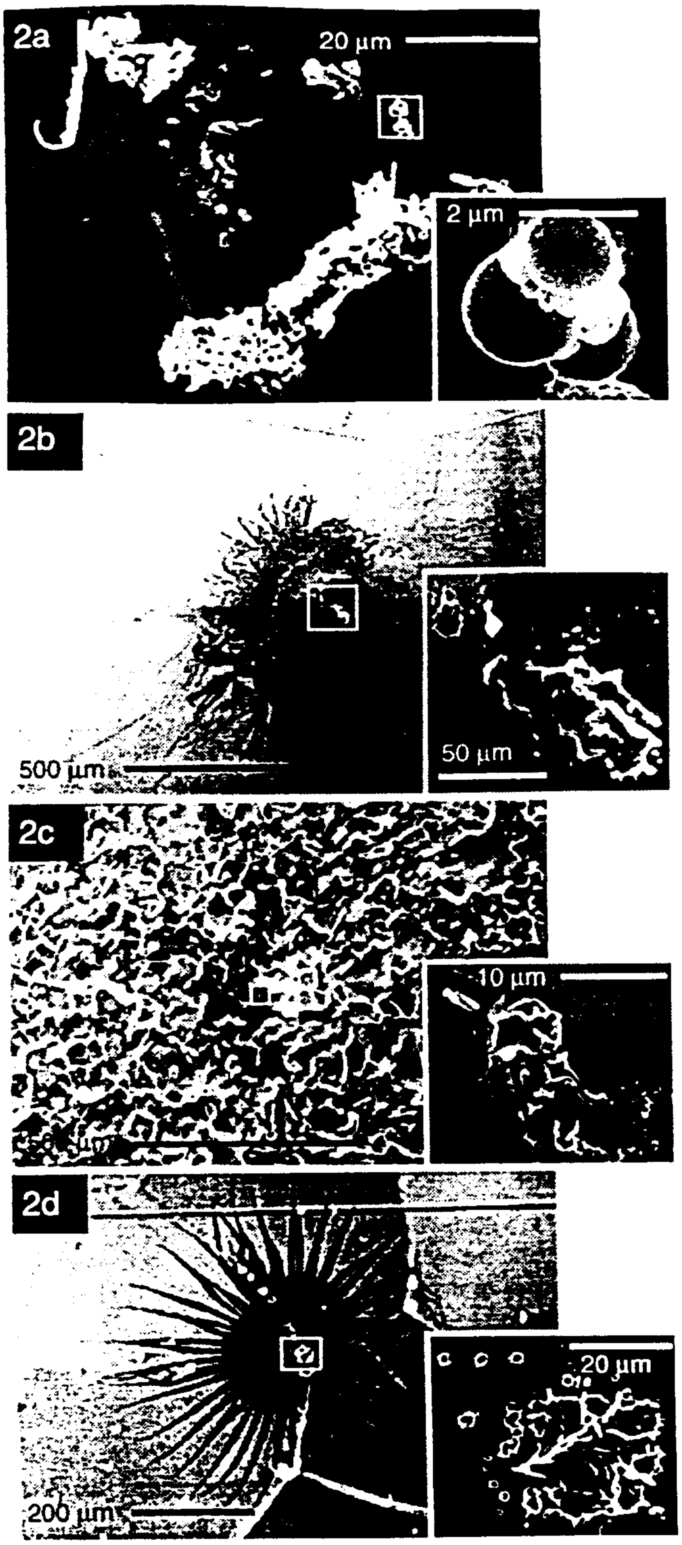
3. Further field increases result in extreme heating (ultimately leading to a local explosive event). A plasma builds up, which is fueled by desorption/evaporation of one or more of the local emitters. Through a cleaning action of the plasma, a starburst is produced [8] (fig. 2b). Neighboring emitters may still be in the first two stages, so that again the overall FE characteristics of the defect are only little changed.

4. Finally, the plasma itself results in significant heating over a region encompassing a large portion of the defect. Once a critical temperature is exceeded the entire defect processes (fig. 2c). The emitter in fig. 2b was perhaps just before this stage. Of particular note is the fact that almost the entire defect seems to have melted.

The new evidence presented here supports that the plasma production is not simply the result of a defect's processing event. Rather it is the heating by the plasma that is essential to its extinction. The heating by the FE current alone may not be sufficient.

The He processed emitter evidence tends to support this notion. The He provides the 'fuel' to enhance the plasma, thereby permitting the defect to process at lower field levels than would ordinarily be possible.

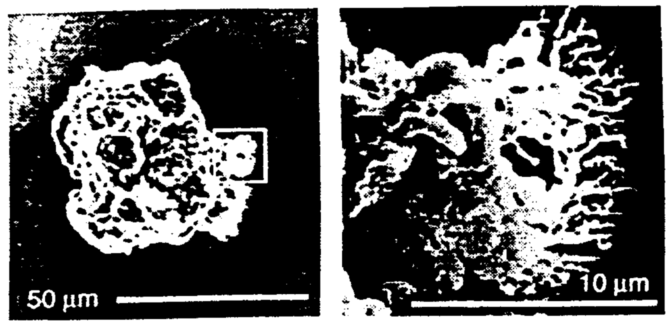
This scenario, of course, is speculative and we are currently running simulations to test our hypothesis. Further cavity tests will be carried out to yield more statistics.



Figures 2a - 2d: Examples of FE defects found for the four cases A - D discussed in the text. It is speculated that these figures represent a natural progression in FE, ultimately leading to the processing of a defect. The insets are magnifications of the areas in the rectangles.

Other Observations:

1. We found a thermal defect (fig. 3), which at higher field levels could have lead to thermal breakdown. The copper particle at that location could not be removed by high pressure solid CO_2 cleaning. Parts of it seem to have melted, which may explain why the particle was so firmly attached. Calculations [9] indicate that melting was possible at the fields attained, provided the particle was thermally isolated.



Figures 3a & 3b: A thermal defect (copper)

2. Comparison with other experiments show that the average starburst size scales inversely with frequency between 1.5 and 5.8 GHz. If starbursts are produced during half an rf cycle, while FE is active, we find that an expansion velocity of ~10^6 m/s is required. This is consistent with the expansion of electrons thermally emitted from plasmas observed during explosive DC FE [10]. Perhaps such electrons are responsible for the starburst production.

3. Generally, cavities were FE free until a threshold field was exceeded, resulting in the irreversible activation of at least one field emitter. Room temperature cycling of the cavity did not deactivate these. This observation seems to be at odds with the use of the "*tip-on-tip*" model [11] to explain FE.

4. The main contaminants in emitters were C, Fe, Cr and Ti, which probably came from assembly tools and the ion pump. Steps are being taken to modify the pump system.

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