RF TECHNOLOGIES FOR IONIZATION COOLING CHANNELS *

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Abstract

Ionization cooling is the preferred method of cooling a muon beam for the purposes of a bright muon source. This process works by sending a muon beam through an absorbing material and replacing the lost longitudinal momentum with radio frequency (RF) cavities. To maximize the effect of cooling, a small optical beta function is required at the locations of the absorbers. Strong focusing is therefore required, and as a result normal conducting RF cavities must operate in external magnetic fields on the order of 10 Tesla. Vacuum and high pressure gas filled RF test cells have been studied at the MuCool Test Area at Fermilab. Methods for mitigating breakdown in both test cells, as well as the effect of plasma loading in the gas filled test cell have been investigated. The results of these tests, as well as the current status of the two leading muon cooling channel designs, will be presented.

INTRODUCTION

Ionization cooling appears to be the only method of significantly reducing the emittance of a muon beam within the lifetime of a muon. The Muon Ionization Cooling Experiment (MICE) will validate simulation codes and demonstrate ionization cooling with reacceleration of a muon beam, and is currently underway [1]. The change in normalized transverse emittance with path length is given by

$$\frac{d\epsilon_n}{ds} = \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0} - \frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu} \qquad (1)$$

where $\beta = v/c$, $\beta_\perp$ is the transverse optical beta function, E_μ and m_μ are the energy and mass of the muon, respectively, and X_0 and $\left\langle \frac{dE_\mu}{ds} \right\rangle$ are the radiation length and stopping power of the absorbing material, respectively. The first term in Eq. 1 is the heating term, due to multiple scattering, and the second is the cooling term. To minimize the effect of multiple scattering, a small beta function at the location of the absorbers and a large absorber radiation length are ideal. Hydrogen and lithium hydride have been selected as absorbing materials, due to their radiation length and stopping powers.

A small beta function dictates strong focusing, and as longitudinal momentum lost in the absorbers is replaced by radio frequency (RF) cavities, these cavities are subject to external magnetic fields larger than 1 T. This immediately rules out the use of superconducting cavities, and an experimental program set out to determine how normal conducting RF cavities performed in such an environment at Lab G and currently the MuCool Test Area (MTA), both at Fermilab.

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BREAKDOWN IN RF CAVITIES

High voltage breakdown in both vacuum and gas has been studied extensively. The presence of a multi-tesla external magnetic field provided a new variable, however. As ionization cooling depends on RF cavities operating in such an environment, the performance of said cavities must be understood and characterized.

Early experiments focused on 805 MHz vacuum RF cavities. Both a six cell standing wave cavity and a single cell pillbox cavity were tested. The pillbox cavity allowed for different materials (copper, beryllium, molybdenum) and endplate structures (flat, curved, electrode) to be studied. The results of each indicated that there was a strong negative correlation between maximum accelerating gradient in the cavity and applied external magnetic field [2–5]. Plots from these experiments are shown in Figures 1 and 3.

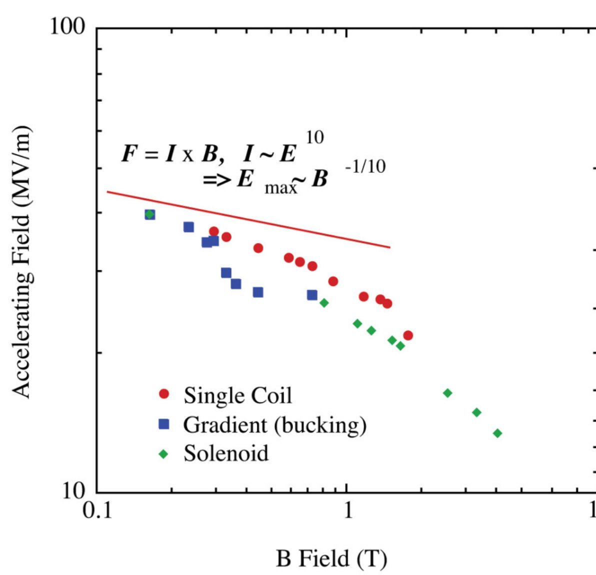

Figure 1: Maximum accelerating gradient as a function of external magnetic field from Ref. [3]. The data were collected with an 805 MHz vacuum pillbox cavity. Various coil configurations of the solenoid are shown.

