BEAM TESTS OF A HIGH PRESSURE GAS-FILLED CAVITY FOR A MUON COLLIDER

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Abstract

In this paper, progress is discussed in the study of a high pressure hydrogen gas-filled RF cavity for use in the cooling channel of a muon collider. An experiment at Fermilab has been performed using a 400 MeV proton beam to study beam effects in the gas of the cavity. Results of these tests and a preliminary model are shown. In addition, some preliminary tests are have been performed using an electronegative gas dopant, which mitigates beam effects induced in the hydrogen gas.

INTRODUCTION

An important milestone in the demonstration of a cooling channel for a muon collider is to operate an RF cavity within a strong magnetic field. Such cavities have reduced maximum field gradients due to the focusing of field emission electrons. Previous experiments have shown that a high pressure hydrogen gas-filled RF (HPRF) cavity can effectively mitigate this effect by de-focusing the field emission electrons through scattering [1,2,3]. A description of the physics processes that govern these effects can be found in [4].

Though an HPRF cavity will successfully hold a high gradient in a strong magnetic field, a beam passing through the cavity will ionize the gas and the resulting electrons will absorb RF energy held in the cavity. Therefore, the energy in the cavity must be restored, and the ionized electrons absorbed, before any subsequent bunch enters. In the case of a muon collider, a 400 MeV muon beam with 10^{11} muons per bunch will generate up to 10^{14} cm^{-3} in a 200 atm HPRF cavity. In such a scenario, nearly half of the RF acceleration field will be lost due to ionized electrons absorbing energy. Though these electrons will recombine with the gas in the cavity, this rate is not sufficient to restore the accelerating field before the next bunch arrives. However, the high pressure gas in the cavity can be doped with an electronegative gas to increase the rate of recombination. This paper describes preliminary results and analysis of beam tests of an HPRF cavity with and without an electronegative gas dopant using a 400 MeV H$^-$ beam at the MuCool Test Area (MTA) at Fermi National Laboratory. This paper also documents the first demonstration of an HPRF cavity at high gradient, in a strong magnetic field, while beam is passed through the cavity.

EXPERIMENT

The Muon Test Area (MTA)

A diagram of the HPRF experiment at the MTA is shown in Figure 1. From the MTA beamline, a 10 us pulse of $1.5x10^{12}$ H$^-$ is delivered at 400 MeV. The beam enters a pair of collimators with 20% transmission efficiency. The H$^-$ beam turns to a proton beam at the vacuum window and cavity wall as the electrons are stripped away. After the collimators, the beam passes through an 800 MHz pillbox cavity half-spherical electrodes in the center to enhance the field to enhance breakdown. Instrumentation for the HPRF experiment consists of a CCD camera to passively monitor the beam spot, two toroids before to measure the beam intensity, an RF pickup probe and two optical probes in the cavity connected to a spectrometer.

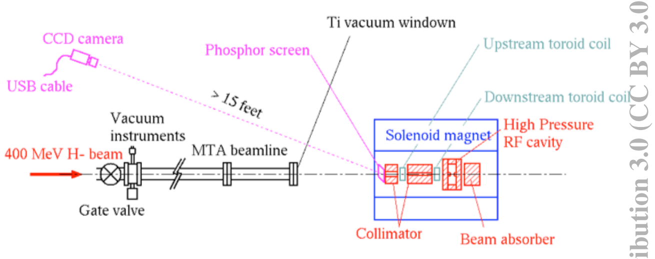

Figure 1: The Muon Test Area and the HPRF experiment.

The diverse instrumentation allows for multiple measurements of the effects of beam in the HPRF cavity. However, for the measurements discussed in this paper only the RF pickup probe and the toroid signals are used. In this experiment, studies were performed using RF field gradients of 0, 10, 20, and 30 MV/m, gas pressure from 300 to 1470 psi, and intensity at full strength, 1/7th and 10/10th of $3.5x10^{11}$ protons per pulse.

HPRF Cavity in a Magnetic Field

Previous studies by this group have demonstrated the potential of using high pressure gas to mitigate RF breakdown in a strong magnetic field [3]. Figure 3 shows the observed maximum gradient of an HPRF cavity as a function of the density (pressure) of hydrogen gas for test cavities with various metal electrodes, with and without a 3 Tesla magnetic field. The results demonstrate the ability of high pressure gas to mitigate the effects of RF breakdown in a strong magnetic field. In the Paschen region, as the pressure in the cavity rises so too does the gradient. Increasing the gas density decreases the mean free path between ion collisions, and therefore reduces the amount of energy an ion can pick up. This in turn reduces the probability of an ion initiating an avalanche or shower, which can lead to breakdown. The maximum gradient of the cavity peaks when the metal in the electrodes begins to break down. At this event, the electrode material is the determining factor for the maximum field gradient. From Figure 3, the maximum gradient found is 50 MV/m for Cu and Be and 65 MV/m for Mo.

