# Letter of Intent to propose a
# SIX-DIMENSIONAL MUON BEAM COOLING
# EXPERIMENT FOR FERMILAB

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## Synopsis

The experiment we will propose involves the construction of a 4 meter long, innovative superconducting magnet called a Helical Cooling Channel (HCC) and the measurement of its beam cooling properties. The measurement also requires a 300 MeV/c muon beam line equipped with up and downstream matching sections, particle spectrometers, and particle ID 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.

The applications of the new technique that will be developed and demonstrated by this experiment involve very bright muon beams for fundamental research using muon colliders, neutrino factories, and muon beams with new characteristics. The ultimate application will be an energy frontier muon collider which achieves high luminosity by virtue of small emittance rather than large muon flux. The small six-dimensional (6D) emittance that is possible as shown by this experiment will allow high-frequency ILC RF accelerating structures to be used for such a collider and also for high flux muon beams for storage ring based neutrino factories.

Ionization cooling is a method to reduce the angular divergence of a beam by passing the beam through an energy absorber to reduce all components of momentum and then regenerating only the longitudinal momentum using RF cavities. Applying this technique along a beam line, where the angle and position of each particle undergoing betatron oscillations are periodically exchanged, both the angular and spatial beam dimensions can be reduced or cooled in each transverse plane. This gives 4-dimensional cooling of the two transverse emittances, which can be continued to the point where heating from Coulomb multiple scattering in the energy absorber exactly offsets the ionization cooling. Compared to other techniques such as stochastic or electron cooling, ionization cooling is faster and the only known technique compatible with the short muon lifetime.

To use ionization cooling to reduce the longitudinal and momentum distributions of a beam requires the exchange the longitudinal and transverse emittances. The innovation that is the heart of this proposal is to use a continuous absorber in a dispersive magnetic field such that higher momentum particles have a longer path length and suffer greater dE/dx energy loss than those of lower energy. Since higher momentum particles then lose energy faster than those of lower momentum, the momentum spread of the beam is reduced. However, since dispersion spreads the beam transversely, the transverse emittance is increased. The usual ionization cooling then acts on the transverse emittance for 6D cooling.

The magnetic field configuration for this 6D Muon and Neutrino Experiment (6DMANX) that we will propose uses a helical dipole magnet to provide dispersion and a solenoidal magnet to provide focusing. Helical dipole magnets are known from their use in the Siberian Snake technique to control spin resonances in particle accelerators and storage rings. Helical quadrupole and sextupole magnets are added to increase beam acceptance. The solenoidal, helical dipole, helical quadrupole, and helical sextupole magnets form the Helical Cooling Channel (HCC) that will be tested in the experiment. The theory of the HCC has been published and numerical simulations have verified its remarkable properties. Cooling a muon beam with a HCC leaves the emittances small enough that even newer cooling techniques such as parametric-resonance ionization cooling or reverse emittance exchange can be used for deeper emittance reduction for more effective muon collider designs.

The particular HCC of the 6DMANX experiment was originally invented to follow the pion decay region at the start of a muon beam channel to provide the first cooling as the muons slow down to an optimum cooling energy. Thus the HCC experimental device to be built and tested is a prototype of a precooling device. In a second application, the HCC device is a prototype segment of a complete cooling channel formed of 8 to 10 such HCC segments, each followed by an RF section to reaccelerate the beam to the original energy of the decay channel. In these two examples, the field strengths of the HCC magnets must be reduced as the momentum decreases to maintain the required focusing and dispersion conditions. Practical magnets that satisfy these conditions are being designed so that realistic fields can be used in numerical simulations.

Several iterations of the 6DMANX design have already eased its engineering and construction difficulties with only a slight reduction in the cooling performance. The maximum field at any conductor is 5.2 T, so that NbTi can be used. The liquid hydrogen energy absorber has been replaced with liquid helium to alleviate safety concerns and to provide a straightforward way to refrigerate the magnet coils. A major simplification is the elimination of RF cavities. Measurements of the invariant emittances will achieve the goals of the experiment, which are 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 will request that Fermilab construct the HCC magnets to be tested and help determine the most expedient location for the experiment. We have started to examine two possible locations. First is the possibility of a merging of MICE and 6DMANX, such that the tests would be done at RAL using the MICE spectrometers. An alternative is to use an appropriate beam line at Fermilab, such as the MiniBooNE line or a muon test line in the Meson Lab, where the necessary modifications are just starting to be investigated.

The document that follows is most of the experimental proposal. The details of the matching section modifications and their costs are yet to be added for the RAL option. The estimates of the costs and required development effort to build the components of the experiment and to execute it at Fermilab are also to be added.

# 6DMANX

# SIX-DIMENSIONAL MUON BEAM COOLING EXPERIMENT

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## Background and Motivation

Ionization Cooling (IC) is currently the only practical technique fast enough to cool a muon beam. An experiment to show that adequate ionization cooling can be achieved in a practical device has yet to be completed but is in progress at Rutherford Appleton Lab (RAL).

IC is intrinsically transverse in nature, reducing only the angular spread of a muon beam; longitudinal cooling with IC requires emittance exchange. A practical scheme for emittance exchange and 6D cooling is yet to be demonstrated.

For much of the last century High Energy Physics has relied on particle accelerators of the highest energy to discover and elucidate the fundamental forces of nature. The most promising path to the energy-frontier machine to follow the Large Hadron Collider (LHC, with quark-antiquark collision energy around 1.5 TeV) has yet to be determined. Electron-positron colliders are probably limited to about 1.5 TeV center-of-mass energy because of radiative processes. Proton colliders, because of the composite nature of the proton, must have even higher energy and may require large amounts of politically sensitive real estate. However, a muon collider of nearly 10 TeV center-of-mass energy could fit on the present Fermilab site.

A Neutrino Factory is an attractive first step toward a Muon Collider. Neutrino physics is extremely interesting at this time and there is considerable pressure to build such a machine. Rapid muon cooling exists at the forefront of basic HEP research in accelerator physics. When muons are sufficiently cooled, existing RF structures, designed primarily for electron acceleration, can be used for efficient muon acceleration. This makes rapid muon cooling an enabling technology that opens up a wide range of muon applications that piggyback on existing technology.

### Potential Applications

Muon beams with small transverse and longitudinal emittance are needed for **muon colliders** in order to get the highest luminosity with the fewest muons. We would like to emphasize that strong reduction of emittance has at least nine very beneficial consequences for a muon collider. The reduction of the required muon current for a given luminosity diminishes several problems:

1) radiation levels due to the high energy neutrinos from muon beams circulating and decaying in the collider that interact in the dirt near the site boundary;
2) electrons from the same decays that cause background in the experimental detectors;
3) difficulty in creating a proton driver that can produce enough protons to create the muons;
4) proton target heat deposition and radiation levels;
5) heating of the ionization cooling energy absorber and
6) beam loading and wake field effects in the accelerating RF cavities.

Smaller emittance also:

7) allows smaller, higher-frequency RF cavities with higher gradient for acceleration;
8) makes beam transport easier; and
9) allows stronger focusing at the interaction point since that is limited by the beam extension in the quadrupole magnets of the low beta insertion.

Reasons 7) and 8) also apply to affordable **neutrino factories** based on muon storage rings. The costs of the acceleration systems for past neutrino factory design studies have been a large fraction of the totals and would have benefited from higher frequency RF systems with their higher gradients and lower component costs. Reference [1] describes how a future Fermilab proton driver [2] based on TESLA superconducting linac modules can perform as both the source of protons to produce the muons and as the accelerator of the muons to be used for a neutrino factory or muon collider, allowing a single linac to serve the dual function of production and subsequent acceleration of the muons. Recent advances in muon cooling [3] have the promise of muon emittances that are compatible with the 1300 MHz accelerating structures that are the basis for the ILC design. In the design described in reference [1], $H^-$ ions are accelerated to 8 GeV in the superconducting Linac, stripped and stored as protons in a ring, then bunched during the 300 microseconds it takes the Linac cavities to be rephased for muon accleleration. The protons are then extracted from the ring to produce pions and muons which are cooled in a few hundred meters, accelerated to a few GeV and injected back into the Linac at the $\beta = 1$ point for acceleration to add 7 GeV. By recirculating the muons in the constant frequency section of such a proton driver Linac, even higher energies can be achieved quickly so that losses from muon decay are minimized. Additional RF power and refrigeration can increase the repetition rate of the Linac to make large increases in the average flux of a neutrino factory and the average luminosity of a muon collider.