A model to explain breakdown of RF cavities in external magnetic fields was proposed [6]. In this model, the mag-

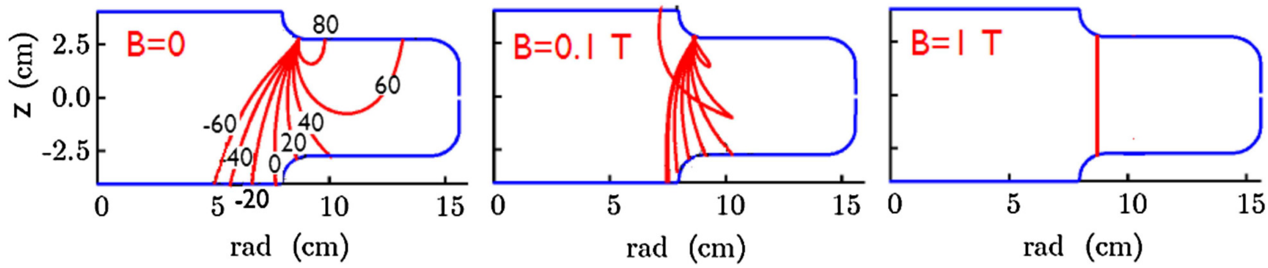

Figure 2: Simulation of the trajectories of field emission electrons as a function of magnetic field in an 805 MHz vacuum pillbox cavity from Ref. [6]. Phases of emitted electrons relative to the peak of the electric field are shown.

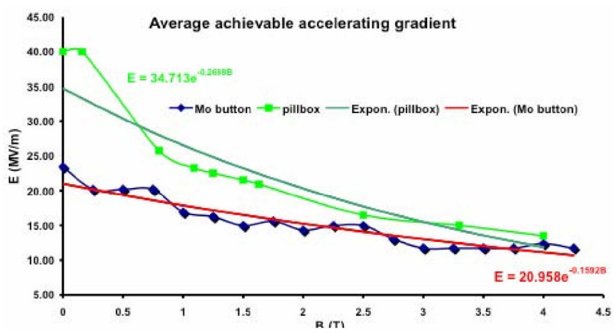

Figure 3: Maximum accelerating gradient as a function of external magnetic field from Ref. [2]. The data were collected with an 805 MHz vacuum pillbox cavity. Data for both the configuration of flat copper plates and a molybdenum electrode placed on the cavity axis are shown.

netic field focuses field emission electrons along trajectories with radii determined by the strength of the magnetic field. These "beamlets" of electrons impact the opposite surface of the cavity, depositing their energy. The surface heats after repeated bombardment, becoming damaged and creating new sources of field emission. This limits the achievable electric field. The stronger the magnetic field, the more focused the beamlets become, depositing energy in a smaller volume and more quickly leading to damage on the surface of the cavity. Figure 2 shows a simulation of how an external magnetic field affects the trajectories of electrons emitted from a location on one surface of an RF cavity.

GAS FILLED CAVITIES

It was suggested that filling an RF cavity with a high pressure gas would both prevent high voltage breakdown and provide an absorbing material [7]. Field emission electrons lose energy through collisions with gas molecules, regardless of the presence of an external magnetic field. The denser the gas, the more quickly energy is lost. The physics of gas breakdown still applies, and once electrons gain enough energy to ionize the gas, an electron cascade will take place, shorting the cavity.

In addition to pushing the breakdown limit higher, the gas can act as a cooling medium for the beam. Hydrogen provides an ideal stopping power and radiation length for ionization cooling. Experiments on both gas species and metallic material were performed. The results are shown in Figures 4 and 5.

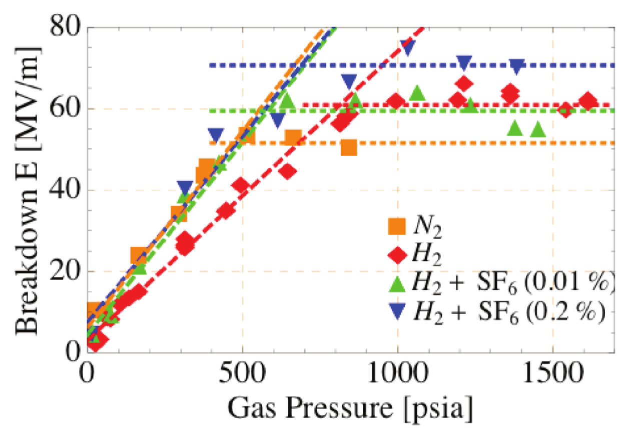

Figure 4: Maximum electric field as a function of gas pressure from Ref. [8]. Different gas species and dopants are shown for this 805 MHz pillbox cavity. A copper electrode was placed on the cavity axis to localize breakdown.

