VOLTAGE BREAKDOWN ON NIOBIUM AND COPPER SURFACES*

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Abstract

Experiments have shown that voltage breakdown in superconducting niobium RF cavities is in many ways similar to voltage breakdown on niobium cathodes in DC voltage gaps; most striking are the distinctive starburst patterns and craters that mark the site of voltage breakdown in both superconducting cavities and DC vacuum gaps. Therefore, we can learn much about RF breakdown from simpler, faster DC experiments. We have direct evidence, in the form of "before" and "after" pictures, that breakdown events caused by high surface electric fields occur with high probability at contaminant particles on surfaces. Although the pre-breakdown behavior (field emission) seems to depend mostly on the contaminant particles present and little on the substrate, the breakdown event itself is greatly affected by the substrate—niobium, heavily oxidized niobium, electropolished copper, and diamond-machined copper cathodes lead to different kinds of breakdown events. By studying DC voltage breakdown we hope to learn more details about the processes involved in the transition from field emission to catastrophic arcing and the cratering of the surface; as well as learning how to prevent breakdown, we would like to learn how to cause breakdown, which could be important when "processing" cavities to reduce field emission.

1 WHY STUDY DC BREAKDOWN?

DC breakdown shares many characteristics with RF breakdown due to high electric fields in superconducting cavities. Most striking is the similarity among distinctive starburst-shaped remnants after voltage breakdown under both DC and RF conditions (see Figure 1). Because experiments probing DC breakdown are much easier and faster than similar RF experiments, we can efficiently study RF voltage breakdown using a large number of DC results to guide a smaller number of RF experiments.

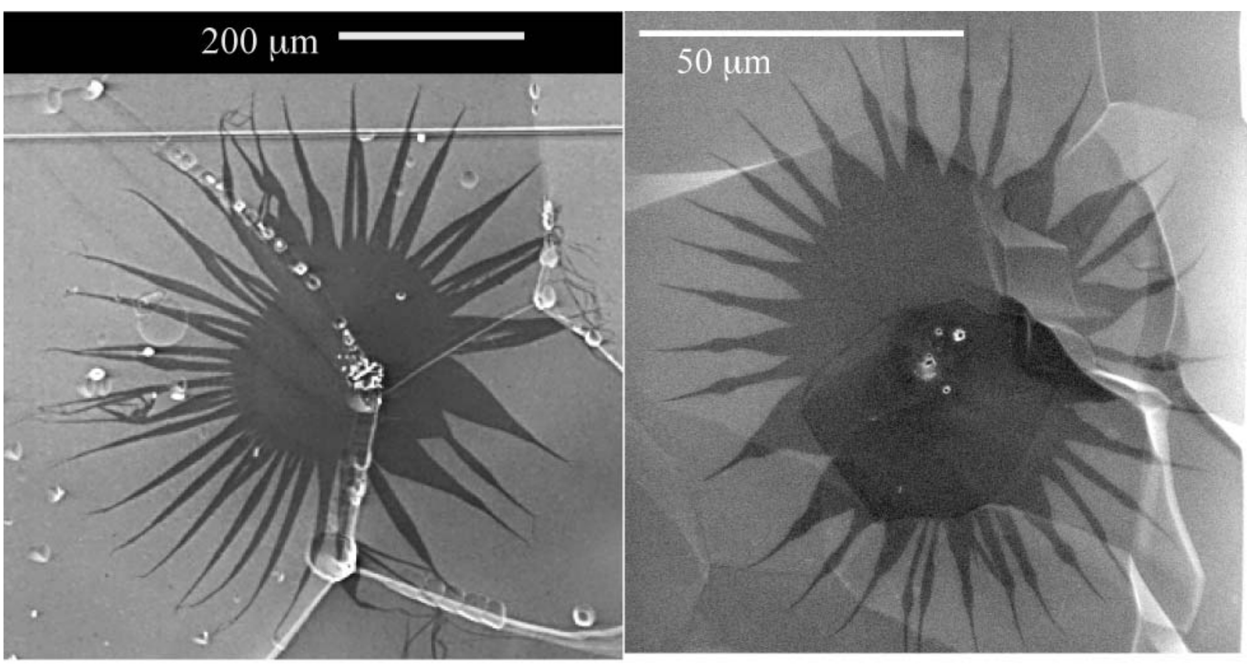

Figure 1: Starburst from 1.5GHz superconducting niobium cavity (left) and room temperature DC gap (right). Note that the RF starburst is about four times larger.

