A SIX-DIMENSIONAL MUON BEAM COOLING EXPERIMENT*

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Abstract

Ionization cooling, a method for shrinking the size of a particle beam, is an essential technique for the use of muons in future particle accelerators. Muon colliders and neutrino factories, examples of such future accelerators, depend on the development of robust and affordable ionization cooling technologies. A 6D cooling experiment has been proposed, incorporating a novel configuration of helical and solenoidal magnets in a prototype cooling channel. This Helical Cooling Channel (HCC) experiment is being designed to provide an affordable and striking demonstration that 6D muon beam cooling is understood well enough to enable intense neutrino factories and high-luminosity muon colliders. Because of the large amount of expected beam cooling, helium instead of hydrogen can be used for the initial experiment, avoiding the safety complications of hydrogen. The main points of the experiment are described and corresponding numerical simulations are reviewed.

INTRODUCTION

Ionization cooling is the only technology that can rapidly reduce muon beam emittances [1] before acceleration. This technique uses energy absorption via ionization loss with RF acceleration to restore the longitudinal momentum within a strongly focusing magnetic lattice to increase the particle density in transverse phase space. Multiple scattering in the absorber introduces “heating” that competes with the ionization “cooling”, leading to the choice of a low Z material for the absorber. Liquid or gaseous hydrogen optimizes the heating/cooling trade-off, though safety concerns make engineering such cooling channels a significant challenge.

This technique only reduces the emittance in the transverse directions. In order to cool the six dimensional (6D) emittance of a beam, longitudinal emittance must be transferred to transverse emittance where ionization cooling is effective. This “emittance exchange” had been accomplished in earlier cooling schemes by introducing dispersion via a dipole and directing the higher momentum muons through more ionization energy loss in a wedge-shaped absorber. The idea of pressurized RF cavities [2,3], described elsewhere in this conference, led to the concept of a cooling channel filled with a continuous homogeneous absorber, that exploits the path length (and therefore energy loss) correlation with momentum in a magnetic channel with positive dispersion, such that the momentum spread of the beam is reduced. Since dispersion spreads the beam transversely, the transverse emittance is increased. The usual ionization cooling then acts on the transverse emittance for 6D cooling. Figure 1 depicts the old and new concepts for emittance exchange.

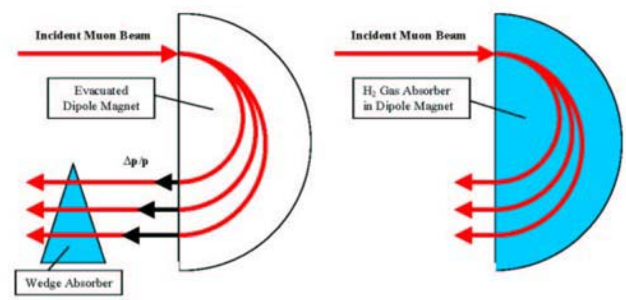

Figure 1: Emittance exchange: the use of a wedge absorber is shown at left, compared with the use of a continuous absorber (right).

The experiment we will propose exploits the emittance exchange concept by using a 4 meter long Helical Cooling Channel (HCC) [4], and measuring its beam cooling properties. This experiment will require a 300 MeV/c muon beam line equipped with up and downstream matching sections, particle spectrometers, and particle identification detectors. The expected cooling factor of nearly 500% will be a striking demonstration of a new technique to cool all dimensions of a muon beam in a time much shorter than the muon lifetime.

HELICAL DIPOLE MAGNET

The emittance exchange described above is accomplished in the HCC by superimposing a transverse helical dipole magnet and a solenoidal magnet with a continuous absorber medium. The helical dipole magnet creates an outward radial force due to the longitudinal momentum of the particle while the solenoidal magnet creates an inward radial force due to the transverse momentum, or

$$\begin{aligned} F_{h-dipole} &\approx \quad p_z \times B_\perp; \quad b \equiv B_\perp \\ F_{solenoid} &\approx -p_\perp \times B_z; \quad B \equiv B_z \end{aligned} \tag{1}$$

where B is the field of the solenoid, the axis of which defines the z axis, and b is the field of the transverse helical dipole at the particle position. In the HCC described above, RF cavities restored the longitudinal

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momentum, and the fields were kept constant. However, in the case where the muon momentum is decreasing through material with no compensating RF, the fields can be adjusted to maintain a stable orbit. The solution for a particle in a HCC with period $2\pi/k$ on an equilibrium orbit with radius a and momentum p can be written:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{k} b\right] \qquad (2)$$

where $\kappa = ka = p_\perp / p_z$ is the arctangent of the helix pitch angle at the periodic orbit, This relationship can be exploited to accommodate a muon beam losing momentum to ionization in a continuous medium to provide the required dispersion and orbit for effective cooling.

