HIGH PRESSURE, HIGH GRADIENT RF CAVITIES FOR MUON BEAM COOLING*

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Abstract

High intensity, low emittance muon beams are needed for new applications such as muon colliders and neutrino factories based on muon storage rings. Ionization cooling, where muon energy is lost in a low-Z absorber and only the longitudinal component is regenerated using RF cavities, is presently the only known cooling technique that is fast enough to be effective in the short muon lifetime. RF cavities filled with high-pressure hydrogen gas bring two advantages to the ionization cooling technique. First, the energy absorption and energy regeneration happen simultaneously rather than sequentially, and second, higher RF gradients and better cavity breakdown behavior are possible due to the Paschen effect. A first step in a program to develop ionization cooling using pressurized cavities is the measurement of RF breakdown of hydrogen at high density. In the study reported here, the linear dependence of breakdown on pressure was verified in an 800 MHz hydrogen-filled test cavity up to 80 MV/m, which was the surface gradient limit of the molybdenum electrodes of the cavity. We note that the conditioning of the electrodes was unusually fast in the gas and needed only a few hundred thousand pulses. Planned research includes experimental measurements of pressurized RF cavity behavior in strong magnetic and ionizing radiation fields. Analytical and simulation calculations are also being made to examine how these cavities might be used in a practical cooling channel, effectively a rather complex Linac.

INTRODUCTION

Accelerators and colliding beam storage rings for High Energy Physics research have used protons and/or electrons and their antiparticles. Muons, despite their short lifetime, have several advantages to make them attractive candidate particles for the next generation of energy frontier colliders. Muons are point like, rather than composite, so that all of their collision energy can be used to create new states of matter. Thus a muon collider can have an energy and footprint one tenth that of the equivalent proton collider. Muons are more massive than electrons so that problems with synchrotron radiation are greatly diminished. Thus a muon collider can be a multi-turn ring of high-field magnets and each beam will not be disrupted by the electromagnetic field of the other at interaction regions. Because of the reduced disruption, a muon collider can be built with center of mass energy much greater than the 1.5 TeV that linear electron-positron colliders are likely to be limited to.

The muon advantage that is the subject of the studies reported here, however, has to do with passage through matter. Unlike protons, muons do not interact through the strong interaction and rarely suffer large scattering angles. Unlike electrons, muons create few electro-magnetic showers since they are more massive. Thus, muons have one other important virtue compared to protons and electrons in that they can pass through material with losses and scattering small enough to still be useful in accelerators, storage rings, and colliders.

This paper describes efforts to use this muon virtue of acceptable scattering through matter to rapidly cool a muon beam and quickly accelerate it to high energy. The new idea that is being exploited is that RF cavities used for muons can be filled with high-pressure gas to suppress high voltage breakdown. The gas, if it is low-Z, can also be the energy absorber for ionization cooling.

Ionization Cooling

Neutrino Factories or Muon Colliders, which require intense beams of muons, are dependent on a scheme to quickly reduce or cool the emittance of a muon beam before it can be injected into a practical accelerator[1]. Ionization cooling of a muon beam involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced, and through RF cavities, where only the longitudinal component is regenerated. After some distance, the transverse components shrink to the point where they come into equilibrium with the heating caused by multiple coulomb scattering.

The equation describing the rate of cooling is a balance between these cooling (first term) and heating (second term) effects[2]:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}.$$

Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity.

Setting the heating and cooling terms equal defines the equilibrium emittance, the very smallest possible with the given parameters:

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$$\varepsilon_n^{(equ.)} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0}.$$

A cooling factor ($F_{cool} = X_0 dE_\mu/ds$) can be uniquely defined for each material, and since cooling takes place in each transverse plane, the figure of merit is F_{cool}^2[3]. The inverse of F_{cool}^2 corresponds to the best equilibrium emittance that can be achieved. Super-conducting solenoidal focusing is used to give a value of $\beta_\perp$ as low as 10 cm. Figure 1 shows F_{cool}^2 for many materials of interest, where gaseous hydrogen is twice as effective as helium, the next best material from the standpoint of the final equilibrium emittance. Also, since the exponential cooling rate depends on the difference between the initial and final emittances, it provides the very best cooling rate.