Other important uses for **bright muon beams** range from basic studies of fundamental interactions to muon catalyzed fusion. Many applications such as muon spin relaxation techniques or an improved g-2 experiment would benefit greatly from bright, highly polarized muon beams, a topic yet to be fully investigated.

### Timeliness

New ideas on muon cooling have the potential to rejuvenate the idea of an energy frontier muon collider to be built in the nearer future. The work being done in the development of accelerating structures for the International Linear Collider could be immediately applicable to muon acceleration if the beam can be cooled as described above. The multi-pass recirculation through an ILC acceleration section that is only possible with a muon beam could lead to collision energies 10 or more times higher than those of the ILC with less cost.

The incremental cost of a neutrino factory based on a muon storage ring that is fed by recirculating muons in a linear superconducting proton driver may be a fraction of the amount now envisioned for a dedicated neutrino factory with its own proton driver and independent acceleration scheme. Further, if the Linac were to operate in a CW mode such that a higher repetition rate were possible, considerably more neutrinos could be produced than with the schemes that have been investigated so far.

The next step towards the goals of an affordable neutrino factory and a compelling muon collider is to demonstrate that an effective 6D cooling channel can be built that has the properties predicted by analytic calculations and computer simulations.

## Technical Approach

### Helical Cooling Channel (HCC) in Context

The theory of the HCC filled with a continuous absorber has been published [4]. Numerical simulations show almost 5 orders of magnitude reduction in 6D emittance in a 160 meter long HCC using gas filled RF cavities [5]. Recent experimental work at Fermilab [6], as shown in figure 1, supports the idea that RF cavities filled with gaseous hydrogen energy absorber can be used in the HCC and other configurations to take advantage of the unique properties of the muon. That is, a gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve [7].

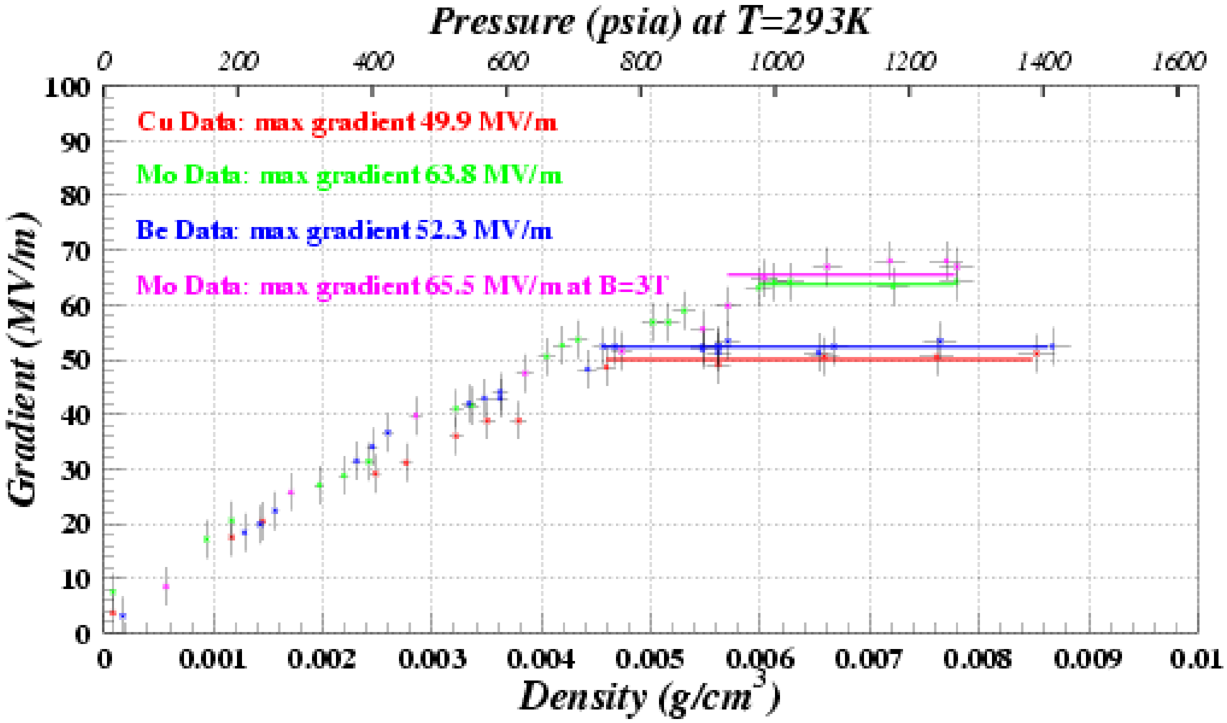

*FIG 1 Measurements of the maximum stable TC gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue). As the pressure increases, the mean free path for ion collisions shortens so 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. This can be compared with measurements of 805 MHz evacuated cavities that show the maximum surface gradient is reduced from 50 MV/m to about 15 MV/m at an external magnetic field of 3 T.*

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 or shower as do less-massive electrons. Although the experiment we are proposing supports the use of a HCC filled with hydrogen-filled RF cavities, the experiment itself does not require RF cavities and, in addition, also supports an alternative to the gas filled RF cavity approach to 6D cooling.

The HCC incorporating hydrogen filled RF cavities will provide the fastest possible muon beam cooling because it will have the highest possible gradients due to the breakdown suppression of the dense gas in a magnetic field and because the same gas simultaneously acts as the energy absorber. However the HCC will not provide the smallest possible emittances unless extremely high fields of the order of 50 T are available.

Parametric-resonance Ionization Cooling and Reverse Emittance Exchange [8], new techniques for muon beams to get transverse emittances that are as small as those used in proton or electron colliders, are being investigated. In these schemes, a linear channel of dipoles and quadrupole or solenoidal magnets periodically provides dispersion and strong focusing at the positions of beryllium wedge absorbers. Very careful compensation of chromatic and spherical aberrations and control of space charge tune spreads is required for these techniques to work. And most important for the experiment being proposed here, the initial emittances at the beginning of the periodic focusing channel must be small in all dimensions. Thus the HCC is the key to extreme muon beam cooling and to the Low Emittance Muon Collider [9].

### HCC Concept

In order to cool the 6D emittance of a beam, the longitudinal emittance must be transferred to transverse emittance where ionization cooling is effective. This emittance exchange is accomplished in the HCC by superimposing a transverse helical dipole magnet and a solenoidal magnet to make possible longitudinal as well as transverse cooling. 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 of the particle, or

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

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. These Lorentz forces are the starting point for the derivations of the stability conditions for particle motion discussed in reference [4]. By moving to the rotating or helical frame of reference that moves with the field of the helical dipole magnet, a time and z-independent Hamiltonian is then developed to explore the characteristics of particle motion in the magnetic fields of the channel. After this, a continuous homogeneous energy absorber is added along with the “continuous” RF cavities needed to compensate for the energy loss and thus maintain the radius of the equilibrium orbit. Equations describing six-dimensional cooling in this channel are also derived in reference [4], including explicit expressions for cooling decrements and equilibrium emittances.

### HCC with z-dependent Field Amplitudes

As discussed in the section above, the results of analytical calculations and numerical simulations of 6D cooling based on a HCC are very encouraging. In these studies, a long HCC encompasses a series of contiguous RF cavities that are filled with dense hydrogen gas so that the beam energy is kept nearly constant, where the RF continuously compensates for the energy lost in the absorber. In this case, the strengths of the magnetic solenoid, helical dipole, and quadrupole magnets of the HCC are also held constant. This feature of the HCC channel is exploited in the mathematical derivation of its properties, where the transverse field is subject only to a simple rotation about the solenoid axis as a function of distance, $z$, along the channel. This rotational invariance leads to a $z$ and time-independent Hamiltonian, which in turn allows the dynamical and cooling behavior of the channel to be examined in great detail. An important relationship between the momentum, $p$, for the stability of an equilibrium orbit at a given radius, $a$, and magnetic field parameters is derived in reference [4]:

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

where $B$ is the solenoid strength, $b$ is the helical dipole strength at the particle position, $k$ is the helix wave number ($k = 2\pi/\lambda$), and $\kappa \equiv ka = p_\perp / p_z$ is the tangent of the helix pitch angle.