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2 APPARATUS AND PROCEDURE

The apparatus (Figure 2) comprises two electrodes in a vacuum chamber and a 15kV DC generator with appropriate measuring equipment. The cathode is a thin plate 25.4mm in diameter, usually with five raised pedestals, each a square millimeter in size; the anode has a rounded tip with an effective area of about a square millimeter. The cathode can be moved vertically to adjust the gap between electrodes, and the anode can be moved laterally to center it under a particular pedestal on the cathode (which is mounted electric-field-side down to prevent particles falling on it).

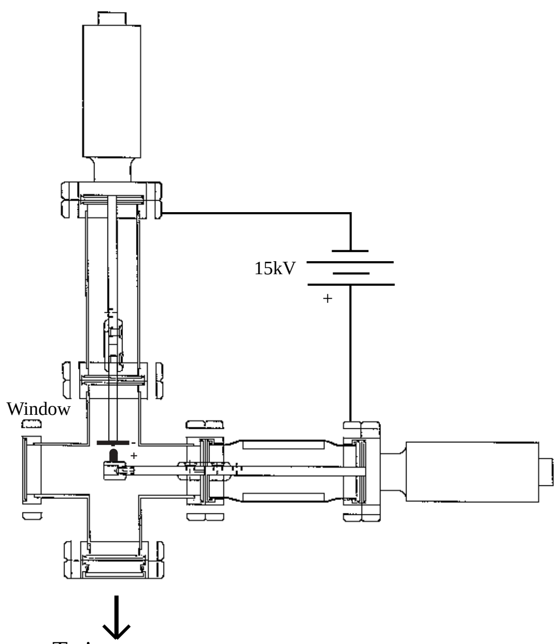

Figure 2: The Apparatus

During a test we measure the gap voltage as well as field emission current; recently we added a video camera to monitor light output (the spark) during the breakdown event.

During a typical experiment

1. the cathode is cleaned (etched and/or high-pressure rinsed). For some niobium samples the thickness of the oxide layer is increased by anodization in weak ammonium hydroxide.
2. Since particles attract voltage breakdown, we usually contaminate the cathode with particles by dissolving powder in methanol and placing a drop of methanol on the cathode.
3. The cathode is scanned in the SEM (scanning electron microscope), where particles and other points of interest are examined and photographed. EDX (energy dispersive x-ray) analysis is used to determine the elemental composition of particles.
4. After installing the cathode in the vacuum chamber and adjusting the gap, the voltage is slowly raised until breakdown, which is indicated by the sudden decrease in gap voltage. After this is done for each pedestal on the cathode,
5. the cathode is removed and examined in the SEM; any changes are recorded. Sometimes we take the cathode to Evans East Analytical Services for more sensitive surface analyses (AES—auger electron spectroscopy, or TOF-SIMS—time-of-flight secondary ion mass spectroscopy).

Usually we use niobium cathodes prepared in the same way as superconducting RF cavities, and the anode is made of a tantalum-tungsten alloy; recently we have also experimented with cathodes of copper and anodized niobium.

