HIGH PRESSURE RF CAVITIES IN MAGNETIC FIELDS *

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Abstract

The RF breakdown of dense hydrogen gas between metallic electrodes has been studied as part of a program to develop gas-filled RF cavities to be used for muon ionization cooling. A pressurized 805 MHz test cell was used at Fermilab to measure the increase in the breakdown threshold as a function of gas density, known as the Paschen effect. The breakdown behavior of copper, molybdenum, and beryllium electrodes as functions of hydrogen gas density are also reported. First results are reported of RF breakdown using molybdenum electrodes in dense hydrogen in a strong external magnetic field. Unlike evacuated cavities, the pressurized cavity shows no degradation of maximum stable gradient with increasing magnetic field.

INTRODUCTION

Most RF cavities associated with particle accelerators operate in excellent vacuum to avoid electrical breakdown. Electrons or ions that are accelerated by the high voltages in an evacuated RF cavity rarely encounter atoms of residual gas, so the avalanche process of breakdown does not occur. Other RF systems that do not require the ultrahigh vacuum of an accelerator typically suppress RF breakdown by using dense materials between electrodes. Ions passing through these materials, which include high-pressure and/or high-density gases, have such a short mean free path between collisions that they do not accelerate to energies high enough to create an avalanche. The relationship between the electrical breakdown voltage and the product of gas pressure and gap width is known as Paschen's Law. Based on the argument above, the threshold gradient for high voltage RF breakdown of a gas should depend on the gas density [1], the form of Paschen's Law that we will use.

This idea of filling RF cavities with gas is new [2,3] for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower electromagnetically as do less-massive electrons. The interest in intense muon beams, muon colliders, and neutrino factories based on muon storage rings has lead to interest in muon accelerators, and thus the need for muon beam cooling. Besides suppressing breakdown, the gas in the cavities also acts as the energy absorber needed for ionization cooling [4], where the angular spread in a beam is reduced by passing the beam through an absorber to reduce all momentum components and RF acceleration is used to replace the longitudinal component.

Although this dual function of suppressing RF breakdown and providing simultaneous energy loss for ionization cooling is the primary motivation for the development of such pressurized RF cavities, there is another very important function. That is, pressurized RF cavities can provide a continuous absorber for ionization cooling which can be used to cool the longitudinal motion of a muon beam [5,6]. This is achieved by providing a magnetic field to create dispersion such that higher momentum particles have a larger path length and correspondingly larger energy loss in the continuous absorber.

For ionization cooling, hydrogen and helium are the best gases because of their favorable energy loss and radiation length. However, hydrogen is superior in all aspects except for safety concerns. Hydrogen gas has over twice the ionization cooling effectiveness as helium in that it allows a final cooled emittance that is smaller by a factor of 1.5 in each transverse plane. At the same pressure, hydrogen suppresses RF breakdown at a voltage that is six times higher than helium [7]. Hydrogen is also superior in heat capacity and viscosity, which are important parameters for the engineering of a practical cooling channel.

APPARATUS

The Test Cell (TC) is a cylindrical RF cavity used for testing in the MuCool Test Area (MTA) at the Fermi National Accelerator Laboratory (Fermilab). The TC is made of copper-plated stainless steel, and has inner height by diameter dimensions of 3.2 x 9.0 in^2. Within the TC, two replaceable 1 inch radius hemispherical electrodes are mounted along the cylindrical 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, which has an epoxy-sealed pressure barrier 23 inches from the TC. A capacitively coupled pickup (PU) probe is mounted in the upper plate of the TC to measure the RF voltage as shown in figure 1. In addition to the pickup probe inside the cavity, there are two sets of directional couplers (DC) along the coaxial line which are used to measure the transmitted and reflected voltages into or from the cavity.

The cavity is designed to have a resonant frequency of 805 MHz and to couple to a 50 Ohm impedance waveguide/coaxial line. For an ideal pillbox cavity, the resonant frequency is given by $\nu_0 = 2.405\big/\sqrt{\varepsilon\mu R}$, where

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2.405 is the first zero of the first regular Bessel function, and R is the radius of the cavity. Since the material used in the cavity is non-magnetic, then $\mu = \mu_0$. The electrodes modify the TC behavior such that it does not act as in ideal pillbox cavity; however, the gas density within the cavity still determines ε and changes the resonant frequency by as much as 10 MHz over the range of densities of interest. Depending on the power required, the practical range of tuning for the klystron is about ν ~ 805±5 MHz, so that the TC has to be shimmed according to the expected frequency range of the planned experimental conditions. Circular 15 mil aluminum shims between the electrodes and the end plates are used to adjust the TC resonant frequency primarily by changing the capacitance due to the gap between the electrodes.