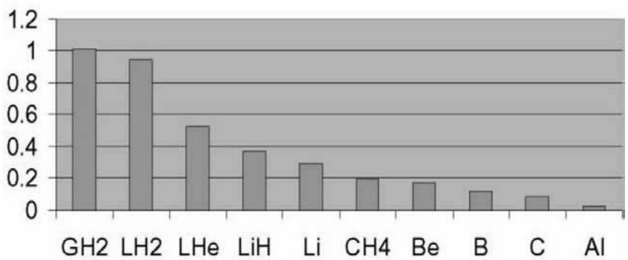

Figure 1: A comparison of F_{cool}^2 for light materials relative to gaseous hydrogen. The equilibrium beam emittance in each transverse plane is inversely proportional to the product of the energy loss and the radiation length. F_{cool}^2 for a material is independent of density, since $dE_\mu/ds \sim \rho$ and $X_0 \sim 1/\rho$.

Up to now, liquid hydrogen has been the energy-absorbing medium of choice, with dE_μ/ds= 30 MeV/m and X_0 = 8.7 m. Most liquid hydrogen cooling channel designs use an energy absorber with a total length that corresponds to twice the energy of the initial beam. Thus a 200 MeV beam would require 400 MeV of energy loss, or about 13 meters of liquid hydrogen separated into about 40 flasks, each 33 cm long in the beam direction and a similar useful diameter. In between each flask, 3 or 4 RF cavities operating in vacuum occupy about 2.2 meters, giving an effective average energy loss of about 4 MeV/m. The gaseous hydrogen channel advocated here would have a higher average energy loss, perhaps as much as 15 MeV/m and be correspondingly shorter and cheaper.

Paschen's Law

Most RF cavities associated with particle accelerators operate in as good a vacuum as possible to avoid electrical breakdown. This is done so that ions that are accelerated by the high voltages in the RF cavity rarely encounter atoms of the low-pressure residual gas, and so the avalanche process of breakdown is inhibited. Other RF systems that do not require the ultrahigh vacuum of an accelerator typically suppress RF breakdown by using dense insulating 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 in the high-pressure regime between the electrical breakdown voltage and the pressure times gap width is known as Paschen's Law[4]. Here we use gradient and pressure to express the same relationship. The goal of the study below is to examine this relationship for hydrogen gas to a pressure of 110 atmospheres at 77K, where the gas density is about half that of liquid hydrogen. Extrapolated from the measurements below, hydrogen at that density will support almost 700 MV/m. Also seen below, hydrogen suppresses breakdown about six times better than helium at the same pressure.

HIGH-PRESSURE TEST CELL

Earlier measurements with the "Mark I" prototype test cell and copper electrodes have been reported[5]. Figure 2 shows a schematic of the "Mark II" RF test cell used for the measurements reported here, which were carried out in Fermilab's Laboratory G using molybdenum electrodes. The construction uses copper-plated, 5 cm thick, stainless steel disks that are bolted onto a cylinder of the same material with 0.4 mm aluminum gaskets.

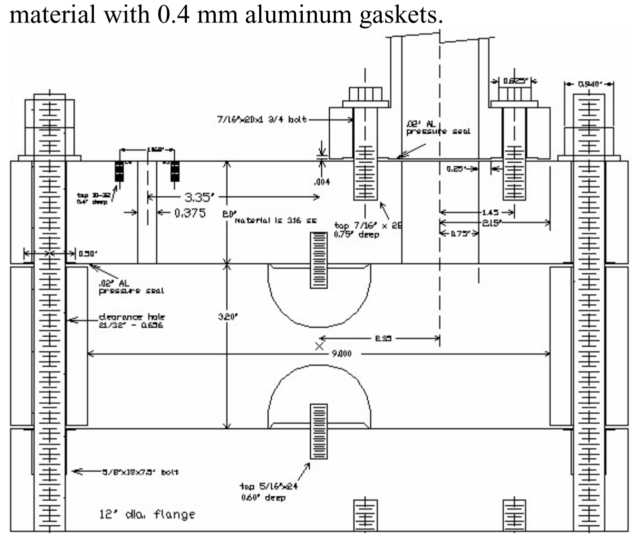

Figure 2: A schematic of the Mark II 805 MHz test cell (TC) used at Fermilab Lab G to measure the electrical breakdown properties of gases under extreme conditions. The top and bottom disks and the cylinder are copper-plated stainless steel. The TC is easily opened to allow inspections and to change the doorknob electrodes for cavity tuning or studies of RF breakdown. The central conductors of the coax feed line and of the pick-up are not shown.