The new idea that is the basis for this proposal is that equation (2) is not just a description of the requirements for a simple HCC, but is also a recipe 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. Examples of these purposes that we have examined include:

1) a precooling device to cool a muon beam as it decelerates by energy loss in a continuous, homogeneous absorber, where the cooling can be all transverse, all longitudinal, or any combination;

2) a device similar to a precooler, but used as a full 6-dimensional muon cooling demonstration experiment (this 6DMANX idea is the subject of this proposal);

3) a transition section between two HCC sections with different diameters. For example, this can be used when the RF frequency can be increased once the beam is sufficiently cold to allow smaller and more effective cavities and magnetic coils; and

4) an alternative to the original HCC filled with pressurized RF cavities. In this alternate case, the muons would lose a few hundred MeV/c in a HCC section with momentum dependent fields and then pass through RF cavities to replenish the lost energy, where this sequence could be repeated several times.

Additional constraints to equation (2) are needed to determine the cooling properties of the channel. For example, to achieve equal cooling decrements in the two transverse and the longitudinal coordinates:

$$q \equiv \frac{k_c}{k} - 1 = \beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}} \tag{3}$$

where $k_c = B\sqrt{1+\kappa^2}/p$ is related to the cyclotron motion, $q$ is an effective field index, and $\beta = v/c$. Another example, to achieve a condition where all the cooling is in the longitudinal direction, is to require that: $\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2}$ and $q = 0$.

### HCC Precooling Examples

Figure 2 shows the G4BL simulation of a combination decay (40 m) and precooler (5 m) HCC example. Pions and muons are created in the vacuum of the decay channel and captured in the HCC. At the end of the decay region, the muons pass through a thin aluminum window into a region of liquid energy absorber. By having a continuous HCC for the two sections, the problem of emittance matching into and out of the precooler has been avoided. Simulation studies of various precooler dimensions and magnet strengths have been done.

Figure 3 shows the normalized average transverse, longitudinal, and 6D emittances plotted as a function of the distance down the channel to study the use of liquid hydrogen and liquid helium and the effects of the aluminum containment windows of a 6 m long precooler section. In this simulation, 400 MeV/c muons are degraded to less than 200 MeV/c in making 6 turns in a HCC filled with liquid hydrogen or liquid helium, without or with 1.6 mm aluminum windows on each end of the section. Far from the equilibrium emittances, the cooling with liquid helium absorber is almost as good as with liquid hydrogen. The aluminum windows do not significantly degrade the cooling.

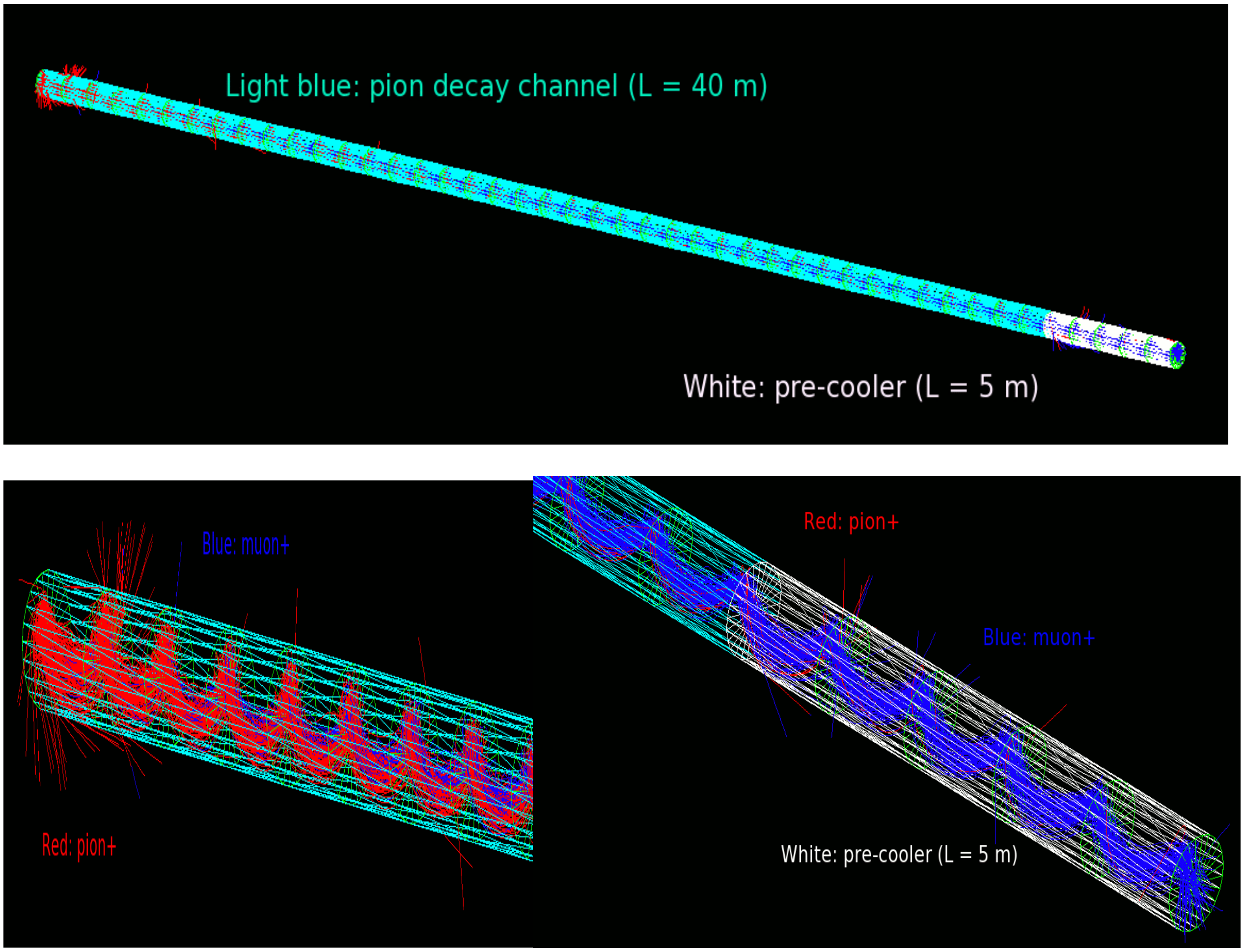

*FIG 2: G4BL display of a pion decay HCC (light blue) followed by a 5 m precooling (white) HCC. The top display shows the whole layout, the lower left display is the beginning of the decay channel, and the lower right display shows the precooler end. The red and blue lines show the pion and muon tracks, respectively. The helix period is 1 meter.*

The settings of the helical dipole and quadrupole magnets and the solenoid are chosen to give equal cooling decrements in all three planes. The combined 6D cooling factor is 6.5 for liquid helium and 8.3 for liquid hydrogen. The improved performance of this HCC simulation relative to designs in which short flasks of liquid absorber alternate with RF cavities comes from the effectiveness of the HCC, from the greater path length in the absorber ($6/\cos(45^0) = 8.5$ m), and from less heating by the high-Z windows. MICE, for example, has several aluminum windows for hydrogen containment and separation from RF cavities, while the two thin windows needed for this precooler design are negligible in their heating effect compared to the length of the liquid absorber. This precooling example inspired the idea of a 6D cooling demonstration experiment that is described below. In fact, the device that we propose to design as a 6D demonstration experiment also serves as a precooler prototype.