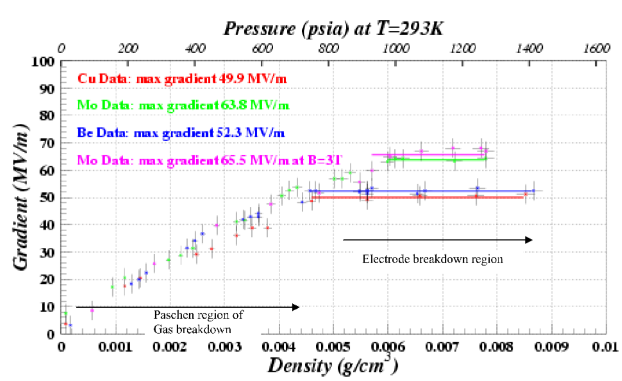

Figure 5: Maximum electric field as a function of gas pressure from Ref. [9]. Different material electrodes were placed on the cavity axis. This 805 MHz pillbox cavity was filled with hydrogen gas.

There was little difference in the breakdown gradient using molybdenum electrodes in hydrogen gas between no external magnetic field and a 3 T field. This provided the first demonstration of a technique to mitigate RF breakdown in an external magnetic field.

To demonstrate the viability of a gas filled RF cavity in an ionization cooling channel, the effect of an intense beam passing through a gas filled cavity was studied. The beam will ionize the gas within the cavity, creating a plasma. The plasma dissipates RF power through collisions with gas molecules; this process is called plasma loading. The amount of RF power a charged particle dissipates depends on its mobility (which roughly scales with mass) and the gas density. The plasma evolves over time through a number of processes. First, electrons recombine with positively charged ions. To speed up the charge neutralization time, an electronegative dopant may be added. Electrons may become attached to an electronegative molecule, and this process is typically much faster than electron-ion recombination. Finally, the negative ions formed by electron attachment may neutralize with positive ions, with a time scale longer than either electron-ion recombination or electron attachment. The RF envelopes shown in Figure 6 demonstrate this narrative.

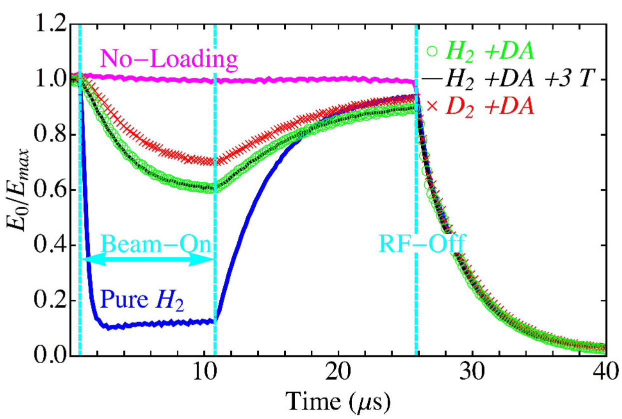

Figure 6: Normalized RF electric field envelope as a function of time from Ref. [10]. Various conditions are shown: normal RF envelope / "No Loading" (magenta), pure hydrogen with beam (blue), hydrogen doped with dry air with beam (green), hydrogen doped with dry air with beam in a 3 T external magnetic field (black), and deuterium doped with dry air with beam (red). The vertical dashed lines indicate the times at which the beam turned on and off, and the time at which the RF source shut off. The RF turn on has been omitted.

An RF envelope showing the flat top and decay once the source was turned off is shown for reference. Significant plasma loading in pure hydrogen is observed with the beam is turned on. The electric field recovers once the beam is turned off, as electrons recombine with hydrogen ions. When hydrogen or deuterium is doped with dry air, electrons may become attached to oxygen, which happens much faster than recombination. The observed plasma loading is then significantly less. The performance of the cavity is virtually identical in the presence of a 3 T external magnetic field.

