RF BREAKDOWN STUDIES USING PRESSURIZED CAVITIES*

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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 gas and geometry found in evacuated cavities to isolate and study the role of the metallic surfaces in RF cavity breakdown as a function of radiofrequency and surface preparation. A 1.3-GHz RF test cell with replaceable electrodes (e.g. Mo, Cu, Be, W, and Nb) has been built, and a series of detailed experiments is planned at the Argonne Wakefield Accelerator. These experiments will be followed by additional experiments using a second test cell operating at 402.5 MHz.

INTRODUCTION (EARLIER 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 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.

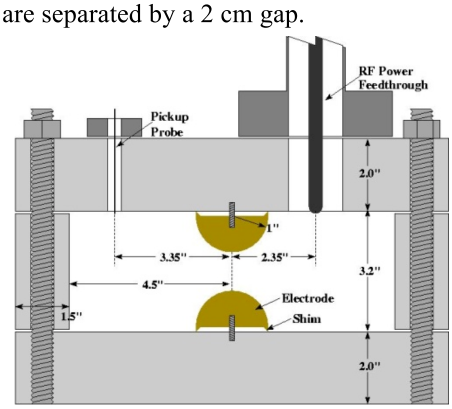

Figure 1: Cross section of the 805-MHz test cell showing the replaceable one inch radius Cu, Mo, W, or Be hemispherical electrodes. The top and bottom plates and the cylinder are copper-plated stainless steel (the gas input/exhaust port is not shown in the figure).

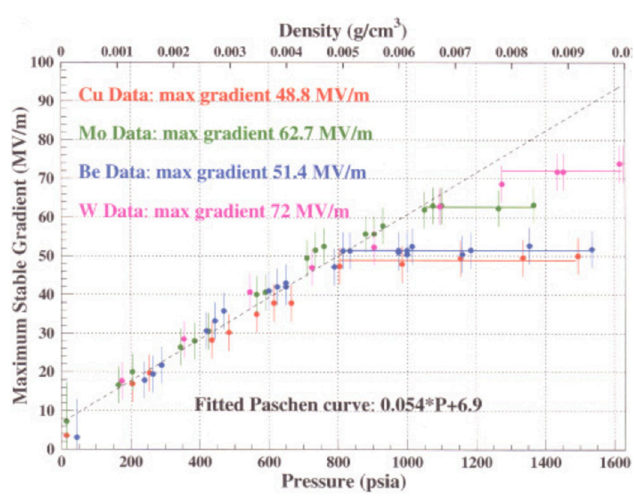

Figure 2: Maximum stable TC gradient as a function of hydrogen gas density or pressure for Cu, Be, Mo, and W with no external magnetic field.

Experimental Results: RF breakdown

Increasing gas density reduces the mean free collision path for ions giving them less chance to accelerate to

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*work supported in part by USDOE STTR Grant DE-FG02-08ER86352 and FRA DOE Contract DE-AC02-07CH11359

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, while W achieved values near 72 MV/m [2].

NEW TEST CELLS

1.3 GHz Test Cell

A 1.3 GHz test cell was designed by scaling the 805 MHz cell internal dimensions. 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 .141 coax antenna with an OSM connector as shown in Figure 5.

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, but other interchangeable electrodes can be used.

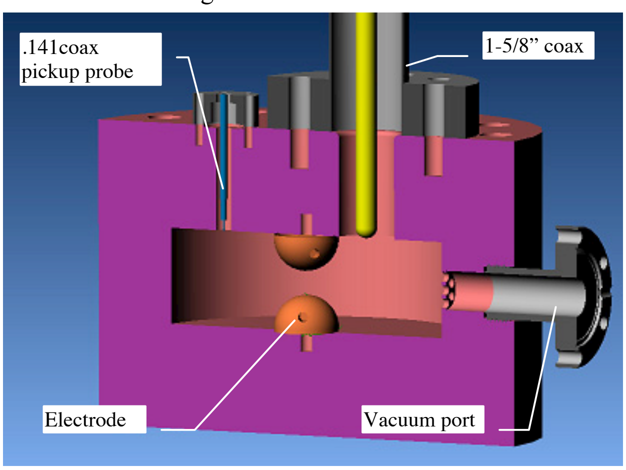

Figure 3: Cutaway view of the 1.3 GHz Cavity.

After assembly and vacuum testing at Fermilab, 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.

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. 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 electrodes made of different metals, surface preparation, and different gases.

Frequency Tuning

High-pressure testing of the 1.3-GHz test cell will involve pressures of 0 to 1500 psi. For a fixed test-cell geometry, the resonant frequency will vary as the pressure of the hydrogen gas, according to Figure 4 below.

