EVIDENCE FOR FOWLER-NORDHEIM BEHAVIOR IN RF BREAKDOWN*

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Abstract

Microscopic images of the surfaces of metallic electrodes used in high-pressure gas-filled 805 MHz RF cavity experiments are used to investigate the mechanism of RF breakdown. The images show evidence for melting and boiling in small regions of ~10 micron diameter on tungsten, molybdenum, and beryllium electrode surfaces. In these experiments, the dense hydrogen gas in the cavity prevents electrons or ions from being accelerated to high enough energy to participate in the breakdown process so that the only important variables are the fields and the metallic surfaces. The distributions of breakdown remnants on the electrode surfaces are compared to the maximum surface gradient E predicted by an ANSYS model of the cavity. The local surface density of spark remnants, proportional to the probability of breakdown, shows a power law dependence on the maximum gradient, with E^{10} for tungsten, $E^{11.5}$ for molybdenum, and E^{7} for beryllium. This strong E dependence is reminiscent of Fowler-Nordheim behaviour [1] of electron emission from a cold cathode, which is explained by the quantum-mechanical penetration of a barrier that is characterized by the work function of the metal.

INTRODUCTION

RF cavities pressurized with hydrogen gas are being developed to produce low emittance, high intensity muon beams for muon colliders, neutrino factories, and many other applications. The high-pressure gas suppresses dark currents, multipacting, and other effects that are complicating factors in the study of breakdown in usual RF cavities that operate in vacuum. In the studies reported here, various metals are tested in a pressurized cavity where RF breakdown is expected to be due only to the interaction of the metallic surfaces with the electromagnetic fields. After exposure to the RF fields, metallic Be, Mo, Cu, and W samples were examined using High-Scope Advance microscope (Hirox†) and scanning electron microscope (SEM) to determine if breakdown events are associated with characteristics of the material surfaces.

Apparatus

The Test Cell (TC) [2] is a cylindrical RF cavity used in the MuCool Test Area (MTA) at Fermilab. The TC is made of copper-plated stainless steel, and has inner height by diameter dimensions of 3.2 in x 9.0 in. Within the TC, two 1 in radius hemispherical electrodes of various materials are interchangeable and mounted along the cylinder axis as shown in Figure 1. The cavity is powered at 805 MHz by a klystron located in the Fermilab Linac gallery via an 87 m waveguide and short coaxial line.

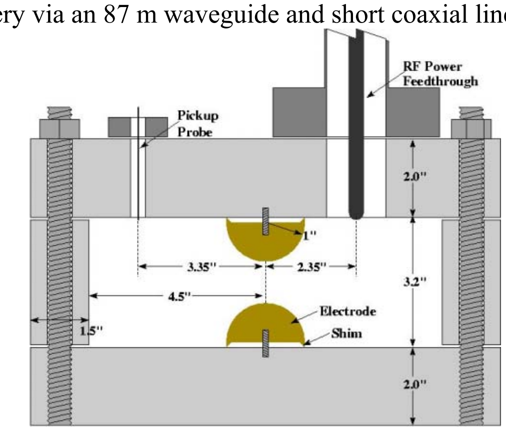

Figure 1: Cross-section of the Muons, Inc. Test Cell.

EXPERIMENTAL RESULTS

The experimental results of maximum stable RF gradient as a function of hydrogen pressure for both the external magnetic field on and off are shown in Figure 2. The usual model for this is that increased gas density reduces the mean free collision path for ions giving them less chance to accelerate to energies sufficient to initiate showers and avalanches.

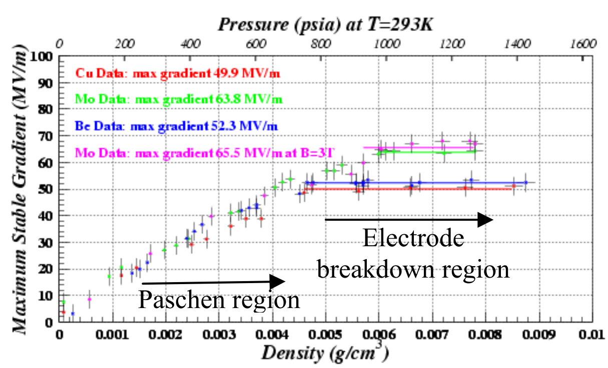

Figure 2: Maximum stable TC gradient as a function of hydrogen gas density and pressure.

