BREAKDOWN IN PRESSURIZED RF CAVITIES*

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Abstract

The performance of many particle accelerators is limited by the maximum electric gradient that can be realized in RF cavities. Recent studies have shown that high gradients can be achieved quickly in 805-MHz cavities pressurized with dense hydrogen gas, because the gas can suppress, or essentially eliminate, dark currents and multipacting. In this project, two new test cells operating at 500 MHz and 1.3 GHz will be built and tested, and the high pressure technique will be used to suppress the vacuum effects of evacuated RF cavities, so that the role of metallic surfaces in RF cavity breakdown can be isolated and studied as a function of external magnetic field, frequency, and surface preparation. Previous studies have indicated that the breakdown probability is proportional to a high power of the surface electromagnetic field, in accordance with the Fowler-Nordheim description of electron emission from a cold cathode. The experiments will be compared with computer simulations of the RF breakdown process.

INTRODUCTION

RF cavities pressurized with hydrogen gas are being developed to produce low emittance, high intensity muon beams for muon colliders, neutrino factories, and 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 were 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 a Hirox microscope and a scanning electron microscope (SEM) to measure the distribution of breakdown events on the electrode surfaces [1].

Apparatus

A schematic of the 805 MHz Test Cell (TC) geometry is shown in Figure 1. The TC is a cylindrical stainless steel pressure vessel. RF power is fed into the chamber via a coaxial line. A solenoid magnet (not shown in the figure) provides an axial magnetic field of up to 3 T, which is used in some of the data sets. Replaceable hemispherical electrodes of various materials (Cu, Mo, Be, W) are separated by a 2 cm gap.

*Supported in part by the US DOE under grants DE-FG02-08ER86350, -08ER86352, and -05ER86252
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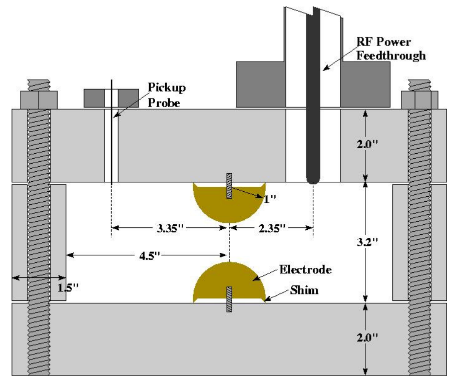

Figure 1: Cross section of the 805-MHz test cell showing the replaceable one inch radius Cu, Be, Mo, or W, hemispherical electrodes. The top and bottom plates and the cylinder are copper-plated stainless steel (the gas input/exhaust port is not shown in the figure).

EXPERIMENTAL RESULTS

RF Breakdown

Increasing gas density reduces the mean free collision path for ions giving them less chance to accelerate to energies sufficient to initiate showers and avalanches. As shown in Figure 2, it is found that Cu and Be electrodes operated stably with surface gradients near 50 MV/m, Mo near 63 MV/m, and W near 72 MV/m [2].

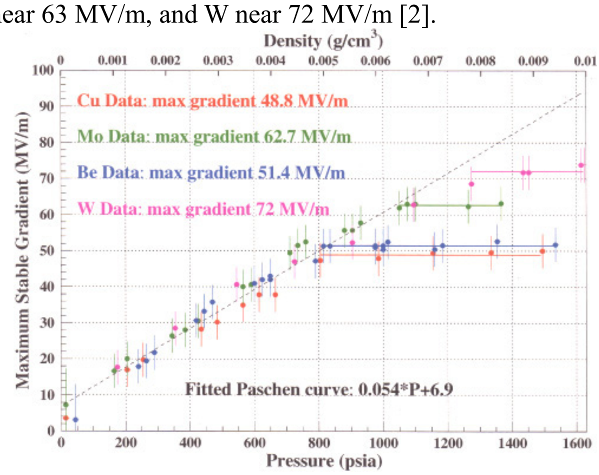

Figure 2: Maximum stable TC gradient as a function of hydrogen gas density or pressure for Cu, Be, Mo, and W with no external magnetic field.

EXPERIMENTAL DATA ANALYSIS

To investigate the correlation of breakdown and the electric field, the local surface density of breakdown remnants was compared with the maximum expected surface electric field, which was calculated 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. Figure 3 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 4 and 5 show the experimental data, the ANSYS model data, and best fits for Mo and W respectively.