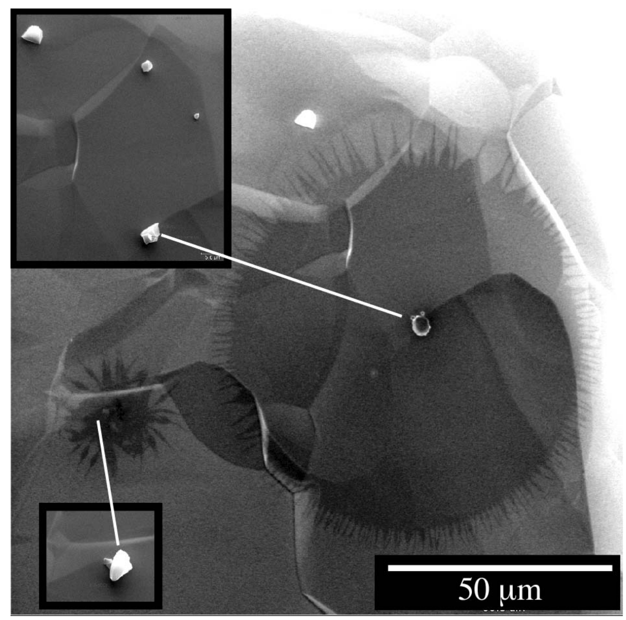

Figure 3: Two starbursts that occurred at 50MV/m (gap distance 225μm); the two insets show the particles before breakdown at the center of each starburst.

3 RESULTS

3.1 Direct Confirmation of What Has Long Been Suspected

1. Starbursts appear after DC (as well as RF) breakdown, so they are phenomena related to the interaction of high electric fields with electrode surfaces, and not specific to conditions involving RF, high magnetic fields, or superconductivity.
2. Starbursts on niobium contain none of the fluorine otherwise present in the oxide due to etching in hydrofluoric acid (HF).
3. Comparing pictures "before" and "after" the breakdown, we find that whenever there are contaminant particles on the surface, the breakdown event is extremely likely to be centered around one

(or more) of them as shown in Figure 3; afterwards there is very little trace of the original particle.

3.2 New Results and Conclusions

Using AES to map elemental concentrations around starbursts, we have found that starbursts are depleted not only of fluorine (at least on niobium surfaces that had been etched in HF), but also of surface carbon (see Figure 4). On copper cathodes the starbursts, though harder to see in normal SEM images, show up clearly on an AES carbon map. It appears that the plasma activity during breakdown "cleans" a starburst-shaped area of the surface, very likely by ion bombardment.

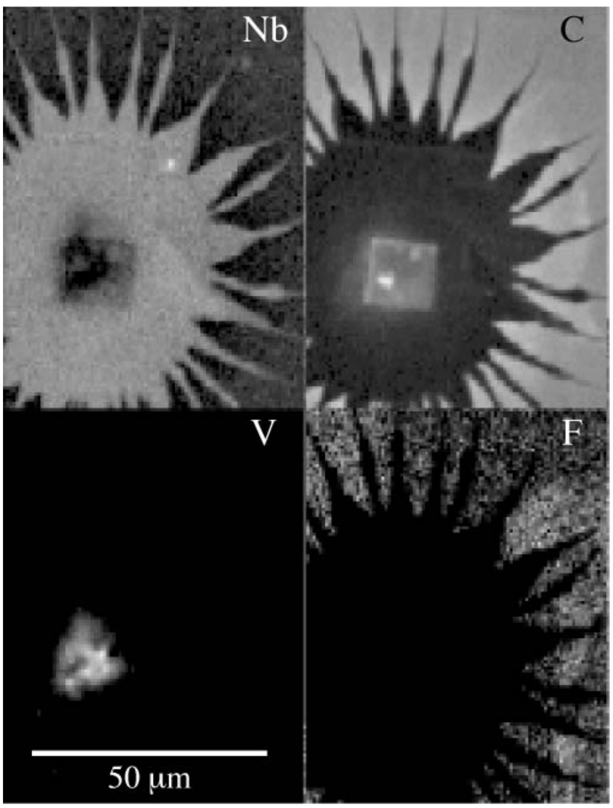

Figure 4: The abundance of the elements Nb, C, V, and F (in a 100Å thick surface layer) in the starburst shown in Figure 1. Blacker areas contain lower concentrations. Originally there was a V particle at the center (see Figure 5); the breakdown event cleaned away all F and some C, providing the contrast in the SEM image.