Power from the Lab G klystron was fed through a stainless steel coaxial line that has a segment with an epoxied central conductor that acts as a room-temperature pressure barrier located well above the liquid nitrogen bath that surrounds the test cell. A smaller coaxial pick-up is used to monitor the voltage in the test cell. Both the feed and the calibrated pick-up are capacitively coupled to the test cell. Two removable hemispherical doorknob electrodes inside the test cell define the resonant frequency and the breakdown location. Figure 3 is a picture of the stainless steel disks and cylinder before copper plating. Details of the construction and operation of the test cell can be found in a MuCool Note[6].

Figure 3: Picture of the Test Cell Stainless Steel Disks and Cylinder before copper plating.

Figure 4 shows the 800 MHz RF envelope as measured by the calibrated pick-up. Conditioning and measurements were with 20 microsecond pulses at 5 Hz. Measurements started at high pressure then gas was released for subsequent measurements so that it was not necessary to wait for the gas to come to thermal equilibrium with the test cell and liquid nitrogen bath.

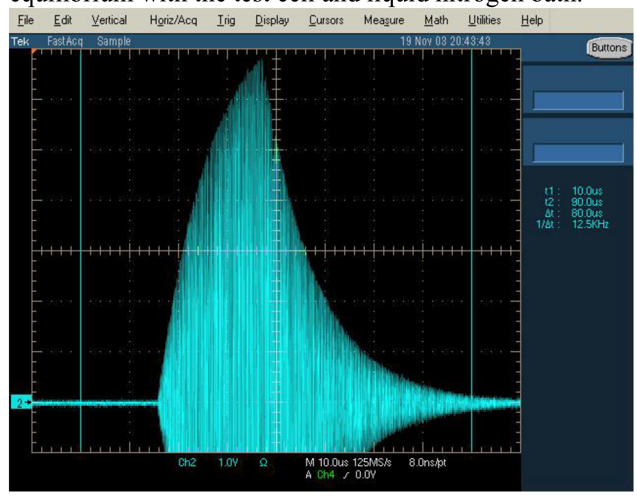

Figure 4: The probe signal taken during the last hours of operation at 250PSI and 77K. The pulse time of 20 µs corresponds to the rising part of the 800MHz envelope.