As shown in Figure 2, it is found that Cu and Be electrodes operated stably with surface gradients near 50 MV/m, Mo near 65 MV/m, while W achieved values near 75 MV/m. These results differ considerably from the predictions of most models of breakdown in evacuated cavities [3]. The four electrode materials were run at their maximum voltages for several hours. Later, they were

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examined with an SEM. The copper electrodes were too badly damaged to interpret the breakdown events. The data reported below are from the other three materials.

To study breakdown behavior, the electrode surfaces were mapped and scanned using SEM and Hirox microscope. Small areas on each electrode were examined and the local surface density of breakdown remnants was recorded as a function of the zenith angle, defined on figure 3.

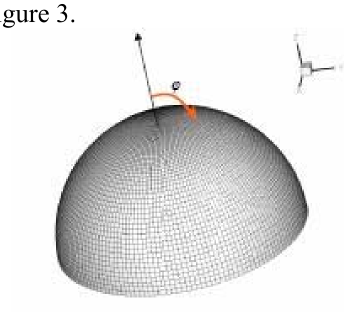

Figure 3: Schematic of the mapped electrode.

Beryllium

On Be, breakdown remnants mostly look like melted areas in a tadpole shape with head and tail (figure 4). Bubble holes seen in the head may represent evidence of boiling.

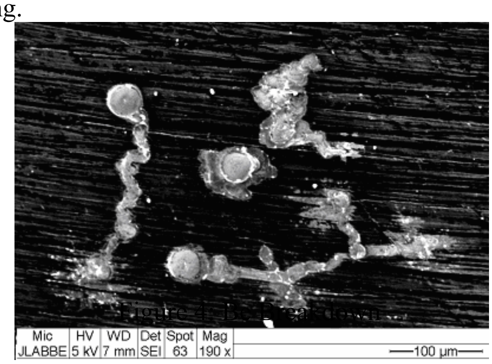

Figure 4: Beryllium breakdown remnants.

Molybdenum

For Mo the breakdown remnants look like overlapped circular melted regions. Small holes in the melted region may be vents of metallic vapor due to boiling (Figures 5, 6). Tiny cracks are mostly seen in the breakdown areas. The other type of breakdown seen on Mo, looks like exploded areas with some splashes that can be seen more individually as moving farther from the center of the electrode.

Figure 5: Molybdenum remnants.

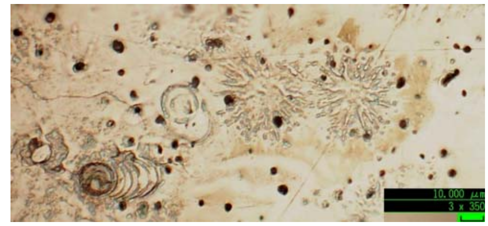

Figure 6: Molybdenum Breakdown.

Tungsten

Tungsten breakdowns look like furrow shape melted areas extended on the surface ending in a series of overlapped circles (Figures 7, 8, 9). There are cracks that are seen on the breakdown areas; the assumption is that cracks occurred subsequent to breakdowns because they are seen on the last ending circle of the set of repeated circles.

Figures 7, 8, 9: Tungsten Breakdown.

DATA ANALYSIS

To investigate the correlation of breakdown and the electric field, the local surface density of breakdown remnants has been compared with the maximum expected electric field using an ANSYS model. Least squares fits of the data to a power of the predicted maximum electric gradient at the surfaces of the electrodes show good agreement for high values of the exponent. A systematic error of 20% was assigned to each data point based on

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variations of independent density determinations at constant zenith angle. The statistical error from the number of breakdown events in the examined area was added in quadrature with the systematic error. Figure 10 shows the predicted maximum surface gradient (dashed), the data (black with error bars) as described above, and the best least squares fit (red) to the data y=0.34E^7 versus zenith angle for Be. Figures 11 and 12 show the experimental data, the ANSYS model data, and best fits for Mo and W respectively.