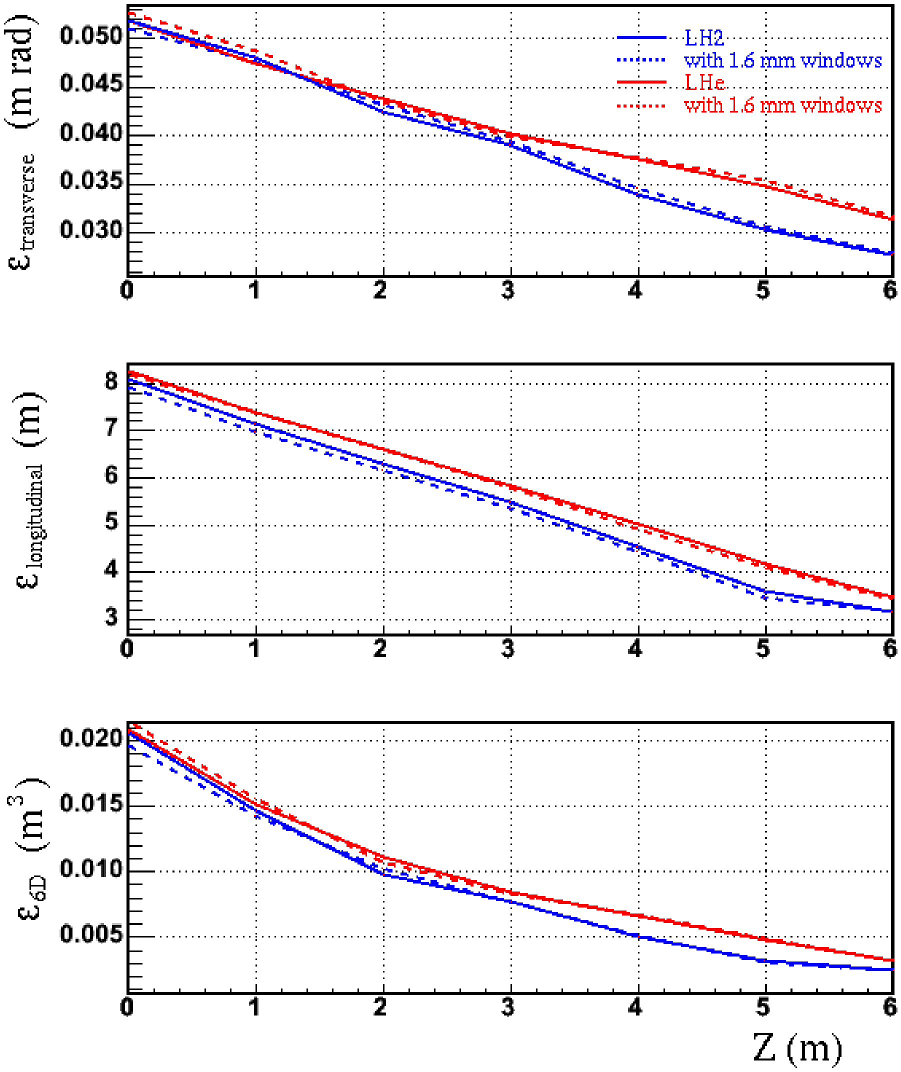

*FIG 3: Simulations showing normalized emittance evolution for particles that survive to 6 m for a HCC precooler filled with liquid hydrogen (blue) or liquid helium (red), with (dashed) and without (solid) 1.6 mm thick aluminum windows on each end.*

## The 6DMANX Experiment

The ultimate goal of the experiment is to build a HCC cooling channel magnet using available technology and to use it in a muon beam to make a striking demonstration that exceptional 6D beam cooling is technically feasible.

6DMANX will demonstrate the use of a HCC with a continuous homogeneous absorber to achieve emittance exchange and 6D cooling. Contrary to previously described demonstration experiments, including MICE and a previous SBIR project using high-pressure hydrogen-filled RF cavities, we have eliminated the RF cavities altogether in order to reduce the cost and complexity of the experiment. Implicit in this approach is that the experiment need only demonstrate the reduction of the invariant normalized emittances. The elimination of the RF component of the experiment will ultimately simplify the analysis of the results and will demonstrate the effectiveness of the cooling plan without the added complication of RF acceleration. Without the RF cavities in the HCC, there is no reason to use the dense gas that was originally envisioned to allow high RF gradients. This means that we do not need to use cold, high pressure hydrogen. In fact, liquid hydrogen or helium will provide the continuous energy absorber that we need, without the need for thick windows that would be required for high-pressure gaseous absorber and would degrade the cooling performance of the demonstration.

In the following discussion we assume that the measurements will be of single particles, using the same technique that has been adopted by the MICE collaboration. We note, however, that the beam cooling performance of the HCC should be good enough that we can consider measurements of ensembles of particles as another method that may be complementary to the single particle approach.

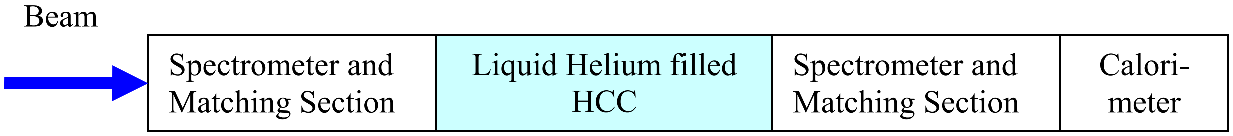

*FIG 4: Generic diagram of the 6DMANX experiment.*

A generic diagram of the 6DMANX experiment is shown in figure 4. An incident beam of muons with momentum around 300 MeV/c passes through an upstream spectrometer where the trajectory, time, and momentum of each particle are measured. 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 where the momentum is degraded and 6D cooling occurs. The ~150 MeV/c beam exits the HCC through another thin window into the matching and spectrometer sections and is stopped in the calorimeter. Timing counters and Cherenkov counters in the spectrometer sections and the calorimeter at the end of the channel will be used for particle identification.

This spectrometer can be based on conventional quadrupole and dipole Cartesian coordinates or based on a solenoidal geometry as is done in MICE. The matching section then depends on which spectrometer type is chosen. Muons, Inc. and Fermilab have just received an STTR phase I grant to study these matching problems.

### Solenoidal Spectrometer and Matching Section

The most attractive matching section that we have envisioned is based on the use of the equation above relating the radius *a*, the momentum *p*, the solenoid field *B*, and the helical dipole strength *b* and wavelength $\lambda$. If the initial beam is focused by a solenoidal magnet, the matching section should be straightforward. That is, the strength of the beam line solenoidal field can be increased to match the strength of the HCC solenoid at the same time that the helical dipole strength can be increased from zero to that of the HCC. All that should be required is that the relationship in the equation be followed. There is some requirement that this matching be done in an adiabatic fashion, and we need to simulate this technique to know how much space will be required for each matching section. It is possible that the MICE spectrometers will be useful in this approach since they have coils which may do part of the solenoidal match.

Our first attempt at matching using this adiabatic approach indicates what we believe is an unacceptably long upstream matching section of about 15 m. The downstream matching section would be only one half as long, but to have over 20 m of matching section for a 4 m experiment seems extravagant.

### Dipole Spectrometer and Matching Section

Another approach is based on the idea that there may be some dipole magnets and spectrometer elements available from previous experiments. In this case a quadrupole focused beam would go through a conventional Cartesian spectrometer and then be matched to the HCC.

We note that several of our close collaborators have worked on the general solution for matching between solenoidal lattices and those based on quadrupole and dipole magnets [10, 11, 12]. The effectiveness of this approach has been seen in the development of techniques for flat beams for linear colliders and most recently for the electron cooling of the antiproton beams for the Fermilab Tevatron Collider.

### First Experimental Configuration

A conceptual picture of a 6DMANX demonstration experiment is shown in figure 5 using the MICE spectrometers at Rutherford Appleton Laboratory (RAL). In this example, the helical dipole component of the matching section was not used and an attempt was made to put the beam onto the HCC equilibrium orbit by “brute force”. Although the beam did follow the HCC trajectories, it was very difficult to get the beam to enter the downstream spectrometer on an acceptable path. As with all HCC simulations, we learned that it is almost impossible to get the parameters right without careful analytical guidance.

The gray cylinder represents the HCC, which is the new device to be built. It is a solenoid with transverse helical dipole and quadrupole magnets that is filled with liquid helium or hydrogen. Muons enter from the left of the picture and pass through the (yellow) solenoidal spectrometer section instrumented with the scintillating fiber detectors that are being built for the MICE experiment.

The muons then enter the HCC at a horizontal angle and vertical offset to match the equilibrium orbit. Here, $\kappa \equiv ka = p_\perp / p_z = 1$, the helix pitch angle and beam entrance angle is 45 degrees, and the helix period $\lambda = 1$ m, giving a radial offset $a = 1/2\pi = 15.9$ cm. The equilibrium orbit then follows a helical path with 3 turns in the HCC before exiting into the downstream spectrometer system. A 32 cm diameter window at each end of the HCC contains the liquid absorber, where the downstream window is seen as a black ellipse on the end of the gray cylinder in the upper view of figure 5.

