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RF BREAKDOWN STUDIES USING A 1.3-GHZ TEST CELL*

R. Sah†, R. P. Johnson, M. Neubauer, Muons, Inc., Batavia IL
M. Conde, W. Gai, ANL, Argonne, IL
A. Moretti, M. Popovic, K. Yonehara, Fermilab, Batavia, IL
J. Byrd, D. Li, LBNL, Berkeley, CA
M. BastaniNejad, M. Elmustafa, ODU, Norfolk,VA

Abstract

Many present and future particle accelerators are limited by the maximum electric gradient and peak surface fields that can be realized in RF cavities. Despite considerable effort, a comprehensive theory of RF breakdown has not been achieved and mitigation techniques to improve practical maximum accelerating gradients have had only limited success. Recent studies have shown that high gradients can be achieved quickly in 805 MHz RF cavities pressurized with dense hydrogen gas without the need for long conditioning times, because the dense gas can dramatically reduce dark currents and multipacting. In this project we use this high pressure technique to suppress effects of residual vacuum and geometry found in evacuated cavities to isolate and study the role of the metallic surfaces in RF cavity breakdown as a function of magnetic field, frequency, and surface preparation. A 1.3-GHz RF test cell with replaceable electrodes (e.g. Mo, Cu, Be, W, and Nb) and pressure barrier capable of operating both at high pressure and in vacuum has been designed and built, and preliminary testing has been completed. A series of detailed experiments is planned at the Argonne Wakefield Accelerator. At the same time, computer simulations of the RF Breakdown process will be carried out to help develop a consistent physics model of RF Breakdown. In order to study the effect of the radiofrequency on RF Breakdown, a second test cell will be designed, fabricated, and tested at a lower frequency, most likely 402.5 MHz.

INTRODUCTION (805-MHZ STUDIES)

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 earlier 805-MHz studies, various metals were tested in a pressurized cavity where RF breakdown is expected to be due 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].

Experimental Results: RF breakdown

Unlike in the case of vacuum RF breakdown, high-pressure RF breakdown exhibits different behavior in two distinct regimes: (1) a gas breakdown region where the maximum gradient follows the Paschen curve, and (2) a surface breakdown region where increasing the gas pressure does not change the maximum gradient. See Figure 1.

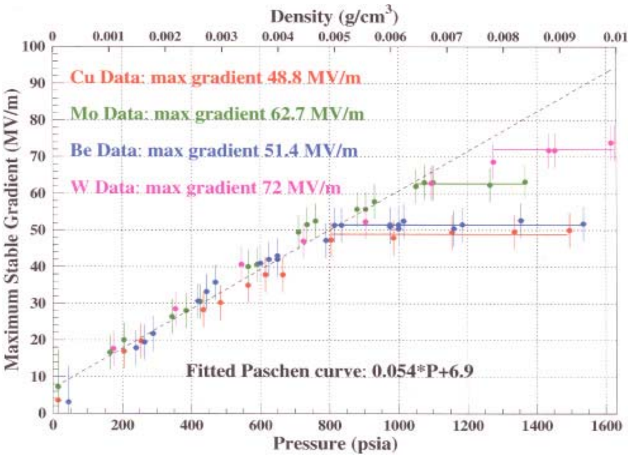

Figure 1: Maximum stable TC gradient as a function of hydrogen gas density or pressure for Cu, Be, Mo, and W with no external magnetic field.

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. It was found that Cu and Be electrodes operated stably with surface gradients near 50 MV/m, Mo near 63 MV/m, while W achieved values near 72 MV/m [2].

To investigate the correlation of breakdown and the electric field, the local surface density of breakdown remnants was 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 showed good agreement for high values of the exponent. These results showed that the breakdown data correlated with a high power of electric field (7 for Be, 11.5 for Mo, and 10 for W) and suggest that the breakdown is a quantum mechanical effect described by the Fowler-Nordheim

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†richard@muonsinc.com

theory of field emission [3] by tunneling of electrons through a barrier in the presence of a high electric field.

Recent Experimental Results

The experiments at Fermilab were recently extended to include electrodes made of tin, aluminum, and copper. The maximum stable RF gradient in the surface breakdown region increased linearly with the melting point of the metallic electrodes. Since the melting point should scale with the bond strength, it is possible that the important parameter might be bond strength or fatigue limits, as has been suggested by recent work by Dolgashev and Tantawi [4].