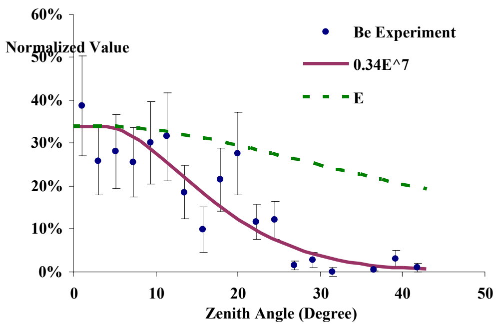

Figure 10: Be breakdown area fraction vs. zenith angle.

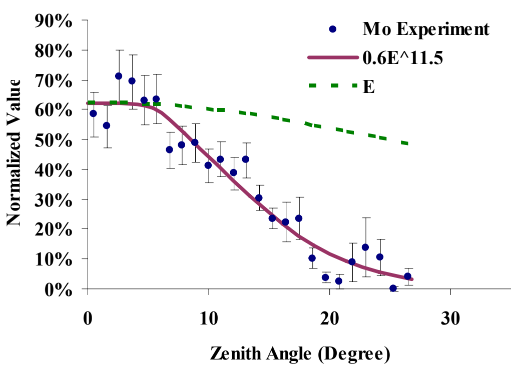

Figure 11: Mo breakdown area fraction vs. zenith angle.

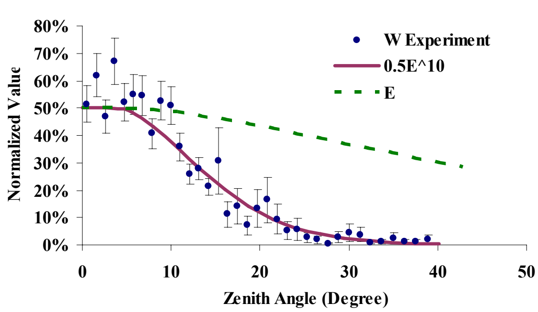

Figure 12: W breakdown area fraction vs. zenith angle.

The plots also show that the breakdown data correlates with the high powers of electric field that is 7 for Be, 11.5 for Mo and 10 for W.

The Fowler-Nordheim theory of field emission is based on a quantum mechanical solution to the Schroedinger equation [5] whereby electrons tunnel through a barrier in the presence of a high electric field. This theory, which describes field emission measurements over many orders of magnitude, can be expressed as [1, 6]:

$$I(E_{Surf}) = \frac{A_{FN}(\beta E_{Surf})^2}{\phi} \exp\left(-\frac{B_{FN}\phi^{3/2}}{\beta E_{Surf}}\right) \quad (1)$$

and $$E = \beta E_{Surf} \quad , \quad (2)$$

where $I(E_{Surf})$ is the dark current in A/m^2, E_{Surf} is the surface electric field in MV/m, ϕ is the work function of the material in eV, $A_{FN} = 1.54 \times 10^6 \, eVA/(MV)^2$, $B_{FN} = 6830 MV/m(eV)^{3/2}$ and β is the ratio of local electric field to the average surface field. The emitted current is $I(E) = A_{rf} A_e i(E)$ where A_e is the total emitter area and A_{rf} is the time variation of the sinusoidal field correction [4, 7, 8]. The observed power-law dependence of *I(E)* and E_{acc} [8] is described as

$$I(E) \propto E_{acc}^n , \quad (3)$$

where E_{acc} is the accelerating field.

CONCLUSION

The breakdown data shown in figures 10, 11 and 12 show good agreement with relation (3). This strong electric field dependence of the breakdown in pressurized gas is so similar to the dark current dependence predicted by Fowler and Nordheim that breakdown of a metal in a strong electromagnetic field is very likely also a quantum mechanical effect. We are designing an experiment to test this hypothesis.

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