PRESSURIZED HYDROGEN-FILLED LINACS FOR MUON COOLING*

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Abstract

New techniques for muon ionization cooling require low-Z energy absorber, strong magnetic fields for focusing and emittance exchange, and high gradient RF cavities to replace the energy lost in the absorber. RF cavities pressurized with hydrogen gas are being developed to provide the most effective muon beam cooling possible in the short lifetime of the muon. We report the status of the cavity development, including the breakdown suppression by the gas and new results showing that pressurized cavities show no degradation of performance in strong magnetic fields. We also comment on the development of the designs of the associated muon cooling Linacs.

INTRODUCTION

High-intensity, low-emittance muon beams are needed for muon colliders, neutrino factories, and diverse experiments that exploit the unique nature of the muon. A crucial step in the formation of such beams involves ionization cooling, a very fast technique [1,2] to reduce the emittance of a beam by passing it through a low-Z energy absorbing material using normal-conducting RF to replenish the energy lost in the absorber. By using special magnetic fields, the longitudinal and transverse emittances can be exchanged, allowing all six phase-space dimensions (6D) of the muon beam to be cooled [3].

Pressurized RF cavities are proposed to provide simultaneous energy absorption and RF energy replenishment, thus minimizing the length of the ionization cooling system and the number of muons lost to decay. Additional advantages of pressurized cavities are that the gas filling the RF cavities will absorb dark currents, suppress electromagnetic breakdown, and allow higher accelerating gradients. This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons nor shower as do less-massive electrons.

Because of the high magnetic fields required to provide focusing and emittance exchange, the cavities cannot be superconducting. Also, they must operate at low frequency at the start of the cooling channel in order to accept the large muon beam. Most important is whether such RF cavities can operate at high gradients in strong magnetic and radiation fields. Radiation tests will start next year in the Fermilab MuCool Test Area (MTA).

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RF MEASUREMENTS

Figure 1 shows a schematic of the 800 MHz RF test cell (TC) used at Fermilab to investigate the breakdown characteristics of hydrogen and other gases. The cavity features replaceable electrodes which are also being used to investigate the intrinsic RF breakdown characteristics of metals in an environment where dark currents and ion effects are suppressed. Figure 2 shows the most recent measurements taken with molybdenum, beryllium, and copper electrodes as a function of hydrogen gas density or pressure.

The molybdenum data were taken with and without an applied solenoidal magnetic field. As shown, the breakdown characteristics of the hydrogen pressurized cavity were unaffected by the magnetic field. This result is considerably different than results from an evacuated RF cavity operating at the same frequency and similar pulse length as shown in figure 3 [4]. In the evacuated case, the maximum operational surface gradient at a field of 2.5 T is approximately 1/3 of the gradient for the case with no external magnetic field.

The next most pressing investigation is to verify that the pressurized RF cavities will operate satisfactorily in radiation fields that correspond to a real muon cooling channel.

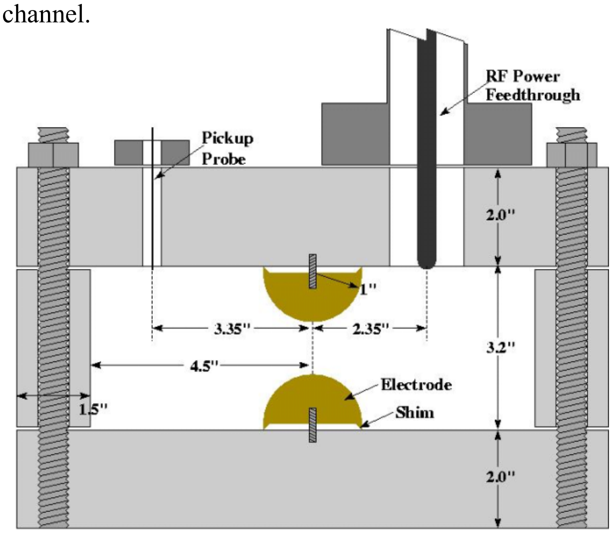

Figure 1: Cross section of the test cell showing the replaceable one inch radius Cu, Mo, or Be hemispherical electrodes. The top and bottom plates and the cylinder are copper-plated stainless steel (the gas input/exhaust port is not shown in the figure).