Current High Pressure Program

Calculations of the plasma loading in two muon cooling channel schemes have been done, and indicate the desired beam intensity should not prohibitively load the cavities [11, 12]. Simulation studies are currently underway to more accurately investigate the effects of the plasma on the performance of the cavity, and the plasma on the evolution of the beam [13, 14].

As it appears that gas filled RF cavities are feasible for use in ionization cooling channels, an experimental effort to validate a possible engineering design is underway. In order to accommodate the small diameter bores of high field superconducting magnets, methods of shrinking the radial size of gas filled cavities are being pursued. One possibility is making the cavities reentrant. Another is increasing the dielectric constant of the material inside the cavities. This can be investigated using the existing high pressure test cell, and adding a dielectric insert. Low power measurements of a number of materials' dielectric constant and loss tangent have been made [15]. Four high purity alumina (Al_2O_3) inserts were subsequently fabricated and are currently being tested to determine their dielectric strength and the interaction in a beam-gas-plasma-dielectric system.

MITIGATING BREAKDOWN IN VACUUM CAVITIES

Recently, techniques to mitigate breakdown in vacuum cavities have been investigated. Figure 7 shows such data, with one data set from Ref. [2] plotted for reference.

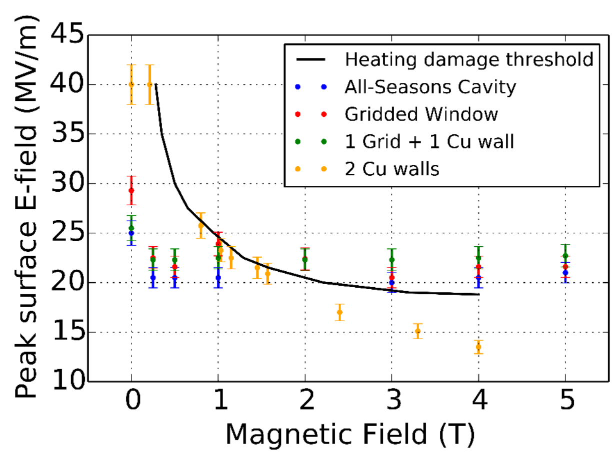

Figure 7: Peak surface electric field as a function of external magnetic field from Ref. [16]. Several experimental data sets from 805 MHz vacuum pillbox cavities are shown: two copper coated stainless steel endplates - "All-Seasons Cavity" (blue), two gridded windows (red), 1 gridded window and one copper endplate (green), and the pillbox data set from Fig. 3 (orange). The black line represents the threshold for surface fracture based on beamlet heating.

One technique tested was to select a cavity length such that the energy of electrons that traversed the cavity and impacted the oppposite side was a minimum, which minimizes energy deposition in the end plates. An 805 MHz vacuum pillbox cavity made of copper coated stainless steel was built in part for this purpose. The results from this cavity are the blue data points in Fig. 7.

If a cavity is terminated with a gridded window, field emission electrons are allowed to exit the cavity volume, without impacting the surface. A set of grids made of aluminum that was then electropolished and titanium nitride coated were fabricated. Two configurations, one with both grids and one with one grid and one copper window, were tested. These are shown in red and green, respectively, in Fig. 7.

All three data sets show better performance than the nominal shorter cavity with two copper end plates and dictate the need for further investigation

CURRENT VACUUM CAVITY EXPERIMENTAL PROGRAM

201 MHz Program

A prototype 201 MHz vacuum pillbox cavity for MICE has recently been tested at the MTA. Figure 8 shows the cavity mounted in its vacuum vessel. This cavity was electropolished in an effort to ensure the surface be as smooth as possible and assembled in a clean room.

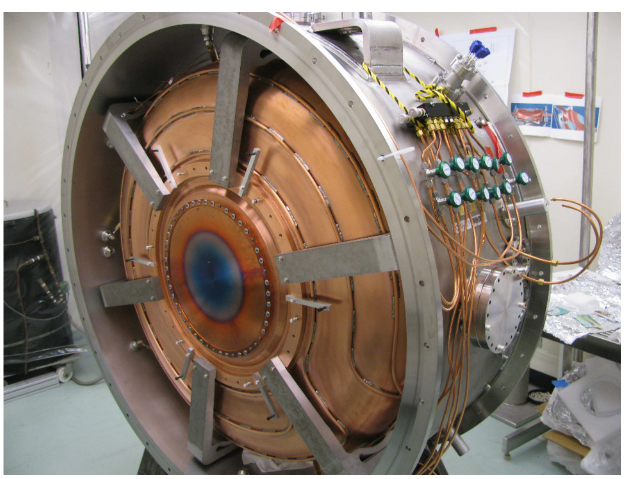

Figure 8: The MICE prototype cavity module opened to expose the 201 MHz vacuum pillbox RF cavity. The cavity is terminated with copper windows.