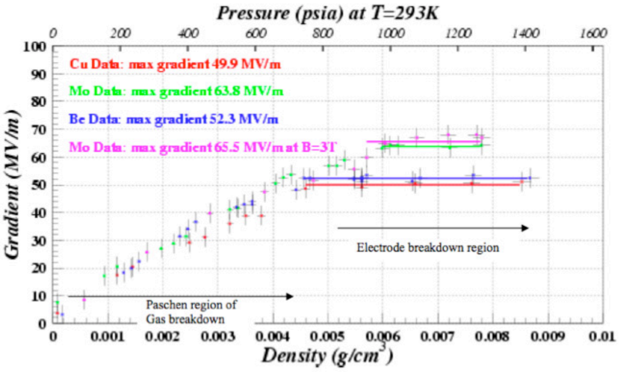

Figure 3: The maximum stable gradient as a function of hydrogen gas density for Be, Cu, and Mo with and without a 3 Tesla external magnetic field. The results demonstrate that high pressure gas can mitigate the effect of RF breakdown in a strong magnetic field.

HPRF Cavity Beam Test

Though previous results are encouraging, a beam passed through an HPRF cavity has the unfortunate effect of ionizing the gas, which in turn will absorb the stored RF energy in the cavity. For a muon collider or neutrino factory, any subsequent bunch after the first will experience a reduced or possibly non-existent accelerating field due to this effect. Figure 4 shows the envelope of the accelerating field in the cavity as measured by the RF pickup probe, as well as the signal of the downstream toroid. As seen in the figure, as the beam turns on the measured RF field is drastically reduced, though not completely absorbed, as an equilibrium state is reached where the electrons produced from the beam are recombining with positively charged ions. Once the beam has turned off, electrons are no longer produced and recombination with the ions in the gas allow for the RF field to be restored.

The recombination process is due to polyatomic hydrogen ions quickly forming cluster ions which in turn recombine with the electrons. This process can be described by $H_2^+ + H_2 \rightarrow H_3^+ + H$ which leads to additional interactions, forming cluster ions such as $H_3^+ + 2H_2 \rightarrow H_5^+ + H_2$, $H_5^+ + 2H_2 \rightarrow H_7^+ + H_2$ etc [4, 5]. This process happens rapidly. These polyatomic clusters recombine with the free electrons faster than H_2^+ or H^+.

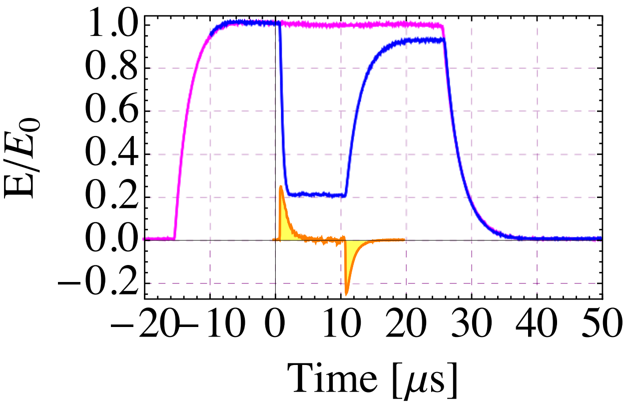

Figure 4: Envelope of the RF pickup probe signal in the HPRF cavity with beam (Blue) and without (Purple). The intensity and timing of the beam is monitored by a toroid (Yellow). The effect of the beam is clearly visible from the absorbed energy in the cavity by the ionized electrons.

The process of the beam producing electrons in the gas, absorbing the RF energy in the cavity, and recombining with positivs ions can be analytically modeled. The number of electrons produced in the cavity is predicted by the Bethe-Bloche formula <dE/dx>, the density of the gas (ρ_{gas}), and an empirically derived correction factor [6].

$$n_e = \left\langle \frac{dE}{dx} \right\rangle \cdot \frac{\rho_{gas}}{35\ eV}$$

The energy absorbed by those electrons per RF cycle (f) is a function of the charge (q), the electric field (E_{Field}), and the average drift velocity of the electron in E_{Field} [3,7].

$$E_{loss} = q \cdot E_{Field} \cdot v_{drift} \cdot \frac{1}{f_0}$$

The combination of these two equations predicts the RF energy loss in the cavity from the beam. As the electrons begin to recombine with the hydrogen ions, an empirically derived recombination rate (β) can be extracted from the above calculated energy loss and the data via:

$$\frac{dn_e}{dt} = \frac{dn_{e,beam}}{dt} - \beta n_e n_{ions}$$

As an example for this experiment, the 400 MeV proton beam and HPRF cavity filled with 950 psi hydrogen gas is predicted to produce 1600 electrons per proton in the cavity with an average energy loss per electron $3.3\text{x}10^{-17}$ J/cm at 30 MV/m. The extracted recombination rate is $1.2\text{x}10^{-8}$ cm^3/s.