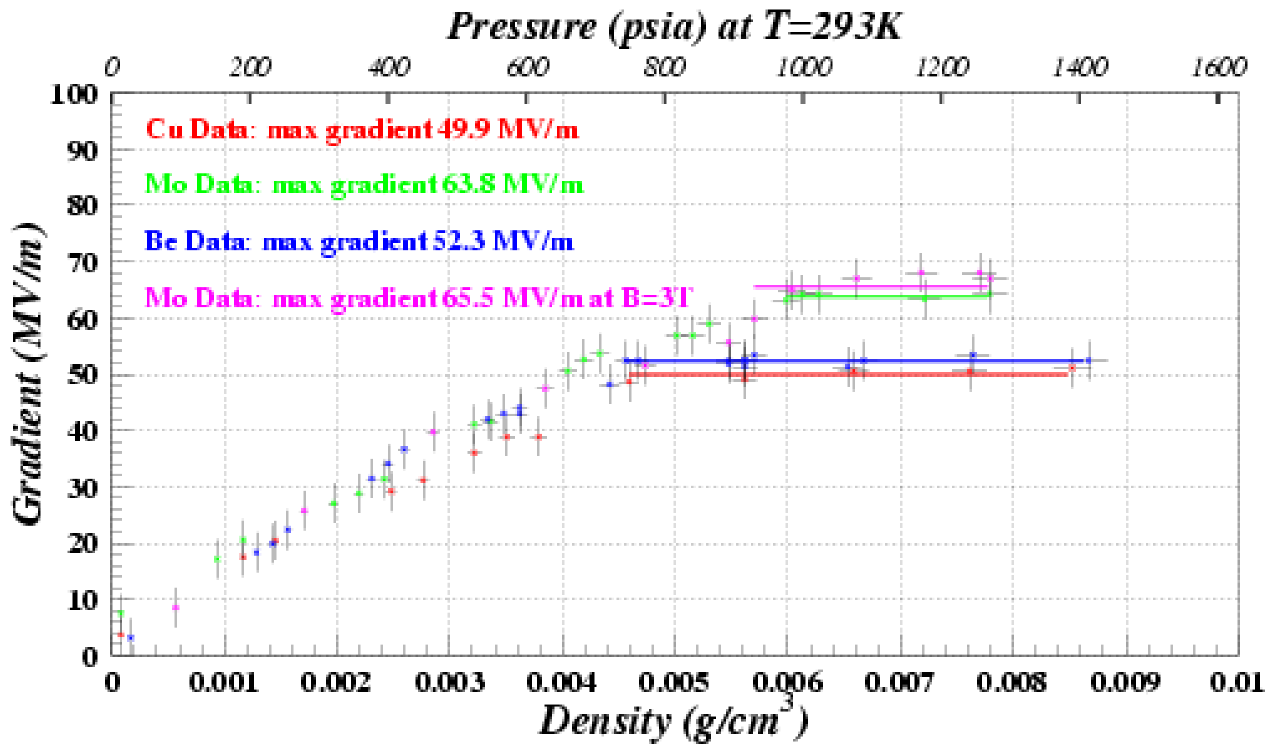

Figure 2: Measurements of the maximum stable TC gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue). As the pressure increases, the mean free path for ion collisions shortens 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.

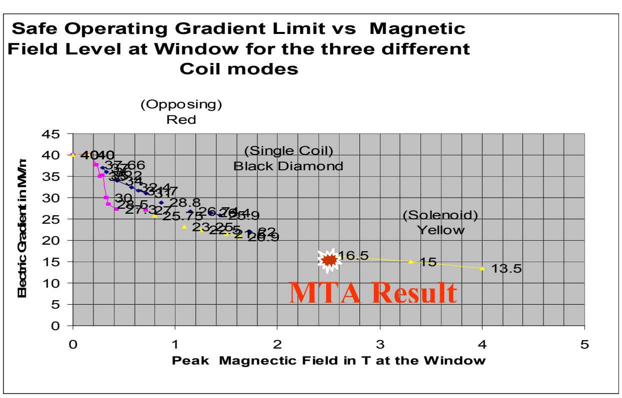

Figure 3: 800 MHz Vacuum cavity Max Gradient vs B. From Al Moretti, MICE meeting IIT, 3/12/06, comparing Lab G and MTA results. http://mice.iit.edu/nfmcc06/nfmcc06_moretti_805mhzprogram.ppt

HCC LINAC PARAMETERS

The series of hydrogen-filled RF cavities that has the design goal to cool the muon beam 6D emittance by a factor of a million makes up a rather unusual Linac. The cavities must contain dense hydrogen gas, which can be achieved by some combination of temperature and pressure. For example, at liquid nitrogen temperature, 110 atmospheres of hydrogen gas would have about half the density of liquid hydrogen and correspond to about 15 MeV/m of dE/ds energy loss. At room temperature the pressure must be four times greater to get the same energy loss rate.