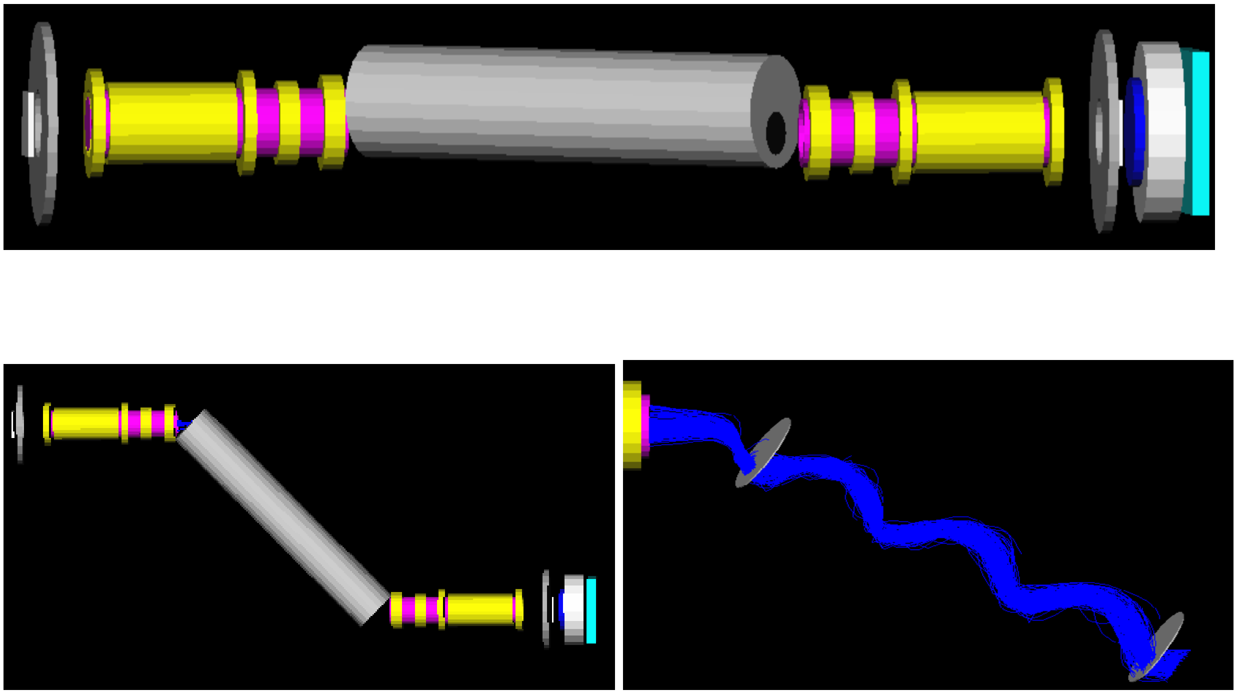

*FIG 5: G4BL simulation program displays of the elevation (upper), plan (lower left) and beam trace (lower right) views of the 6DMANX HCC using the MICE spectrometers. The yellow devices correspond to the matching coils and spectrometer magnets of the particle measurement sections of the MICE experiment. The gray cylinder is the HCC that is the heart of 6DMANX.*

### 6DMANX Design

The magnetic field strengths for the first studies of the precooler and the demonstration experiment were very large at the coils and would require the use of HTS at low temperature. In order to alleviate this technical problem, we have already started to study changes in the experiment to make it easier to build. Figure 6 shows the simulation results for the 6DMANX experiment based on relaxed parameters, where the magnet coils could be made of NbTi and cooled by the same liquid helium that acts as the ionization cooling energy absorber. In order to reduce the fields, the initial momentum has been decreased from 400 to 300 MeV/c (as required for the RAL beam), $\lambda$ has been increased from 1 to 2 m, and $\kappa$ decreased from 1 to 0.8. The maximum field at a conductor then becomes 5.2 T. Figure 7 shows the trajectory and decreasing momentum of an equilibrium orbit. In the range from 0 to z=400 cm, the cooling factors are: average transverse 1.7, longitudinal 1.5, and 6D 4.7.

These simulations using a HCC with momentum dependent magnetic fields indicate that a device originally designed to be used as an excellent precooling device in a practical muon cooling channel can also be used to demonstrate exceptional muon beam cooling. Compared to the 10%

cooling effect expected with MICE, the 470% effect of the LHe 6DMANX simulations implies a lot of room for compromise. That is, some of the parameters such as the beam momentum range, magnet aperture, or channel length could be reduced and there would still be an impressive measurement to be made. For example, it may be possible to make a conventional emittance measurement (using an ensemble of muons rather than one particle at a time) as a cheap, preliminary measure of emittance reduction, further reducing costs. These options can be considered in detail once a muon beam is chosen and matching problems are addressed.

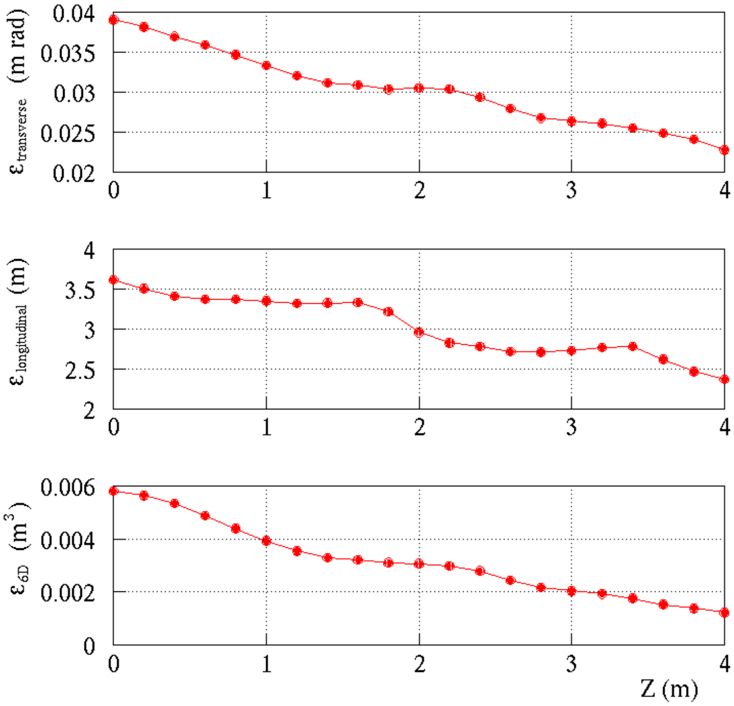

*FIG 6: G4Beamline simulation of a liquid helium filled 6DMANX section with reduced field requirements. The initial momentum has been decreased from 400 to 300 MeV/c (as required for the RAL beam), $\lambda$ has been increased from 1 to 2 m, and $\kappa$ decreased from 1 to 0.8. The maximum field at a conductor has thereby been reduced to 5.2 T. The cooling factors are: average transverse 1.7, longitudinal 1.5, and 6D 4.7.*

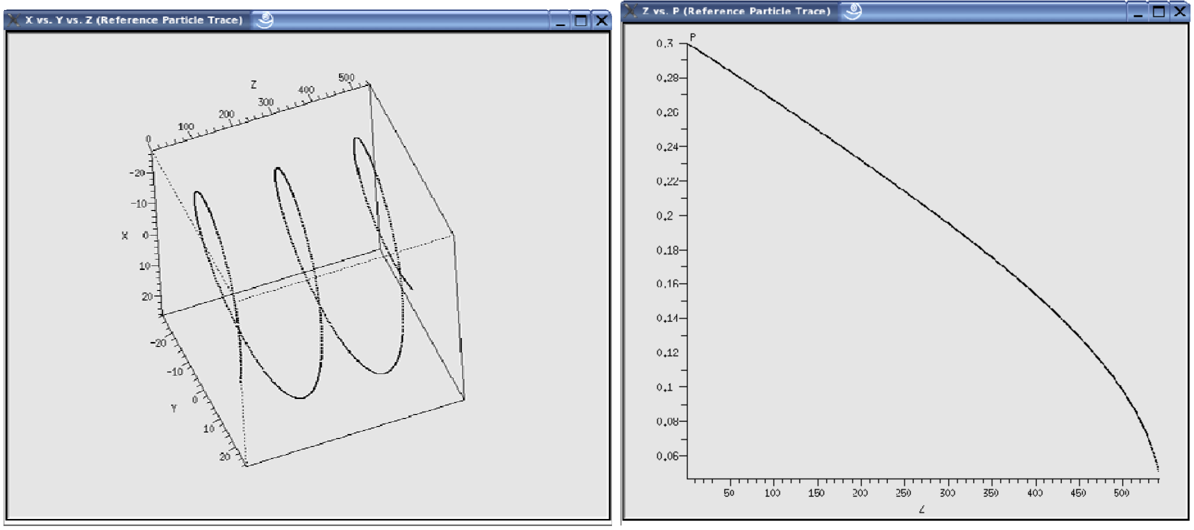

*FIG 7: Path (LEFT) and momentum (RIGHT) of the equilibrium orbit as a function of z.*

## Magnets

The HCC magnet has 4 circuits, which correspond to the solenoidal, helical dipole, helical quadrupole, and helical sextupole fields. The closest example to the helical dipole component that we wish to construct is seen in the helical dipole magnet [13] used at the BNL AGS to control spin resonances in accelerating polarized protons to be transferred to RHIC. A picture of that magnet is shown in figure 8.