This cavity was commishioned with both flat copper endplates and curved beryllium windows. The cavity module was placed in the fringe field of the 5 T superconducting magnet in the MTA. With the copper endplates, the breakdown rate at 13.5 MV/m was measured to be 10^{-6} without magnetic field. With beryllium windows, the cavity achieved the MICE specification of 10.3 MV/m with and without magnetic field with no sparks observed. The cavity was then run up to 14.5 MV/m with Be windows in the fringe field and minimal sparking was observed. The gradient limit in this case was due to the RF source power, rather than breakdown.

805 MHz Program

The apparent success of specialized geometric design and superconducting RF (SRF) techniques (electropolishing, TiN coating, ...) - see Fig. 7 - prompted the design and fabrication of a new 805 MHz vacuum pillbox cavity with the goal of investigating how these techniques, as well as material type, affect vacuum cavities' performances in an external magnetic field.

The cavity, shown in Figure 9, has been named the Modular Cavity as it has replaceable components. The central body is made of copper, and may be replaced with another copper body of different length, in order to investigate the cavity body length dependence indicated by the All Seasons Cavity results. It is currently terminated with two flat copper walls, which have been electropolished and TiN coated, in order to study the effect of SRF preparation techniques. Two Be walls are in fabrication, and will undergo the same SRF preparation. Beryllium has a longer radiation length for electrons than copper, so field emission electrons should deposit their energy in a larger volume.

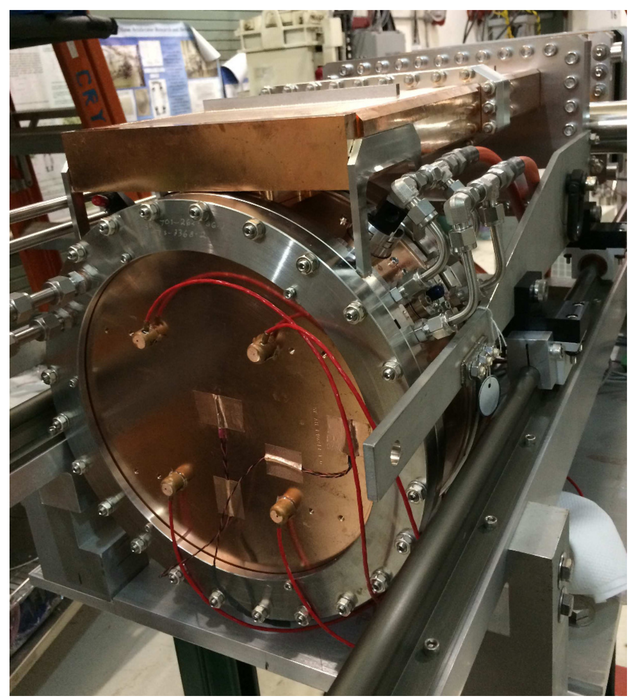

Figure 9: The 805 MHz vacuum pillbox Modular Cavity. The cavity is mounted on rails that secure it in place within the magnet bore. The cavity is side coupled. Instrumentation and water cooling lines are visible.

The Modular Cavity has been commishioned to above 40 MV/m with copper walls at a 10^{-5} sparking rate without magnetic field. A detailed inspection of the copper walls is underway to provide a baseline for the subsequent study in a magnetic field. After the copper walls have been tested, beryllium walls will be attached and a similar program followed.

CONCLUSION

A demonstration experiment of ionization cooling is underway. A requisite of ionization cooling is the operation of high gradient radio frequency cavities in strong external magnetic fields. Initial indications were that traditional vacuum cavities experienced significant accelerating gradient degredation in strong magnetic fields. Filling an RF cavity with a high pressure gas has been demonstrated to be a solution, and furthermore initial findings are that plasma loading is managable in a realistic ionization cooling channel. Recent results based on various techniques used on vacuum cavities appear promising, and have spurred an experimental program aimed at demonstrating such techiques are a viable solution to operating vacuum RF cavities in an ionization cooling channel as well.

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