Although we had at first hoped to characterize the influence of different kinds of particle contaminants on the breakdown field, the wide scatter of results for each kind of particle was so large that we were completely unable to distinguish one type from another on the basis of breakdown field. Recently, however, we found that spiky vanadium particles (*e.g.,* Figure 5) field-emit and cause breakdown at lower fields than any other particles we've tested (Figure 6 shows vanadium compared to carbon and nickel); this was true regardless of the cathode, whether niobium, anodized niobium, or copper. From a different source we obtained vanadium particles that were less spiky; these "blunt" vanadium particles field-emit and cause breakdown at higher fields. We conclude that the enhancement of the electric field due to the geometry of the spiky vanadium particles is responsible for their relatively high field emission and low breakdown fields.

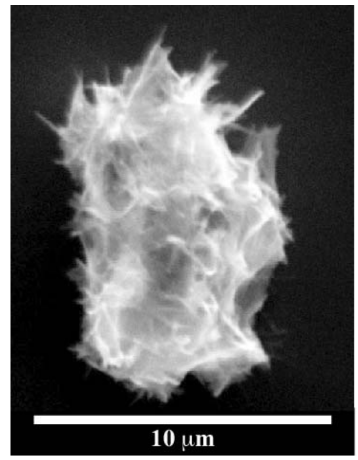

Figure 5: A typically spiky vanadium particle

It is interesting to note that the field emission current *just before breakdown* is generally more than an order of magnitude greater for the *spiky* vanadium than for the *blunt* vanadium.

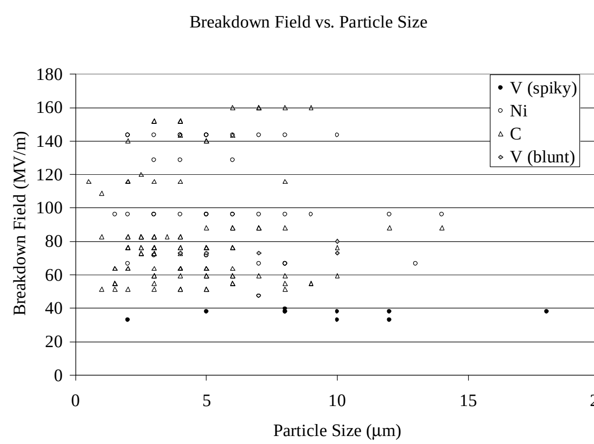

Figure 6: Breakdown field versus particle size for Ni, C, and two kinds of V; note that the spiky V breaks down at much lower fields than the others, regardless of particle size, while the ranges of fields over which Ni and C break down are indistinguishable.

Judging from similarities in the behavior of vanadium compared to other kinds of particles when tested on different cathodes, the cathode surface does not affect the pre-breakdown field emission or the breakdown field. However, starbursts, or the lack thereof, as well as the amount of surface cratering can be quite different according the surface. On niobium with an extra-thick oxide the starbursts and craters vary with the oxide thickness: for oxides roughly 400-600Å thick, the