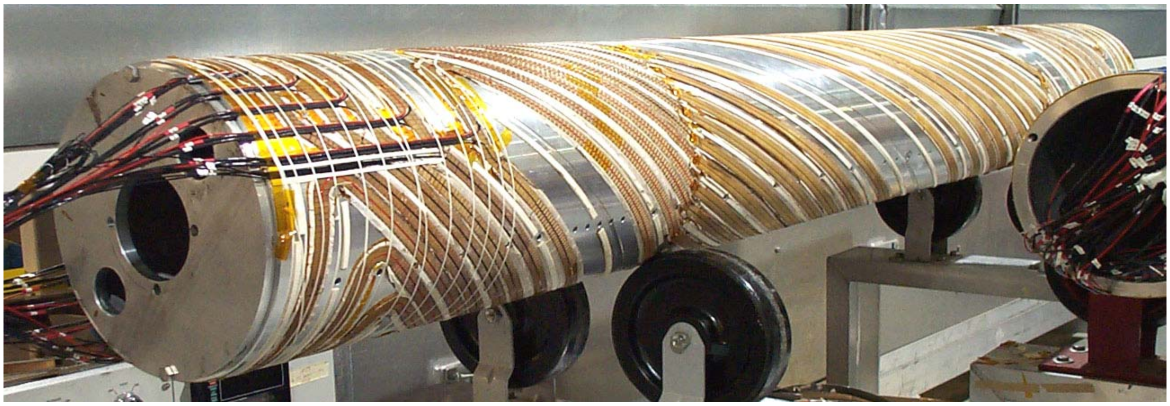

*FIG 8: BNL Helical Dipole magnet used for spin control in the AGS. The inner diameter is 0.20 m and the length is 1.9 m. The field is 3 T and must have exceptionally good field quality as expected for a magnet in a synchrotron. In comparison, the HCC magnet is larger with diameter of 0.80 m, length 4 m, but with smaller dipole field <1 T and easier field quality requirements since it is a single pass device. Another essential difference is that the HCC magnets all must have decreasing strength to match the momentum of the muons as they lose energy.*

The following table gives the significant dimensions of the 6DMANX HCC magnet, where the initial (z=0) and final (z=4 m) fields are indicated as well as the muon beam parameters. Figure 9 shows the variation of the solenoidal and helical multipoles that were used in the simulations. Figures 10 and 11 show the maximum field values inside the HCC and at the coils, showing that NbTi is well suited for magnet construction. It seems that enough NbTi to construct the solenoidal magnet component of the HCC is left over from the construction of the LHC IR quadrupoles. Figure 12 is a simulation study of the effects of random field errors. As expected for a single pass device, magnet tolerances are more relaxed than for accelerator magnets and may imply lower construction costs.

**Helical magnet**
- Total length = 4 meters
- Magnet bore diameter = 0.8 ~ 1.0 meters
- Helix period = 2 meters
- $\kappa = 0.8$
- Initial/Final $B_z$ (solenoid) on reference orbit = -4.4/-2.2 T
- Initial/Final $b$ (dipole) on reference orbit = 0.95/0.45 T
- Initial/Final $b'$ (quadrupole) on reference orbit = 0.60/0.40 T/m
- Initial/Final $b''$ (sextupole) on reference orbit = -0.26/-0.15 T/m$^2$

**Beam**
- Initial <P> = 300 MeV/c
- Final <P> = ~ 150 MeV/c
- $\Delta P/P \sim 7$ %
- Beam diameter ~ 20 cm

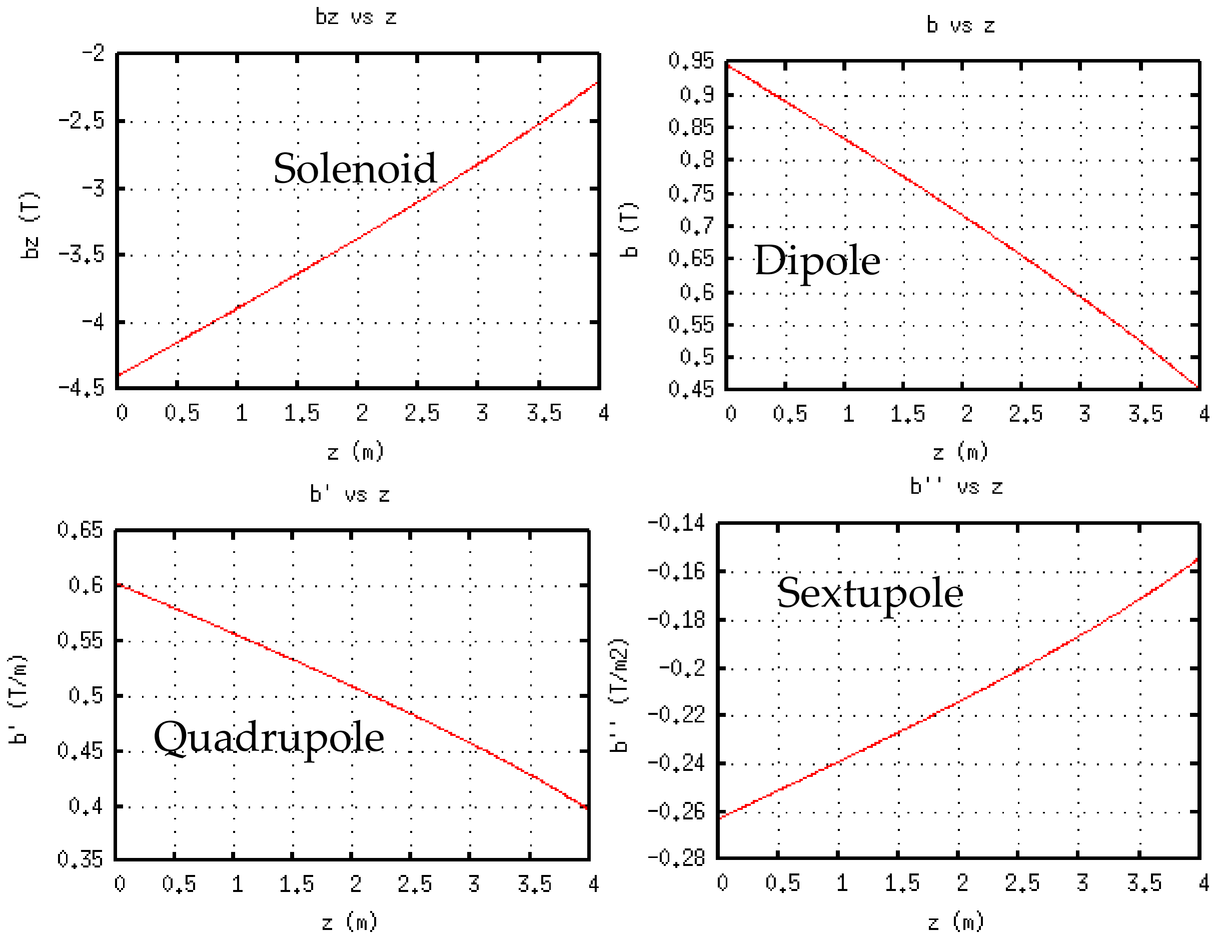

*Fig. 9: Magnet strengths as a function of z for the four circuits of the HCC. Each must have decreasing strength to match the momentum of the muons as they lose energy.*

