Final Technical Report on STTR Project DE-FG02-06ER86282

Development and Demonstration of 6-Dimensional Muon Beam Cooling

Executive Summary

The overarching purpose of this project was to prepare a proposal for an experiment to demonstrate 6-dimensional muon beam cooling. The technical objectives were all steps in preparing the proposal, which was successfully presented to the Fermilab Accelerator Advisory Committee in February 2009. All primary goals of this project have been met.

The High Energy Physics (HEP) community is always searching for “the next big thing”, and Fermilab in particular is considering several options for the next machine capable of reaching the energy frontier. Today a major prospect is a muon collider, which would create copious muons, accelerate them to several TeV, and collide them inside a large detector. This project was an important step in getting a muon collider onto the agenda at Fermilab, because six-dimensional muon beam cooling is essential for such a collider to achieve useful luminosity.

An important goal of this project was the building of an experimental collaboration of people interested in performing the experiment. The MANX Collaboration was formed, comprising 38 physicists and engineers from all relevant technical disciplines, which submitted the proposal.

Fermilab’s Accelerator Advisory Committee reviewed the proposal in February 2009. While their overall response was positive, the experiment has not been approved or funded. Since this project began, outside events in the muon-collider community have occurred that have put this experimental proposal on hold. Specifically, the Muon Accelerator Program (MAP) [1] has begun, and its schedule does not call for a 6-D cooling demonstration experiment at this time.

This STTR project has been highly successful for our company, and has generated three other SBIR/STTR projects [3] [4].

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1. DOE award number: STTR Project DE-FG02-06ER86282
Name of Recipient: Muons, Inc.

2. Project Title: Development and Demonstration of 6-Dimensional Muon Beam Cooling
Name of PI: Dr. Rolland Johnson
Research Partner: Fermi National Accelerator Laboratory
Name of JLab subgrant PI: Dr. Michael Lamm

3. Date of Report: May 24, 2011
Period of Report: July, 2006 to December, 2009

4. Comparison of Accomplishments and Goals:

All of the primary goals of this project have been met.

The primary technical objectives of this project were those on the critical path for the MANX experimental proposal:

Proposal Technical Objective	Accomplishment
G4MANX, the simulation, reconstruction, and analysis program started in Phase I, will be extended and used to optimize experimental parameters by improving beam cooling statistical significance, understanding systematic errors, and exploring engineering simplifications and their ramifications.	G4MANX was developed, and was used to optimize the design of the experiment, reflected in the proposal, Appendix 13. The software has since been superseded by the development of G4MICE by the MICE collaboration [2], in which aspects of G4MANX have been included.
HCC Magnet Development. The engineering of the HCC and emittance-matching magnet systems will be continued, with the construction and testing a three-coil demonstration magnet for the superconducting helical solenoid the most important immediate objective.	Helical Cooling Channel (HCC) magnet development has proceeded, and the three-coil test was expanded to a four-coil test; it was successfully performed. This has become extended into two other SBIR/STTR projects related to HCC innovations [3].
MANX Experimental Proposal. We will work with the Fermilab Muon Collider Task Force to build a collaboration of committed scientists and engineers and to develop and defend a compelling MANX collaborative experimental proposal. We are working with the MCTF to investigate possible Fermilab sites.	The MANX proposal was submitted by the MANX Collaboration to the Fermilab Accelerator Advisory Committee, and was evaluated by them during their February 2009 meeting; their report is in Appendix 14 (the portion relevant to MANX is pages 15-18).
Detector Development. We will continue to investigate possibilities to acquire or develop appropriate particle detectors for the experiment.	Detector development has continued, and has expanded into another SBIR project [4].

5. Summary of Accomplishments and Project Activities:

1. HCC magnet design progressed in considerable detail.
2. HCC four-coil test: The magnet reached 85 percent of short sample, the approximate level of design operation. It also reached a considerably higher current than the design current, albeit in a lower field. The field distributions agree well with predictions (Appendix 7).
3. Several approaches to integrating the RF into the helical magnet were investigated.
4. Placement of the experiment in the MICE hall at Rutherford-Appleton Lab was explored.
5. Investigated the integration and matching of the MANX magnet with the MICE spectrometers and their magnets.
6. The MANX collaboration was formed, held a meeting, and submitted the MANX proposal to the Fermilab AAC; the proposal is in Appendix 13, and the AAC report is in Appendix 14 (the portion relevant to MANX is pages 15-18).
7. Twelve conference posters and papers were prepared and presented, demonstrating progress and attracting new collaborators (Appendices 1-12).