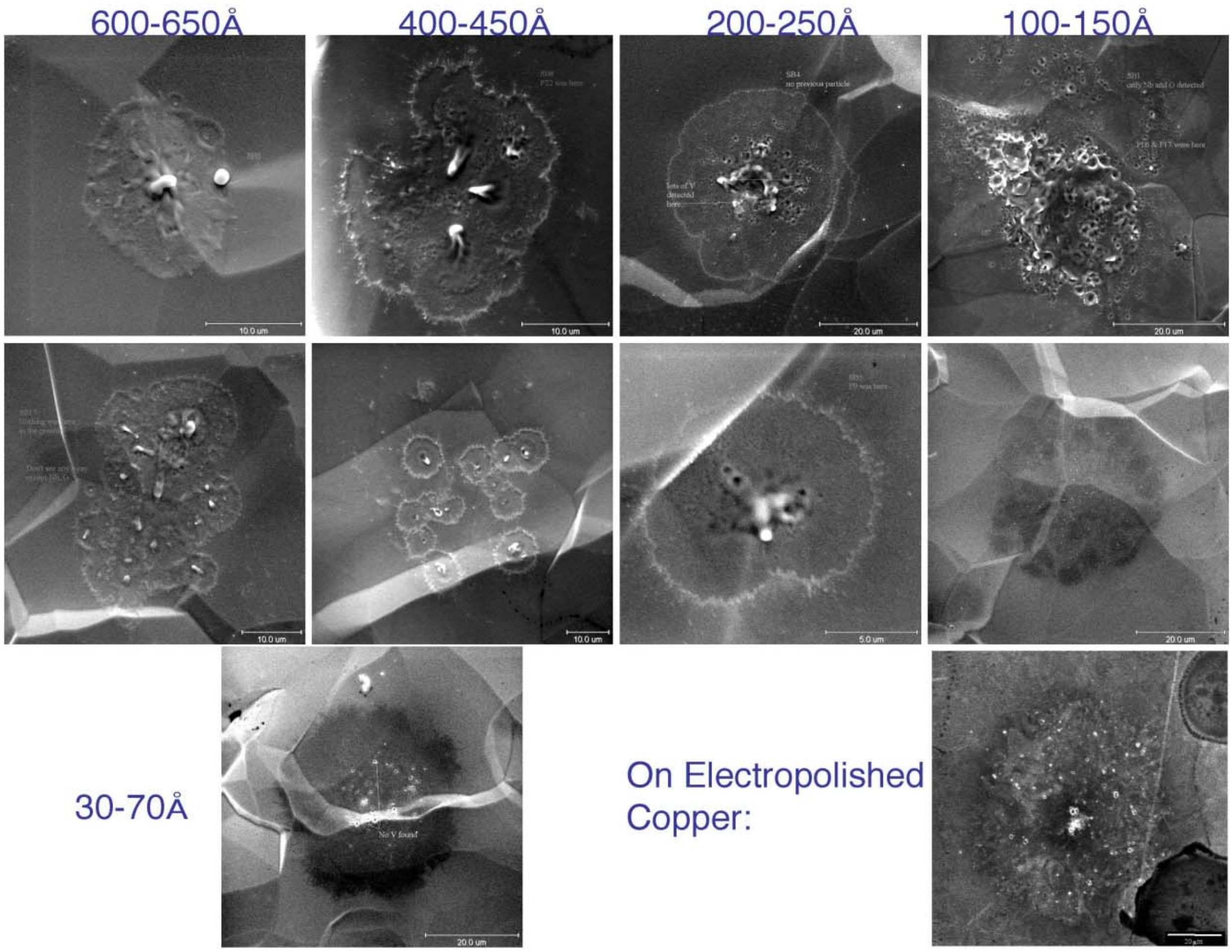

Figure 7: The result of breakdown on the cathode for niobium oxidized to various thicknesses; and (lower right) a starburst on electropolished copper.

disturbed area is relatively small, contains no craters or starburst, but invariably has a column of once-molten metal at the center; oxides 200Å thick often lack a traditional starburst and have a melted center, but they sometimes do have some scattered, shallow craters; on oxides 100Å and less, we see more cratering and sometimes a sort of starburst shadow. Starbursts on electropolished copper surfaces rarely possess the symmetry and long streamers that we see on niobium surfaces (with natural oxide); more intriguing, the starbursts on copper are almost uniformly cratered, unlike those on niobium which tend to show violent activity mostly at the center. (See Figure 7.)

4 A BRIEF SUMMARY

Because of similarities between breakdown in DC vacuum gaps and superconducting RF cavities, such as starburst-shaped shadows of plasma activity after a breakdown event, we can learn about cavity breakdown (due to electric field phenomena) by studying DC breakdown. Initial tests on niobium cathodes with particulate contamination confirmed that breakdown occurs at particle sites, obliterating the original particle. Studies on spiny vanadium particles demonstrate that sharp geometry can play an important role in enhancing field emission and causing breakdown at low fields. Although the cathode surface does not seem to change field emission characteristics or the breakdown field, both of which are determined by the contaminant particles, the surface material and oxide thickness do affect the evolution of the breakdown event and the destruction wreaked on the cathode.

The "starburst" region that is the center of breakdown activity on the cathode is cleaned of surface contaminants during breakdown, probably through ion-bombardment; afterwards this region can be distinguished by electron microscopy and Auger spectroscopy techniques.

5 ACKNOWLEDGEMENT

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