The Linac muon beam must be immersed in a complex and strong magnetic field. The beam follows a helical orbit such that the particle trajectories do not pass through the cavities parallel to the cavity axes. For helical orbits with a 45 degree pitch, the accelerating gradient in this case must be increased by 1.414 just to overcome the energy loss rate;

$dE/dz = (dE/ds)/\cos(pitch\,angle)$. To get a 6D reduction of a factor of a million, the muons must lose by ionization energy loss approximately 6 times their total energy.

Simulations of a 160 meter-long four-stage HCC Linac filled with 400 atmospheres of hydrogen at room temperature with 31 MV/m maximum RF accelerating gradient have achieved a 6D emittance reduction of a factor of 50,000 [5]. Improvements in the scattering model based on recent measurements of muon scattering on hydrogen are expected to improve this by a factor of 3 to 4. Other potential improvements include increasing the strength of the HCC magnets in the final stage of the Linac by using high-temperature superconductor operating at low temperature [6].

In the simulation, there are only two pressure windows. The upstream aluminum pressure window is 30 cm diameter, but has little effect on the emittance of the beam since the beam is diffuse at the beginning of the cooling channel. The downstream window can be rather small and thin since the beam has been cooled to a small size.

Since the pressure window design and most engineering problems can be simplified to the extent that the pressure can be reduced, the opportunity to operate at lower temperature is being investigated. One opportunity is to use the lower resistivity of copper or beryllium at lower temperature to increase the Q of the cavities to ease power requirements.

6D DEMONSTRATION EXPERIMENT

An experiment to demonstrate the use of a helical cooling channel to cool a muon beam in all six dimensions is being developed. A Letter of Intent [7] has been submitted to Fermilab and a task force [8] has been created by the Fermilab directorate to examine the merits and possibilities of such an experiment.

The experiment that is contemplated will be to demonstrate the properties of the HCC and to show that longitudinal cooling can be achieved using ionization cooling in a practical device. In its first stage, the experiment will not have RF and will rely on the measurement of invariant emittance to test the HCC properties. A muon beam of about 300 MeV/c will enter a special HCC channel with z-dependent field strength that is matched to the momentum of the muons as they slow in a liquid helium absorber. Spectrometer and emittance matching sections before and after the HCC will measure the decrease in invariant emittance.

It has recently been shown that a simple configuration of separate coils can be used to generate the solenoidal, helical dipole, and helical quadrupole of the basic HCC. Figure 4 shows a three dimensional representation of such a channel, where the energy absorber fills the volume inside the coils. In the experiment, each coil will be powered independently to achieve the desired z-dependent field strength. In an actual HCC, where the energy loss is replenished by RF cavities, the cavities could be placed between the coils or groups of coils.

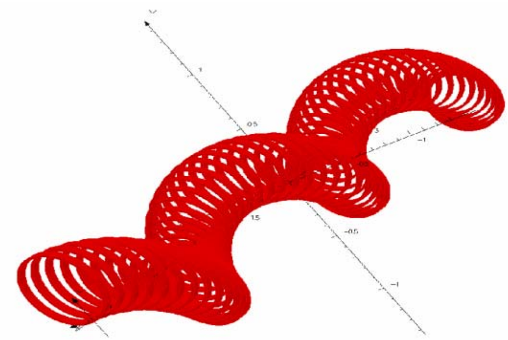

Figure 4: A new solution to the Helical Cooling Channel to be used in the 6D cooling demonstration experiment is made up of a series of superconducting coils which are displaced from each other as shown in the figure to create solenoidal, helical dipole, and helical quadrupole fields. At the beginning of the cooling channel, the 50 cm diameter coils produce about 5.5 T of solenoidal field.

MUON COLLIDER COOLING

Even with the six order of magnitude reduction of 6D phase space that the HCC should provide, additional cooling is required to achieve emittances sufficiently small that a muon collider could easily use ILC RF cavities operating at 1.3 GHz. Two techniques under investigation are parametric-resonance ionization cooling (PIC) and reverse emittance exchange (REMEX) [9]. These techniques require small beams from the HCC Linac in order to provide the additional cooling needed for a low-emittance muon collider [10].

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