Equation (2) shows how to manipulate field parameters to maintain stability for cases where one would like the momentum and/or radius of the equilibrium orbit to change for various purposes [5]. Examples of these purposes that we have examined include a continuous-absorber precooler, a transition section between two HCC magnet sections with different diameters, and an alternative to the original HCC filled with pressurized RF cavities using liquid-filled HCC sections alternate that with evacuated RF cavities. Figure 2 shows a simulation of a decay channel using HCC-type magnets leading to a HCC precooler.

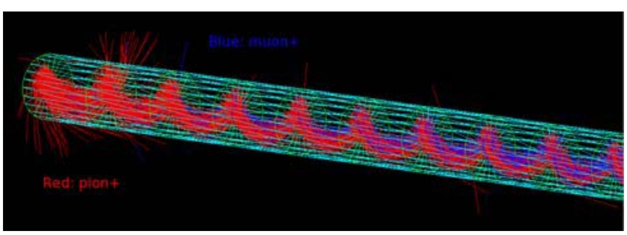

Figure 2. One application of the HCC-type magnet: pion decay channel upstream of the first stages of muon cooling (red tracks are pions, blue tracks are muons).

6D MUON AND NEUTRINO EXPERIMENT (6DMANX)

In 6DMANX, we will demonstrate the use of a HCC with a continuous homogeneous absorber to achieve emittance exchange and 6D cooling. This demonstration simplifies the cooling technique by leaving out the RF cavities altogether. Implicit in this approach is that the experiment need only demonstrate the reduction of the invariant normalized emittance. To avoid the need for thick windows, we will use liquid, rather than high-pressure gas. To avoid safety complications, we will use helium instead of the optimal hydrogen. In addition, equation (2) allows us to design decreasing magnetic fields to maintain an equilibrium orbit as the muons lose momentum.

There are several goals we wish to achieve by this experiment to demonstrate:

1) Emittance exchange and longitudinal cooling,
2) 6D cooling in a continuous absorber,
3) Helical Cooling Channel theory and technology,
4) Practical ionization cooling,
5) A prototype precooler,
6) A prototype of one of ~10 HCC sections alternating with RF sections to get 10^6 6D emittance reduction.

We propose to run this as a single-particle experiment, with the position, momentum and time of each muon traversing the HCC reconstructed offline before and after cooling. The muon beam enters an upstream spectrometer which measures the particle trajectories. A matching section, which can be integrated with the spectrometer, then brings the beam to match the HCC acceptance. The beam then passes through a thin window that contains the liquid helium of the HCC. The beam passes through the liquid helium-filled HCC in which the momentum is decreased and 6D cooling occurs. The ~150 MeV/c beam exits the HCC through another thin window into the downstream matching and spectrometer sections and is stopped in a calorimeter. Timing and Cherenkov counters upstream of the spectrometer sections and the calorimeter at the end of the channel will be used for particle identification.

Muon bunches are selected and reconstructed offline, and the normalized emittances are calculated from the trajectory and momentum information from the spectrometers to measure the cooling. A simple schematic is presented below in Figure 3.

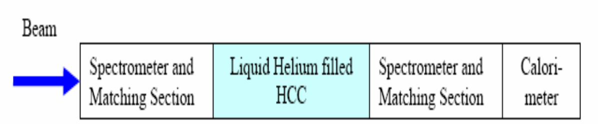

Figure 3: Schematic of a 6DMANX experiment.

We have proposed that Fermilab construct the HCC magnet(s) and help determine the most expedient location for the experiment. The parameters of the 4 meter helical dipole magnet for a possible 6DMANX HCC are presented in Table 1. Further studies may yield refinements that can reduce costs or enhance performance. The orbits and apertures may have to be tuned to accommodate different experimental configurations.

One possibility we are considering is to place a HCC magnet between the MICE (Muon Ionization Cooling Experiment) spectrometers in the ISIS beamline at Rutherford Appleton Laboratory (Fig. 4).