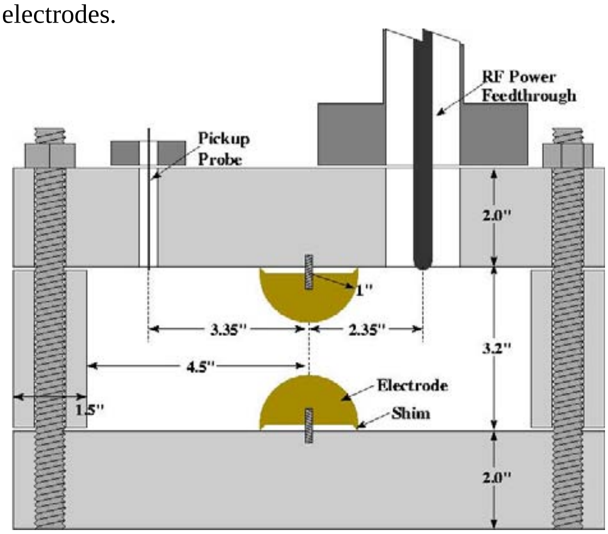

Figure 1: Cross section of the test cell showing the replaceable one inch radius Cu, Mo, or Be hemispherical electrodes. The top and bottom plates and the cylinder are copper-plated stainless steel (the gas input/exhaust port is not shown in the figure).

Small deviations from perfect coupling from the waveguide/coax to the cavity generate reflections of the RF signal due to impedance mismatch. Over the long length of waveguide between the klystron and the MTA, these reflected waves can add constructively to produce resonances. It was important to avoid running at frequencies where these resonances appeared, so the gas pressures were chosen to yield frequencies between these resonances.

A network analyzer was used to measure the quality factor Q_o and calibrate the pickup probe. The programs SuperFish and ANSYS were used to calculate the ideal Q_o and shunt impedance of the cavity from which the power for a given gradient was calculated. Effectively, the programs related the voltage at the pickup to the maximum surface gradient on the electrodes for the ideal quality factor. The ratio of the measured to ideal quality factor was then used to renormalize the pickup sensitivity.

The procedure for taking data was to set the gas pressure in the cavity, adjust the klystron frequency to match the resonant frequency in the cavity, and then ramp up the klystron power until a breakdown occurred. The power was then reduced until the signal was stable in the cavity; at this point the frequency, drive power, and voltages from the pick up and directional couplers were recorded.

Figure 2 is a picture of the TC in the MTA next to the LBNL superconducting solenoid used for the data shown in figure 3.

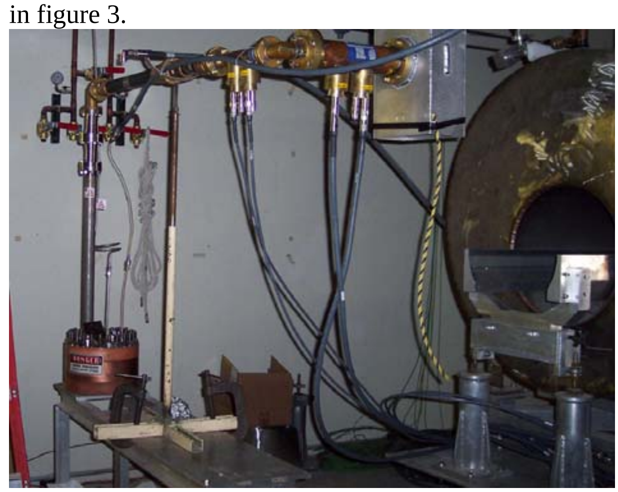

Figure 2: Photograph of the Test Cell in the MTA next to the LBNL superconducting solenoid.

DATA AND DISCUSSION

The data for the external magnetic field both on and off are shown in figure 3. The lower-pressure region in which the maximum stable gradient rises linearly with absolute pressure is called the Paschen region and is determined by the breakdown of the gas. The usual model for this is that increased gas density reduces the mean free collision path for ions or electrons so they have less chance to accelerate to energies sufficient to initiate showers. Within errors, the measurements in the Paschen region seem independent of electrode material and magnetic field.

At higher gradients, the metallic material of the electrodes breaks down. We have studied three electrode materials in order to find the best material for muon cooling applications and to test some theories of RF breakdown. Copper is the standard for RF cavities, molybdenum is a hard material expected to have good resistance to breakdown, and beryllium has a low atomic number that might be useful for ionization cooling of muon beams. As noted in earlier reports, the TC in the electrode-breakdown pressure region conditions quickly with no evidence of multipacting. But because of the short time available for the studies, we cannot be sure that the maximum gradients that were achieved could not have been higher.