Also, the experiments at Fermilab included the use of N_2 gas and the use of SF_6 as an electronegative dopant to capture free electrons.

NEW TEST CELLS

1.3 GHz Test Cell

A 1.3 GHz test cell was designed by scaling the 805 MHz cell internal dimensions. See Figure 2. The input power is through a 1-5/8” coax with an epoxy window designed for high pressure from the 805 MHz cavity test assembly. The pickup probe is a 0.141” coax antenna with an OSM connector. The vacuum seal for the probe is a mini-conflat flange and the seal for the threaded vacuum port is a viton o-ring seal. All other seals are 0.008” aluminum shims. The 1-5/8” coax seal was torqued to 40 ft-lbs and the cavity seals torqued to 90 ft-lbs. The cavity is designed to withstand 1600 psi pressure, and is made from copper-plated 316 stainless steel. The top and bottom “lids” are 2 in. thick and the cylindrical walls are 1.6 in. thick. The electrodes are OFHC copper.

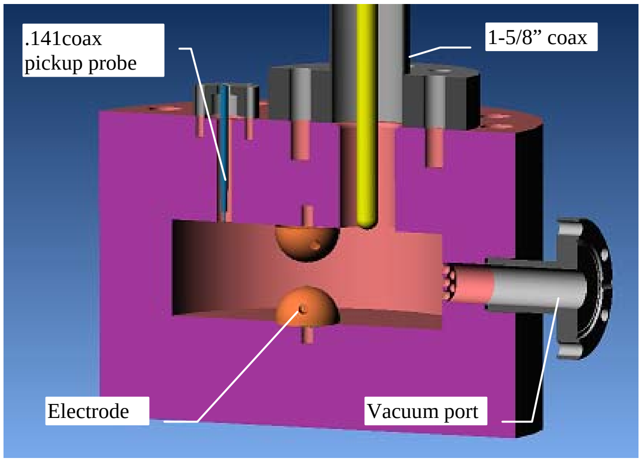

Figure 2: Cutaway view of the 1.3 GHz Cavity

The 1.3-GHz test cell was assembled at Fermilab and mounted on a pump stand, as shown in Figure 3. After cold testing was completed, the test cell was vacuum tested at Fermilab and found to hold a vacuum of about $5\ 10^{-6}$ Torr, measured at the ion pump. This vacuum was good enough to proceed with operation with RF power, so the test cell along with its pump stand was transported to the Argonne Wakefield Accelerator (AWA). Although our primary interest is to study the operation of this test cell under high-pressure conditions, it was decided to initiate high-power tests of this test cell under vacuum conditions, because it was much quicker to acquire safety approvals to operate under vacuum conditions.

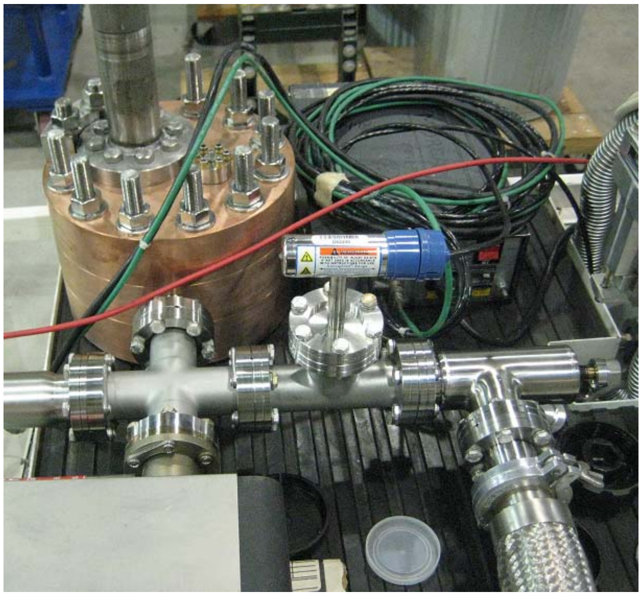

Figure 3: 1.3-GHz Cavity and vacuum System

The test cell’s coax feed line was connected to the output waveguide of the AWA 1.3-GHz test stand, via a transition element, and operation with RF power commenced. At the beginning, of course, there was considerable multipacting, and the gas pressure increased quickly. A process of RF conditioning was undertaken, in which the RF power was slowly increased, while keeping the gas pressure below $1\ 10^{-5}$ Torr. After 2.5 days of effort, the conditioning of the 1.3-GHz test cell was completed. At that point, the gas pressure was typically in the low 10^{-6} range at a 5-Hz pulse rate, and the pulse shape seen at the pickup electrode was clean, without any evidence of multipacting nor of RF breakdown.