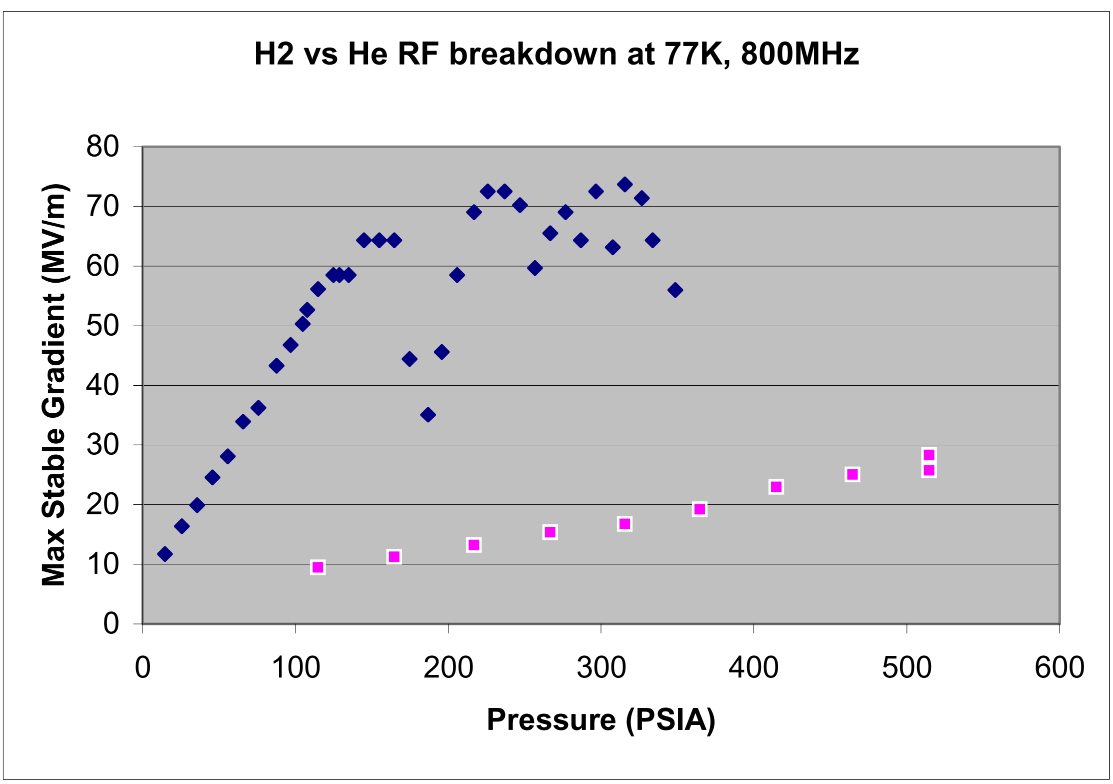

Figure 5: Paschen curve measurements for hydrogen (black diamonds) and helium (red squares) at liquid nitrogen temperature. Each datum was determined by first setting the klystron frequency at reduced voltage, raising the voltage until breakdown occurred regularly, then reducing the voltage until breakdown did not occur.

LAB G MEASUREMENTS

Figure 5 shows the measurements of the Paschen curves for hydrogen and helium at 77K. The linear Paschen region can be seen in the plot for helium over the entire range and for hydrogen below 150 PSIA. The dip around 190 PSIA in the hydrogen data corresponds to a breakdown in the transmission line from the klystron. The hydrogen data at higher pressure are dominated by breakdown at the surface of the molybdenum electrodes. The gold star represents the result of the last 3 hours of conditioning with hydrogen at 265 PSIA, where a maximum stable gradient of 79.9MV/m was attained

The next steps are to demonstrate that such cavities will work in the high magnetic and radiation fields expected in an actual cooling channel. Soon we will operate the test cell in a 5T solenoid to compare to the breakdown behavior we have measured without a field and to the behavior of the evacuated cavities that have been already tested in the solenoidal field.

The extrapolated breakdown gradient of almost 700 MV/m for hydrogen gas in our expected operating conditions gives confidence that the cavities will handle ionizing radiation well. Nevertheless, the demonstration of this prediction is the ultimate goal of this project. Our top priority is to make sure that Fermilab will have beam for us as soon as possible. We are hopeful and enthusiastic that a beam line design can be implemented so that we can do the required tests in 2005.

In order to push the technology for RF cavities, both evacuated and pressurized, we have begun to study construction materials and their breakdown behavior. The molybdenum results reported here are encouraging, and we look forward to our next tests with chromium and beryllium.

COOLING CHANNEL DESIGNS WITH GASEOUS HYDROGEN

In addition to the development of the high-pressure RF cavities themselves, there is considerable effort to develop cooling channels that could use them. One such effort involves the possibility that a continuous gaseous energy absorber in a magnetic channel with dispersion can be used to cool the momentum spread of a muon beam by exploiting the fact that higher-momentum particles have longer path length and therefore larger energy loss. This approach to emittance exchange and six-dimensional cooling has been described analytically[7] and is now the subject of simulation efforts. As an example, figures 6 and 7 show the side and end view of a segment of a six-dimensional cooling simulation that incorporates a continuous solenoid with helical dipole and quadrupole magnets to achieve a channel with good dispersion and acceptance. The simulation code G4Beamline is based on the Geant4 program and is under development by our collaboration[8].