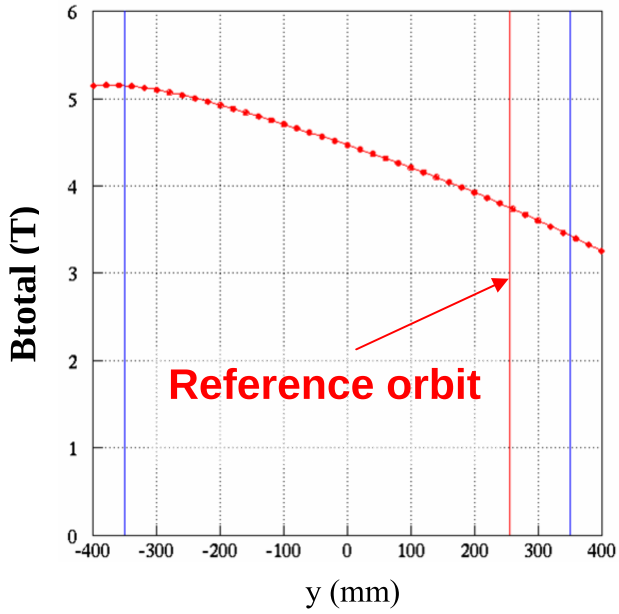

*FIG 10: $B_{total}$ on the y axis at x=0*

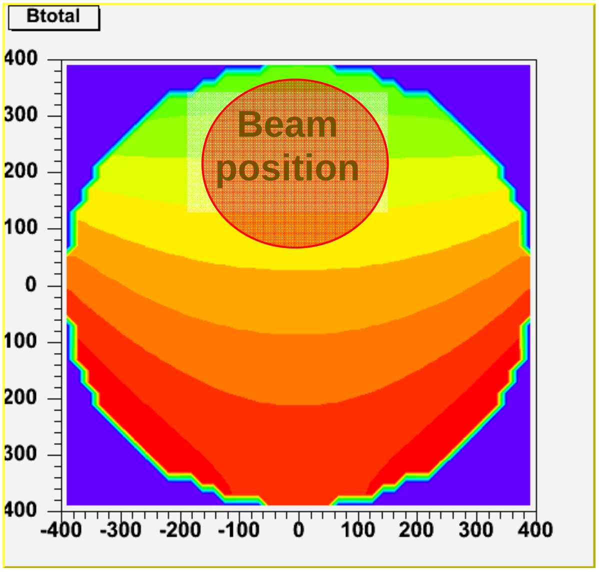

*FIG 11: x-y contour plot of $B_{total}$ in the LHe HCC (red: > 5 T, green 3.5 T, blue = 0)*

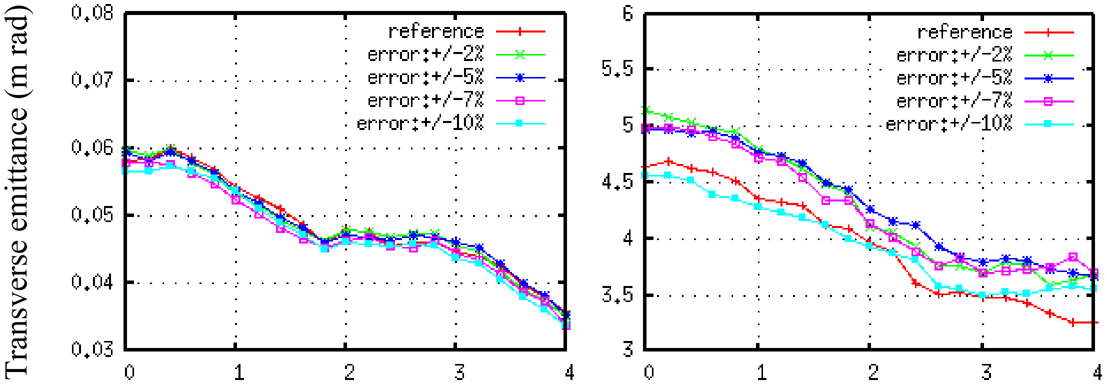

*FIG 12: Simulation study of effects of random field errors on the cooling of the transverse (LEFT) and longitudinal (RIGHT) beam emittances in the 6DMANX HCC.*

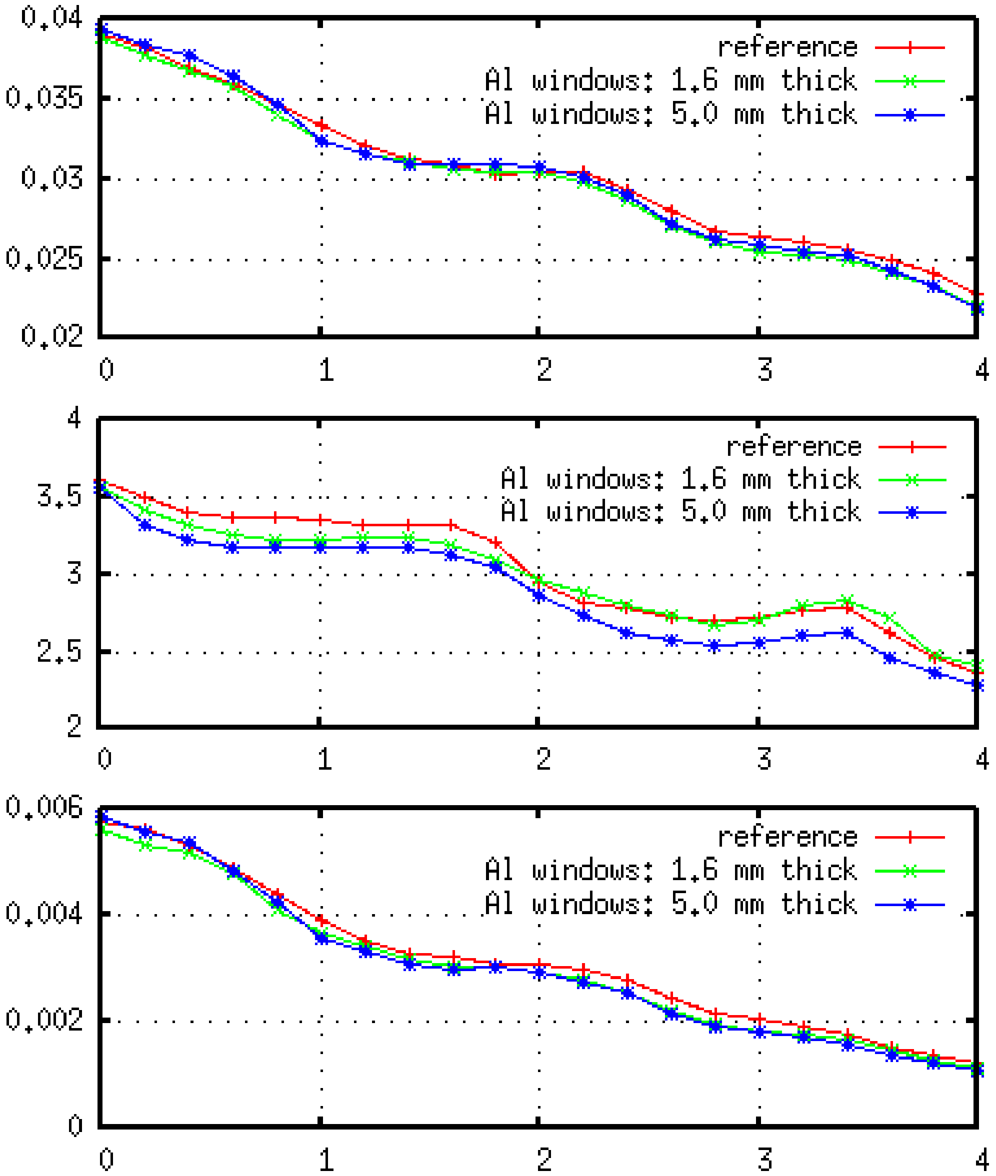

*FIG 13: Simulation study of the effect of window thickness on the cooling of the transverse (TOP) longitudinal (CENTER) and 6D (BOTTOM) emittances in the 6DMANX HCC.*

### LHe Absorber and Containment Windows

The LHe absorber is an advantage in that the extreme safety concerns of liquid hydrogen are avoided. Simple, thin aluminum windows are sufficient to contain it. Even relatively thick windows make a negligible impact on the expected cooling measurements, as shown in figure 13. Since the beam occupies a small part of the volume of the magnet, the part that is not involved can be filled with an inert material such as Styrofoam to reduce the needed amount of liquid helium.