Table 1: Nominal 6DMANX Parameters

Helical Magnet	**z = 0 m**	**z = 4 m**
Total length	4 m	
Magnet bore diameter	~0.8 – 1.0 m	
Helix period	2 m	
κ (atan of helix pitch angle)	0.8	
B (solenoid) on ref. orbit	-4.4 T	-2.2 T
b (dipole)	0.95 T	0.45 T
b' (quadrupole)	0.60 T/m	0.40 T/m
b" (sextupole)	-0.26 T/m^2	- 0.15 T/m^2
Beam		
Beam momentum	300 MeV/c	150 MeV/c
Beam diameter	20 cm	
Beam Δp/p	+/-7%	

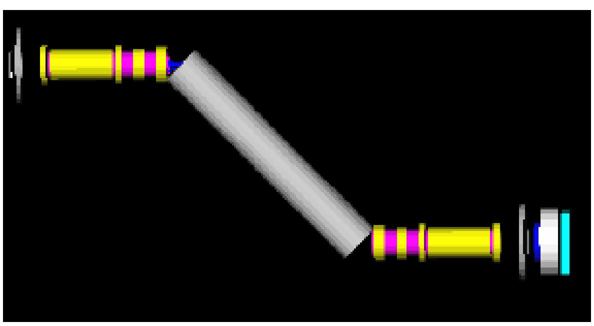

Figure 4: One possible configuration of 6DMANX (HCC in gray) is shown in a GEANT4 simulation using the MICE spectrometers in the RAL ISIS beamline.

Figure 5 shows the normalized transverse (the average radial and azimuthal), longitudinal, and 6D emittances plotted as a function of the distance down the 4 meter HCC. The settings of the helical dipole, helical quadrupole and solenoidal magnets are chosen to give equal cooling decrements in all three planes. The combined 6D cooling factor is about 5.4, corresponding to 1.7 coming from each of the three planes.

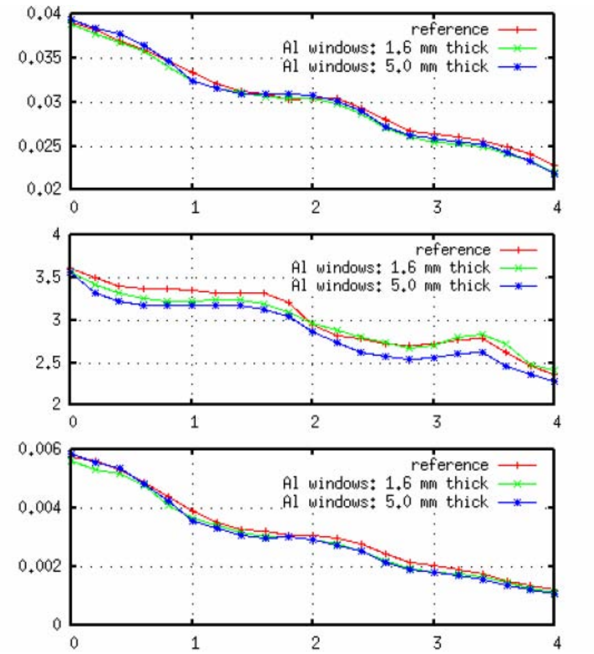

Figure 5: Cooling performance. Shown are the results of simulations (including the effects of windows) of the transverse (top), longitudinal (middle) and 6D (bottom) emittances in the 6DMANX HCC. The axes are emittance (m rad) vs. length of cooling channel (m).

The design of the 6DMANX cryostat for liquid helium can be adapted for a real cooling channel using liquid hydrogen. The very small emittances achievable through such cooling techniques will enable high luminosity for muon colliders [6] and perhaps high intensity for neutrino factories [7]. The small emittances solve many problems for muon colliders: neutrino radiation, decay electrons in detectors and magnets, proton targetry, and heating of the energy absorbers. With enhanced cooling techniques, a muon beam could be quickly cooled to fit into the small apertures of ILC-type RF cavities, reviving the idea of an energy frontier muon collider.

REFERENCES

[1] Daniel M. Kaplan, “Introduction to Muon Cooling”, http://www.slac.stanford.edu/econf/C010630/papers/M102.PDF.
[2] Rolland P. Johnson and Daniel M. Kaplan, http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0195/muc0195.pdf
[3] P. Hanlet et al., these proceedings.
[4] K. Yonehara et al., these proceedings
[5] Y. Derbenev and R. P. Johnson, Phys. Rev. ST Accel. Beams 8, 041002 (2005).
[6] K. Paul et al., Summary of the Low Emittance Muon Collider Workshop, these proceedings.
[7] M. Popovic et al., these proceedings.