6. Products or Technology Transfer:

The primary product of this project is the MANX proposal, appended in Appendix 13. Other products are the conference papers listed below, and the knowledge and experience gained in performing the four-coil HCC magnet test.

a. Publications and Conference Papers:

Copies of these papers are provided in the listed appendix.

Appendix	**Conference**	Title
1	PAC05, Knoxville, TN, May 2005, IEEE, APS, ORNL.	"MANX, A 6-D MUON COOLING DEMONSTRATION EXPERIMENT"
2	PAC07, Albuquerque, NM, June 2007, IEEE, APS, LANL	"MAGNETS FOR THE MANX 6-D MUON COOLING DEMONSTRATION EXPERIMENT"
3		"THE MANX MUON COOLING DEMONSTRATION EXPERIMENT"
4	EPAC08, Genoa, Italy, June 2008, EPS-AG, IEEE, APS	"FOUR-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MUON BEAM COOLING"
5		"MAGNETS FOR THE MANX 6-D MUON COOLING DEMONSTRATION EXPERIMENT"
6		"STATUS OF THE MANX MUON COOLING EXPERIMENT"

7	PAC09, Vancouver, Canada, May 2009, IEEE, APS, TRIUMF	"4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MANX"
8		"RF INTEGRATION INTO HELICAL MAGNET FOR MUON 6-DIMENSIONAL BEAM COOLING"
9		"MANX, A 6-D MUON BEAM COOLING EXPERIMENT FOR RAL"
10		"INTEGRATING THE MANX 6-D MUON COOLING EXPERIMENT WITH THE MICE SPECTROMETERS"
11	NuFact07, Okayama, Japan, August 2007, IEEE, APS, Okayama Univ.	"MANX: A 6D Ionization-Cooling Experiment"
12	CP1218, Advances in Cryogenic Engineering, Tucson, AZ, June 2009	"Mechanical Analysis and Test Results of 4-Coil Superconducting Helical Solenoid Model"

b. Web Site:

http://muonsinc.com

c. Networks or Collaborations Fostered:

One of the objectives of this project was the formation of the MANX Collaboration. That was accomplished, and the collaboration submitted the MANX proposal.

All of the above conference papers were presented as posters at the conference. This has proven to be an excellent way to advertise the capabilities of our company, to interact with current collaborators, and to attract new friends and collaborators.

d. Technologies/Techniques:

The technology of helical cooling channels (HCCs) has become increasingly important in designing several aspects of a muon collider. The HCC was first conceived as a method of 6-dimensional muon cooling. Related helical channels are now being studied for use in the front end (decay, collection, and phase rotation, in which an approximately isochronous helical channel has advantages), and the bunch merging (in which a helical channel can be considerably shorter than a simple drift).

e. Inventions/Patent Applications:
Most of Muons, Inc. inventions are particularly useful for large projects built by the US Government, which will have rights to our inventions as part of SBIR-STTR agreements. It is difficult to imagine commercially important applications for muon colliders in the time frame of a patent. We are pleased, however, to contribute to the progress toward the energy frontier,

which has tremendous importance to humanity as a source of fundamental knowledge of our universe.

f. Other Products:

None.

References

[1] The Muon Accelerator Program, http://map.fnal.gov
[2] The MICE experiment: http://mice.iit.edu/
[3] Further, related HCC projects:
"Magnets for Muon 6D Helical Cooling Channels", SBIR project DE-FG02-07ER84825.
"Epicyclic Helical Channels for Parametric-resonance Ionization Cooling", STTR project DE-SC00005589.
[4] "Fast Time-of-Flight System for Muon Cooling Experiments", SBIR project DE-SC00005445.

MANX, A 6-D MUON COOLING DEMONSTRATION EXPERIMENT*

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Abstract

Most ionization cooling schemes now under consideration are based on using many large flasks of liquid hydrogen energy absorber. One important example is the proposed Muon Ionization Cooling Experiment (MICE), which has recently been approved to run at the Rutherford Appleton Laboratory (RAL). In the work reported here, a potential muon cooling demonstration experiment based on a continuous liquid energy absorber in a helical cooling channel (HCC) is discussed. The original HCC used a gaseous energy absorber for the engineering advantage of combining the energy absorption and RF energy regeneration in hydrogen-filled RF cavities. In the Muon And Neutrino eXperiment (MANX) that is proposed here, a liquid-filled HCC is used without RF energy regeneration to achieve the largest possible cooling rate in six dimensions. In this case, the magnetic fields of the HCC must diminish as the muons lose momentum as they pass through the liquid energy absorber. The length of the MANX device is determined by the maximum momentum of the muon test beam and the maximum practical field that can be sustained at the magnet coils. We have studied a 3 meter-long HCC example that could be inserted between the MICE spectrometers at RAL.