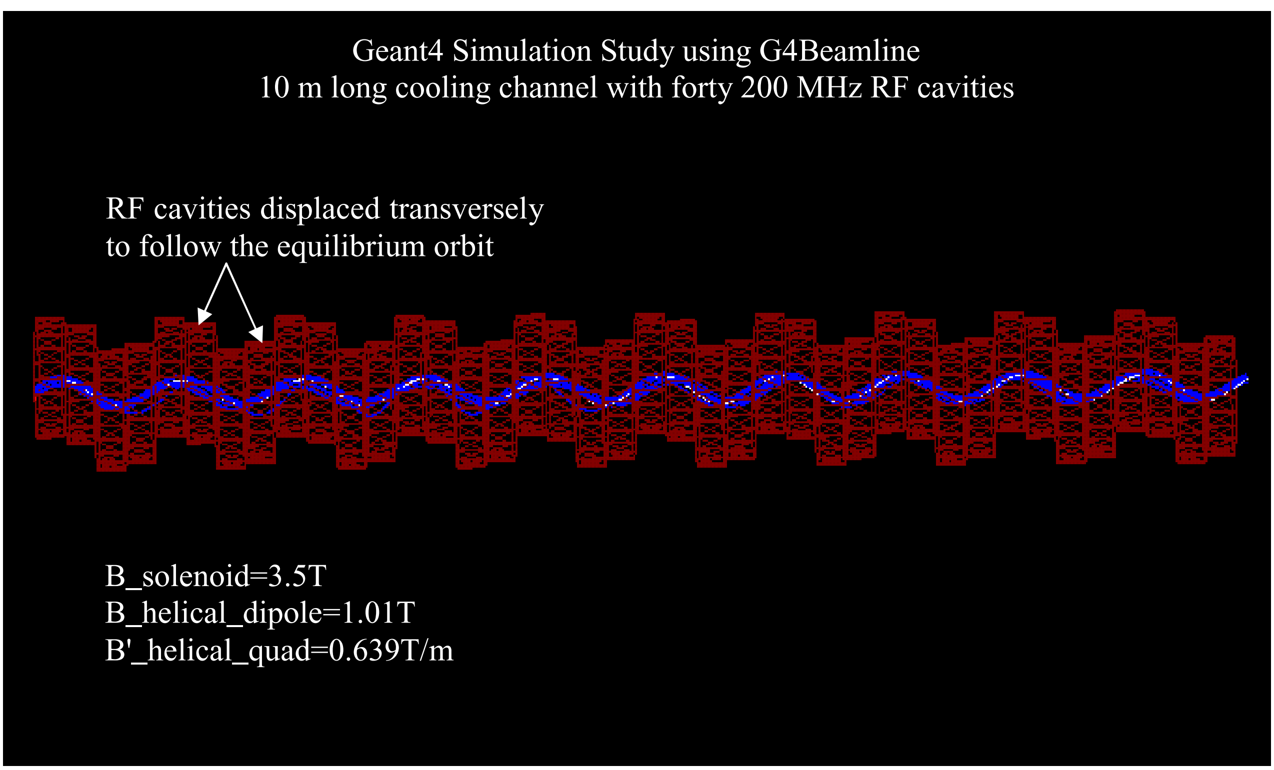

Figure 6: G4Beamline display of the helical cooling channel that is being simulated. In this simulation, superimposed magnetic fields with solenoidal and helical components provide focusing and dispersion as the muons pass through the hydrogen-filled RF cavities. Muon trajectories are shown in blue as they oscillate about the equilibrium orbit shown in white.

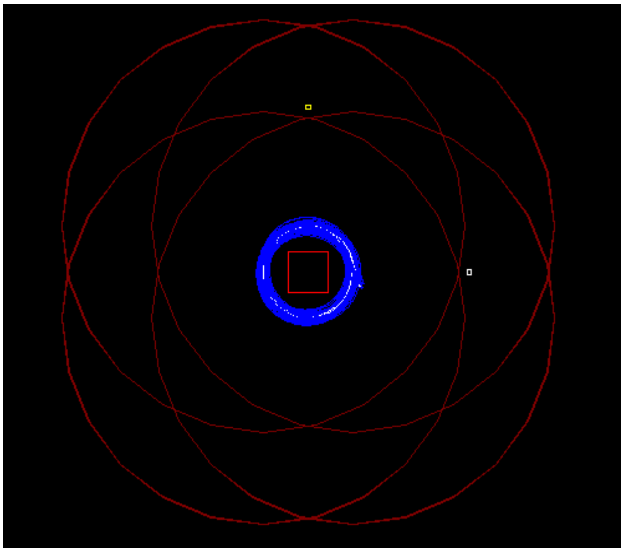

Figure 7: The same as conditions as figure 6, but viewed looking down the cooling channel. The beam here is at 200 MeV/c with a helix radius of 11 cm. The outlines of the radially displaced RF cavities are shown in red. The red box shown for orientation in the center is 10 cm on a side.

CONCLUSIONS

Some new ideas to cool muon beams are being explored. The use of a gaseous hydrogen energy absorber for ionization cooling seems particularly promising in that the gas can fill the RF cavities of a cooling channel to good advantage. First measurements indicate that such cavities will operate at higher gradients, have shorter conditioning times, and have reduced dark currents. Tests in high magnetic fields and in intense ionizing radiation are needed to verify that pressurized RF cavities will work satisfactorily in muon cooling applications. New ideas in cooling channel designs that will incorporate these cavities are starting to be developed as well. If an effective six-dimensional muon beam cooling channel can be developed, the chances for an affordable neutrino factory and a realistic muon collider will be greatly increased.

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