Doping with an Electronegative Gas

The recombination rate for free electrons in the cavity can be improved by adding an electronegative dopant gas. There are several such candidate gases, and because these gases will have a different attachment cross-section as a function of electron kinetic energy, a study must be performed to determine the right gas for the right situation. However, for this experiment, 0.01% SF_6 was simply used because of availability. Mixtures of SF_6 in H_2 have been studied in the HPRF cavity without beam and demonstrated a 20% increase in the maximum RF gradient with these levels of SF_6. To accommodate the effect of the new gas in the rate of change for the number of electrons, the above model can be modified to include an additional attachment rate term (α).

$$\frac{dn_e}{dt} = \frac{dn_{e,beam}}{dt} - \beta n_e n_i - \alpha n_e$$

The measured field via a pickup probe is shown in Figure 5 for a 1470 psi hydrogen-filled 30 MV/m cavity with and without the SF_6 dopant. As seen in the figure, only 0.01% of SF_6 dramatically improves the rate of electrons absorbed back into the gas. In the above case, the average attachment rate is measured to be 14 ns at 30 MV/m and 1470 psi.

Though the results are very encouraging, a different gas than SF_6 must be chosen, as SF_6 may become dissociated during RF breakdown. This will form F^- and HF, which are very active elements that interact with metals. Indeed, damage on the surface of the cavity was observed after these measurements.

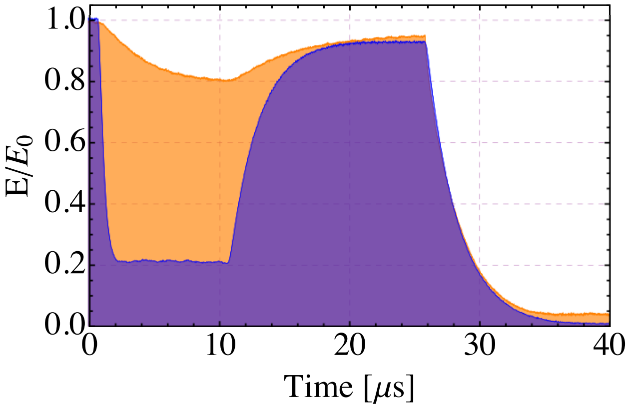

Figure 5: Envelope of the RF pickup probe signal in the HPRF cavity as the beam passes through with (Orange) and without (Purple) the presence of an electronegative gas (0.01% of SF_6). The presence of even a trace amount of SF_6 drastically improves the recombination rate of electrons in the HPRF cavity

Oxygen is also a strong electronegative gas and does not have corrosive properties. Though mixing hydrogen and oxygen can be dangerous, levels of oxygen in this test are kept well below any safety concerns. The measured field via a pickup probe is shown in Figure 6 for a 1470 psi hydrogen-filled 30 MV/m cavity with and without a dry air dopant. As seen in the figure, only 1% of air dramatically improves the rate of electrons absorbed back into the gas. These results demonstrate that an HPRF cavity can be used to drastically improve the maximum stable accelerating gradient in a strong magnetic field, and though more work must follow, a small amount of electronegative gas can be used to mitigate the effects of beam in a gas-filled cavity.

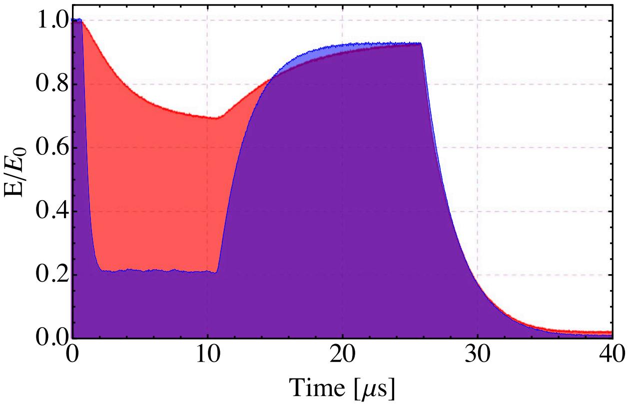

Figure 6: Envelope of the RF pickup probe signal in the HPRF cavity as the beam passes through with (Red) and without (Purple) the presence of an electronegative gas (1% of Dry Air). Similar to SF_6, a small amount of Oxygen drastically improves the recombination rate of electrons in the HPRF cavity.

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