### Cryostat

Figure 14 shows a conceptual diagram of a cryostat for a 5 m long HCC, which would be appropriate for a precooling application. $LH_2$ or LHe would be forced through the coils to cool them, and then circulated through the central volume of the magnets where it would act as the ionization cooling energy absorber. For the case of the $LH_2$ at 15 kelvin, the magnets would be made of high temperature superconductor (HTS). Measurements of the behavior of HTS at this temperature have been made at Fermilab with encouraging results [14]. The cryostat for the 6DMANX experiment would be similar to this design, although for expedience and to reduce costs, the dimensions of the components may be changed according to what pieces are available, for example from leftover LHC quadrupole construction components.

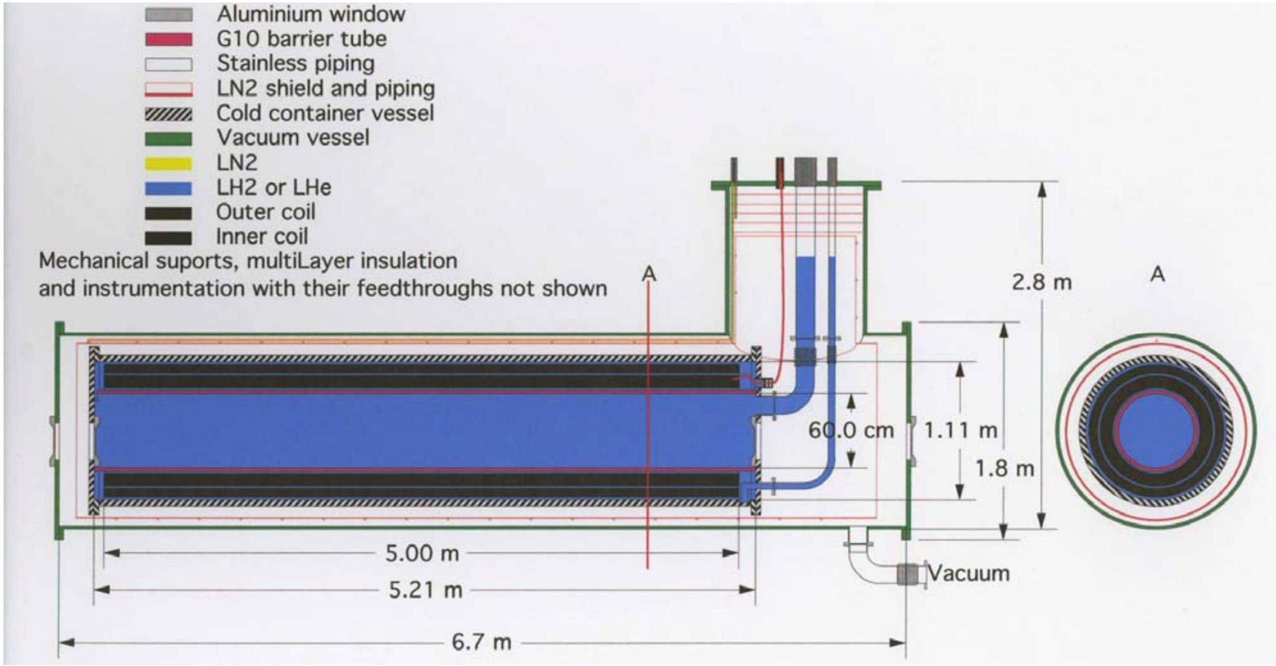

*FIG 14: Five meter long MANX cryostat schematic. For RAL, the length becomes 4 m. At FNAL perhaps 5 m is possible. The use of liquid He at 4 K is possible, with NbTi magnets. Thin Al windows designed for MICE can be used.*

### Spectrometers

The most relevant spectrometer elements that could be used in this 6DMANX experiment are those that are being developed by the MICE collaboration. The scintillating fiber tracking detectors with VLPC readout using boards developed for the Fermilab D0 experiment, the Cherenkov counters, the time-of-flight counters, and the electromagnetic calorimeter now being constructed for MICE would work well for the 6DMANX experiment.

## Costs

The MICE project is well known to us and some of our collaborators are active MICE collaborators. One hoped-for outcome of this 6DMANX proposal is that it will be so attractive as to induce the MICE people to collaborate with us to do this experiment as soon as possible. The first stages of the MICE facility involve the development of the spectrometers that are upstream and downstream of their cooling channel segment, which we hope to show will work for 6DMANX. This would define a natural synthesis of the MICE and 6DMANX projects. If our proposal is granted, we expect to make a strong case for this scenario based on an expected cooling factor of something like 500% for 6DMANX (compared to 10% for MICE) and effective demonstration of emittance exchange and longitudinal cooling, which is not now a part of the MICE program.

According to the MICE experimental proposal to RAL[15] the cost for the hardware for the MICE experiment was estimated to be about \$25.2M, separated into Cooling Section \$13.9M, Spectrometer section \$7.5M, and Ancillary items \$3.8M. In addition, \$5.9M was the estimated cost for RAL to produce a beam line for the experiment.

The beam line has been funded and the spectrometers, with the possible exception of one of the superconducting magnets, are also funded and under construction. The present plan is for the MICE experiment to start using the beam line and two spectrometers in the latter half of 2007 in preparation for the arrival of the cooling sections of the experiment.

One can compare the \$13.9M MICE cooling section hardware cost to the cost of the 6DMANX HCC device that we wish to build and test at RAL. The two major changes are that the HCC has no RF and there is no hydrogen in the HCC. The RF component of the MICE experiment is \$7.58M and the hydrogen absorbers and associated windows and cooling systems are less than \$1M. Thus the magnets and power supplies for the cooling section of MICE are just over \$5M. The three focusing coil assemblies and the two coupling coil assemblies that make up the MICE cooling section magnets can be compared to the HCC solenoidal and helical dipole magnet coils.

| | MICE | | 6DMANX | |
|---|---|---|---|---|
| | Focusing | Coupling | Solenoid | Helical dipole |
| Number of coils | 6 | 2 | 1 | 1 |
| Inner radius (mm) | 255 | 690 | 400 | 400 |
| Coil length (mm) | 200 | 360 | 4000 | 4000 |
| Peak field (T) | 6.27 | 5.45 | 5.12 | 0.95 |

The helical quadrupole and helical sextupole circuits are relatively weak, and it could be argued that the additional 10% acceptance provided by the sextupole circuit is unnecessary. The MICE coils are in their own cryostats with separate mechanical support structures, while the 6DMANX coils are all in one cryostat and wound on two stainless steel or aluminum cylinders. Roughly speaking, the cost and complexity of the cooling section magnets for the two experiments are similar enough to say they are equal at about \$5M.

## Summary and Conclusions

The HCC with a continuous homogeneous absorber is a technical breakthrough in the technology of muon beam cooling. The extension of this idea to a HCC with z-dependent magnet strengths represents another technical breakthrough. The experimental verification of 6D muon beam cooling is an essential step in the progress of accelerator science.

If a 6DMANX cooling section can be designed that is compatible with the MICE spectrometers, synthesizing the MICE and 6DMANX experiments will be an extraordinary win-win opportunity.

The MICE collaboration is making good progress towards a complete demonstration of transverse ionization cooling by about the year 2010. Our goal is to build the necessary equipment for a demonstration of 6D cooling in an HCC on a timescale comparable to that of MICE, so that the HCC performance can then be determined in a collaborative effort with MICE using the MICE muon beamline and spectrometers. The 6D cooling measurements made with the HCC will thus extend and complement the transverse cooling that will already have been demonstrated. In such a synergistic scenario, each collaboration will benefit from the added energy of the other. We intend to work with the MICE collaboration to ensure that compatibility between these two applications of the MICE beam line and spectrometers is maintained. Since the expected cooling factor from the prototype HCC is large, a test at Fermilab with simpler apparatus may also be practical; we intend to simulate such a test to learn what the likely constraints will be.

It is to Fermilab's advantage to design and build a HCC and carry out the experiment as soon as possible. A plan for muon colliders using ILC accelerating structures that would fit on the Fermilab site, first as a Higgs factory and then as an energy frontier muon collider, is an attractive way for Fermilab and its high energy physics community to have a long and healthy future.

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