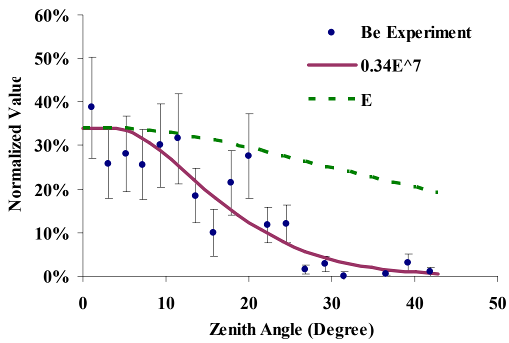

Figure 3: Be breakdown area fraction vs. zenith angle.

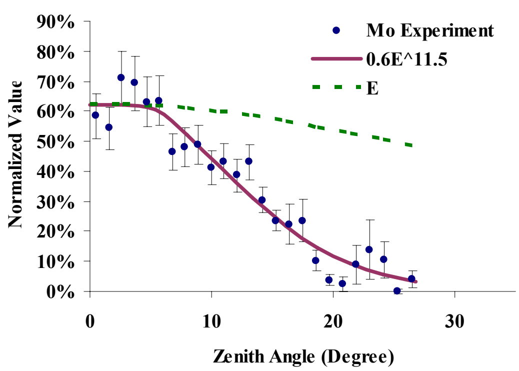

Figure 4: Mo breakdown area fraction vs. zenith angle.

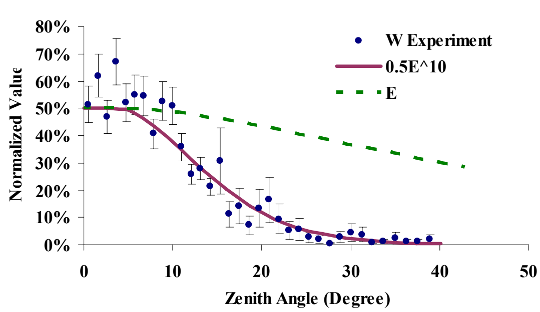

Figure 5: W breakdown area fraction vs. zenith angle.

The plots also show that the breakdown data correlate with a high power of electric field: 7 for Be, 11.5 for Mo and 10 for W. This suggests that the breakdown is a quantum mechanical effect described by the Fowler-Nordheim theory of field emission [3] by tunnelling of electrons through a barrier in the presence of a high electric field.

MELTING OR BOILING POINTS

The maximum stable gradient for each of the four electrode materials is shown on figure 6. For these data, the 805 MHz TC was operated at 5 Hz repetition rate with 100 microsecond long pulses. The maximum gradients that were achieved show a correlation with the melting points and with the boiling points of the electrode metals.

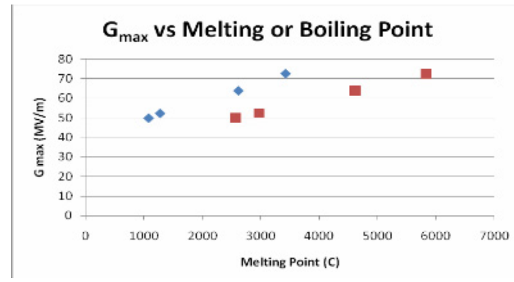

Figure 6: Maximum stable gradient as a function of metallic melting point (blue diamonds) or boiling point (red squares). From left to right, the four data points correspond to Cu, Be, Mo, and W.

Table 1: Material Properties

Metal	Cu	Be	Mo	W
Melting point [C]	1083	1278	2617	3422
Boiling Point [C]	2567	2970	4612	5828
Heat of fusion [KJ/mol]	13.05	12.20	32	35.40
Heat of vaporization [KJ/mol]	300.3	292.4	598.0	824.0

FIRST COMPUTER SIMULATIONS

The first computer simulations of RF Breakdown have begun.

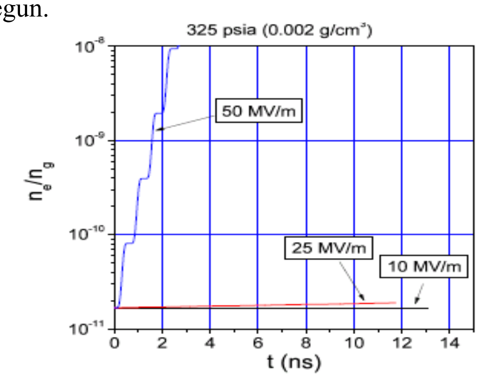

Figure 7: Electron density as a function of time at 805 MHz and gas density 0.002 g/cm^{-3}.