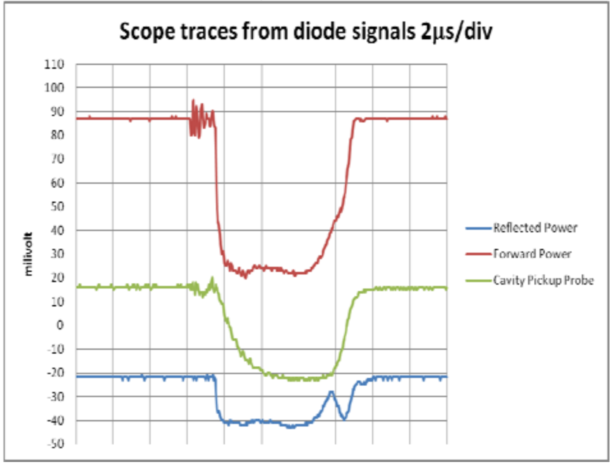

Figure 4: Scope traces of the signals from the 1.3-GHz test cell

Figure 4 shows the scope traces of the forward power, cavity pickup, and reflected power. Measurements of the RF parameters were analyzed, and the power in the test cell was found to be 221 kW, corresponding to a gradient of 71 MV/m.

The process of requesting ANL safety approval for high-pressure operation of this test cell has already begun. After this approval is granted, we plan to conduct a detailed series of experiments using this 1.3-GHz test cell. Among the many experimental variables we hope to study are different electrode metals, different surface preparation, different gases, and different magnetic fields.

402.5 MHz Test Cell

In order to study the effect of the radiofrequency on RF Breakdown in gas-filled cavities, we plan to conduct a follow-up series of experiments at a lower frequency. Because of the availability of a 402.5-MHz test stand at LBNL, it is likely that we shall choose this frequency. The plan is to bring this test stand to operational condition, design and build a 402.5-MHz test cell, and to conduct a similarly-detailed series of experiments at this lower frequency. Earlier, a 500-MHz test cell had already been designed as shown in figure 5, so we anticipate that a modification of the existing design will be used for the 402.5-MHz test cell.

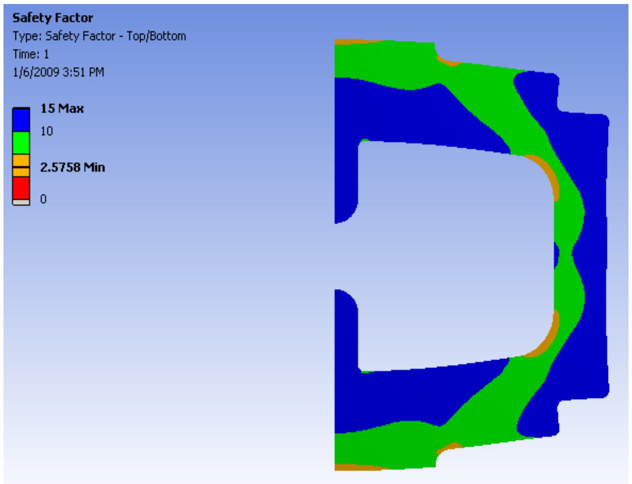

Figure 5: Axi-symmetric ANSYS calculations for the 500 MHz cavity with safety factor calculations at 1600 psi

COMPUTER SIMULATIONS

Separate computer simulations are being carried out for the gas breakdown region and the surface breakdown region.

Gas Discharge Simulations

Muons, Inc. is presently working with Dr. Dave Rose of Voss Scientific on physical models of RF breakdown in hydrogen gas as part of our program to develop RF cavities for muon cooling [5]. This effort is directed toward understanding and mitigating breakdown in the conditions of a muon cooling channel, where there are large magnetic and radiation fields. This modeling effort is focused on the breakdown of the pressurized gas itself, but we now know that the nature of the gas also plays a role in the breakdown of the metallic surfaces of the cavity, even in the surface-breakdown region.

Metal Surface Simulations

ANSYS modeling will be used to study the heating of small areas of the metal surface. We shall examine the effects of current flow at asperities and at low-work-function areas, in order to understand the characteristic behaviors of different physical models. We expect these simple simulations to give us useful insights into the physics at the metal surface.

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