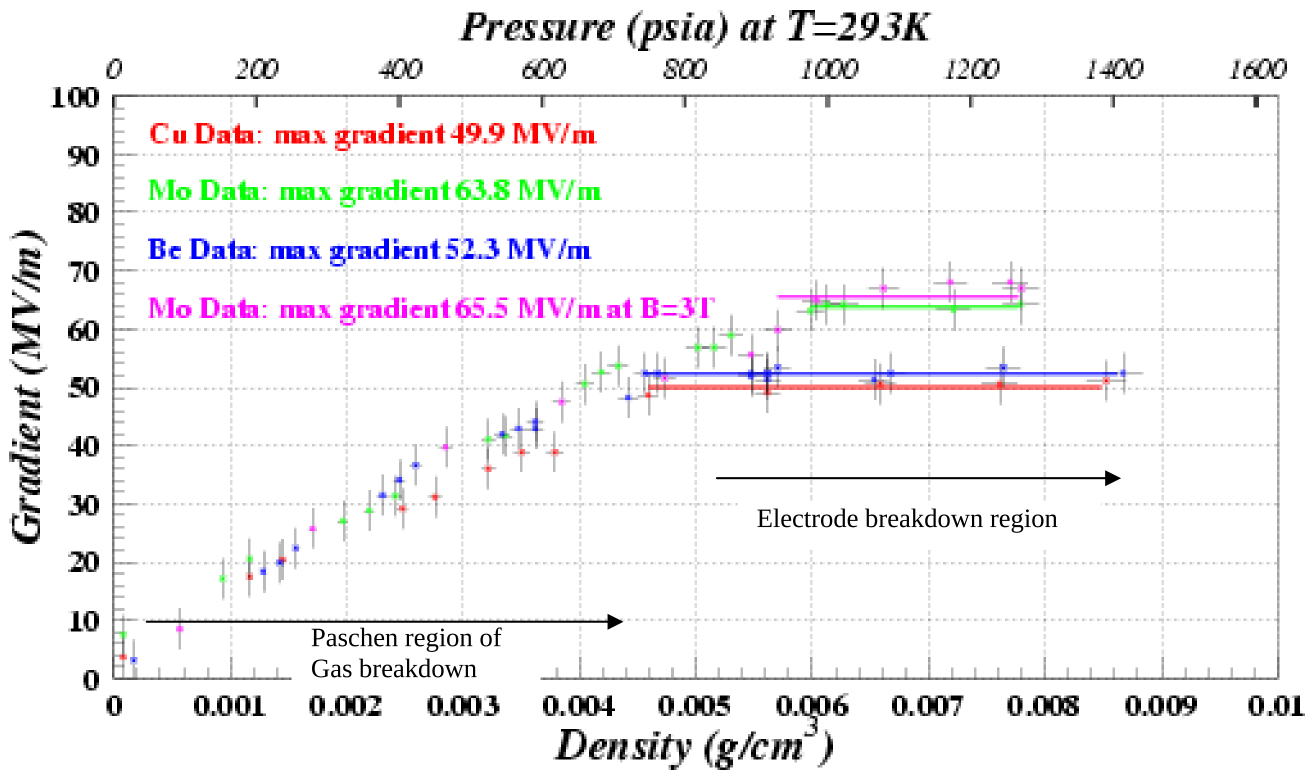

Figure 3: Measurements of the maximum stable TC gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue). As the pressure increases, the mean free path for ion collisions shortens so that the maximum gradient increases linearly with pressure. At sufficiently high pressure, the maximum gradient is determined by electrode breakdown and has little if any dependence on pressure. Unlike predictions for evacuated cavities, the Cu and Be electrodes behave almost identically while the Mo electrodes allow a maximum stable gradient that is 28% higher. The cavity was also operated in a 3 T solenoidal magnetic field with Mo electrodes (magenta); these data show no dependence on the external magnetic field, achieving the same maximum stable gradient as with no magnetic field.

We found that copper and beryllium electrodes operated stably with surface gradients near 50 MV/m while molybdenum achieved values near 65 MV/m. These are considerably different than most models of breakdown in evacuated cavities predict [8].

The maximum stable gradient was unaffected by the magnetic field for the molybdenum electrodes, the only material tested in the external magnetic field so far. This is considerably different than measurements at 800 MHz in evacuated copper cavities indicate, where the maximum surface gradient is reduced from 50 MV/m to 16 MV/m in going from 0 to 2.5 T external field [9]. Future tests will include W, Be, and Cu electrodes in the external magnetic field.

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