Computer calculations to simulate the behaviour of breakdown in helium-filled spark-gap switches have been extended to the case of the hydrogen-filled Muons, Inc. test cell [4]. Figure 7 shows the simulation results for three electric field strengths, where the electron density is stable below the Paschen curve (10 MV/m), slightly unstable at the curve (25 MV/m), and very unstable for values above the curve (50 MV/m). These simulation results agree with the experiments.

SIMPLE MODEL OF BREAKDOWN

The correlation of maximum gradient with melting and boiling points, the SEM and optical pictures, and the Fowler-Nordheim dependence of the observed breakdown probability argue for a simple breakdown model for pressurized RF cavities that should apply to some aspects of vacuum cavity breakdown as well.

1. A feature on the metal surface (perhaps a bump, a grain boundary, or an inclusion) is a source of a strong Fowler-Nordheim field emission current.
2. The electrons flow through the metal below the source and heat the metal, before they are emitted from this source. The resistivity increases locally, and a runaway temperature occurs.
3. When the metal becomes hot enough locally, it can weaken or melt, so that the metal surface deforms into more or enhanced peaks with larger local fields and more local current. These peaks can be blown off and vaporized.
4. Alternatively, the metal can just boil to vent vapor into the gap. Pictures of the Be electrodes show this behavior.
5. A third possibility is that explosive boiling at the metal surface could expel some of the melted metal. Some of the W data show this behavior.
6. In any case, it appears likely that deformed metal surfaces, melted metal in the gap, or metal vapor in the gap may be the initiating events that lead to RF breakdown in pressurized cavities.

FUTURE PLANS FOR THIS STUDY

We have begun a new phase of investigations of RF breakdown in pressurized cavities. It is a multi-institutional study that will include the construction of two new test cells that will operate at 500 MHz and 1.3 GHz. The goal is to use the pressurized cavity to isolate the role of the metallic surfaces in RF breakdown, and breakdown will be studied as a function of external magnetic field, radiofrequency, the metal chosen for the electrodes, and surface preparation. Progress on this study is reported as follows.

1. A brief set of experiments is being carried out with the 805-MHz test cell at Fermilab. New electrode metals and new gas mixtures are being investigated. One important result is the successful operation of the test cell using nitrogen gas, because future experiments using nitrogen will avoid some of the safety concerns of high-pressure hydrogen gas.
2. The next set of experiments will be carried out at LBNL using the 500-MHz test stand. Therefore, a 500-MHz test cell is being designed and fabricated, and it will be assembled and tested at LBNL with nitrogen gas.
3. Details of the 500-MHz RF breakdown studies are being worked out, including metal selection for the electrodes, methods to study the metal surfaces, and other aspects of the experimental design.
4. Numerical simulation efforts have begun, and the goal will be to develop a consistent theoretical model of RF breakdown in pressurized cavities, a model that can be applied to the behavior of metal surfaces in vacuum RF cavities as well.
5. A follow-on experiment has been tentatively defined as the construction and test of a third test cell, one that will operate at 1.3 GHz at a test stand at ANL.

CONCLUSIONS

A series of experiments with an 805 MHz test cell has provided a great deal of data on the characteristics of RF breakdown in pressurized RF cavities. At high gas pressures, the maximum test cell gradient reaches a plateau that reveals properties of the metal surface during RF breakdown. Examination of the metal electrode surfaces reveals evidence of locally high temperatures (melting and boiling), and a study of the local surface density of breakdown remnants suggests that the breakdown process is a quantum mechanical effect described by the Fowler-Nordheim theory of field emission by tunnelling of electrons through a barrier in the presence of a high electric field.

These studies are being extended in a new phase of experimentation that will include the use of a number of metal electrodes in two new test cells designed to operate at 500 MHz and 1.3 GHz. In addition, the numerical simulation of the RF breakdown process will be extended in an effort to develop a consistent and more complete model of RF breakdown in pressurized RF cavities. It is likely that this model will apply to some aspects of RF breakdown in vacuum RF cavities as well.

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