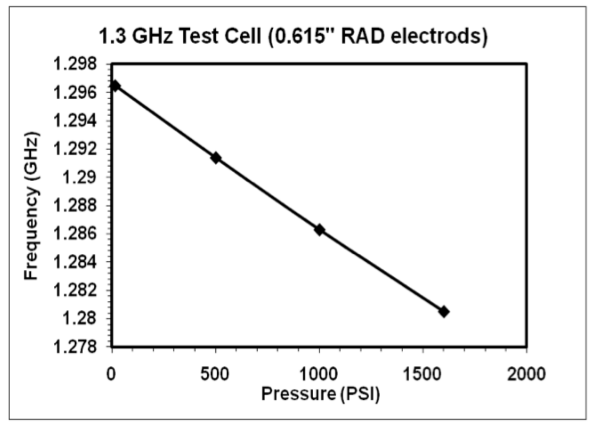

Figure 4: Resonant Frequency Varies with Pressure

Since the AWA test stand cannot provide frequency adjustments over the required range, it will be important to provide frequency adjustment in the design of the test cell itself. That is, when the gas pressure is varied, the frequency shift should be compensated, so that the test-cell resonant frequency remains at 1.3 GHz.

An adjustable electrode has been designed to perform this function without opening the cavity. The electrode will be built into a new cavity end plate, and will be pressure sealed using a Static O-Ring Seal. With proper design these seals are good for sealing up to 103.5 bar (~1500 psi). Our design will incorporate two such O-rings in series, backing rings, and close tolerances. Any "leakage" past the O-rings will be slight. The electrode will electrically contact the end-wall of the cavity using a finger stock ring within the end wall just below the inner surface of the cavity. Superfish and Comsol simulations show that a single electrode movement of ~30 mils will be sufficient to vary cavity frequency over the range necessary to accommodate the change due to the 1500 psi pressure change. When using a 3/32 – 32 threaded rod to move the electrode, approximately one complete turn of the rod will move the electrode by 31 mils. Assuming a test point is taken roughly every 200 psi of pressure, the rod will need to move ~4 mils, or ~45° between test points.

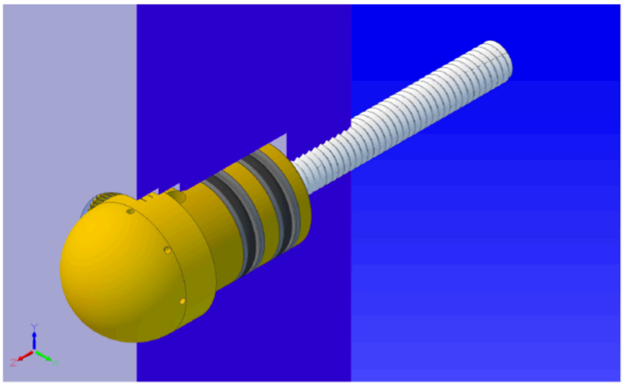

Figure 5: Cut-away view of moveable electrode design.

402.5 MHz Test Cell

In order to study the effect of the radiofrequency on RF Breakdown in gas-filled cavities, we plan to work with our LBNL colleagues to conduct a follow-up series of experiments at a lower frequency, most likely 402.5 MHz.

COMPUTER SIMULATIONS

The data in Figure 2 shows that there are two distinct regimes for the observed RF breakdown: a low-pressure region where the effects of the gas and the gas pressure dominate, and a high-pressure region where the characteristics of the metal surface dominate.

Gas Discharge Simulations

Fully kinetic, collisional particle simulations using the LSP code [3] have been carried out to study breakdown field threshold as a function of pressure for H_2 with small admixtures of electronegative gases. The initial phase of the modeling effort included inter-species elastic and inelastic processes such as electron-neutral and Coulomb scattering, ionization, and attachment. Starting from a low-density seed plasma population, the growth and decay of the plasma density over many RF cycles was used to estimate field gradient breakdown curves for different gas mixtures [4]. This modeling correctly predicted the increased breakdown strength at relatively low gas pressures that could be obtained through the inclusion of small admixtures of an electronegative gas such as SF_6 to H_2-filled RF accelerating cavities [5]. At higher pressures, the field gradient strongly deviates from the Paschen curve. The point at which the measurements begin to deviate from the Paschen curve and the behavior of this deviation at higher pressures is dependent somewhat on the choice of electrode material, gas mixture, the amplitude of an applied transverse magnetic field.

The next phase of the analysis is to examine the dynamic breakdown of high-pressure RF cavities through detailed numerical simulations. Measurements of the formative time associated with breakdown of the RF cavity, including light emission and the change in reflected RF input power, suggest relatively fast streamer-leader propagation times. Recently, a photon transport/ionization capability has been implemented in LSP for treatment of UV and soft x-ray radiation generation, transport and absorption. Preliminary simulations of streamer propagation in H_2 and SF_6 under DC fields are in good agreement with measured streamer propagation speeds [6]. Application of the simulation model to gas-filled RF cavities is planned to assist in the analysis of the measured breakdown characteristics. These models are also applicable to high-vacuum, high-gradient accelerator cavities.

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