INTRODUCTION

In order for the high energy physics community to accept the idea of actually constructing a neutrino factory or a muon collider, it is necessary to demonstrate both the physics and the engineering feasibility of the special components required in their construction. As muons are inherently generated with a very large emittance, a key new component of such a facility is equipment to reduce their emittance to the acceptance of an affordable accelerator; this is known as beam cooling. Due to the short lifetime of the muon, the only suitable method for this is ionization cooling [1]. There are many variations on ionization cooling, and the key innovation discussed here is to combine a long continuous energy absorber with a helical magnetic channel to provide not only a rather large cooling factor, but also cooling in all six dimensions of the beam distribution.

THE HELICAL COOLING CHANNEL

The Helical Cooling Channel (HCC) [2] consists of three superimposed superconducting magnets that provide solenoid, helical dipole, and helical quadrupole fields, plus a continuous energy absorber along the helical magnetic channel. By tailoring the magnetic fields to the muons' energy loss in the absorber, the muon beam can be kept in the magnetic channel as it cools and loses energy. The key design challenge is to maintain the proper relationships among the different components of the field so the muons remain in the helical channel, the desired dispersion is maintained, and the acceptance is as large as possible. The dispersion is the correlation between momentum and transverse position, and in a helical channel it determines the relationship between the muon path length and momentum. That relationship is the essential design parameter that determines the emittance exchange and therefore the longitudinal cooling in the helical channel.

The dipole and quadrupole fields are shown in Figure 1 at the entrance plane of the HCC; in addition there is a larger solenoid field out of the paper. For successive planes into the paper (along the solenoid axis), the figure rotates clockwise around the center of the solenoid, so the acceptance follows the helix. The reference particle (centerline of the acceptance) is at the center of the blue circle, angled 45° into the paper to the right, along the helix (the beam centerline is along the helix, not along the solenoid axis). The dipole field and the solenoid field (not shown) must be designed so that the reference particle follows the desired helix, which means they must decrease as muons lose energy by ionization loss in the absorber. The quadrupole field must vary accordingly to maintain the acceptance.

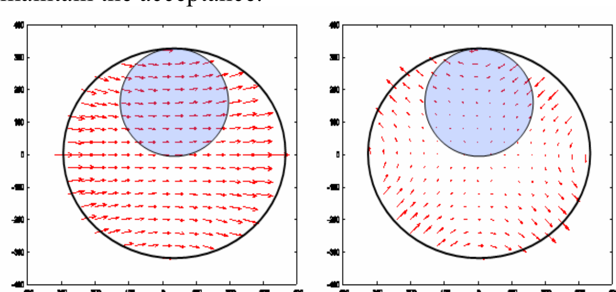

Figure 1. Helical Dipole (left) and Quadrupole (right) fields at the entrance to the HCC. The large circle is the solenoid (64 cm inner diameter), and the smaller blue circle is the region of acceptance of the HCC.

* Work supported by the U.S. DOE SBIR grant DE-FG02-04ER84015.

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The helical cooling channel described here is 3 meters long and 64 cm in diameter (plus the solenoid coils and their supports). The helix has a 1 meter period so the beam makes three turns around the helix inside the HCC. It is designed for a muon beam with a mean momentum of 300 MeV/c, which loses energy in the liquid hydrogen absorber down to a mean momentum of 85 MeV/c. At the entrance the solenoid field is 8.5 Tesla, the dipole field is 3.7 Tesla, and the quadrupole gradient is 7.7 Tesla/meter; all of these decrease along the HCC. These large field values make this a challenging magnet to construct, and a major part of our ongoing design effort will be to trade off the cooling performance with the practical cost and effort of constructing the channel.

The advantage of this HCC over other cooling demonstration approaches is shown in Figure 2: in a section only 3 meters long a reduction in the 6d emittance by a factor of 2 can be achieved, with a third of the cooling being longitudinal. This is about 20 times more cooling than in the MICE experiment [3], which has no longitudinal cooling (an essential requirement for a muon collider).

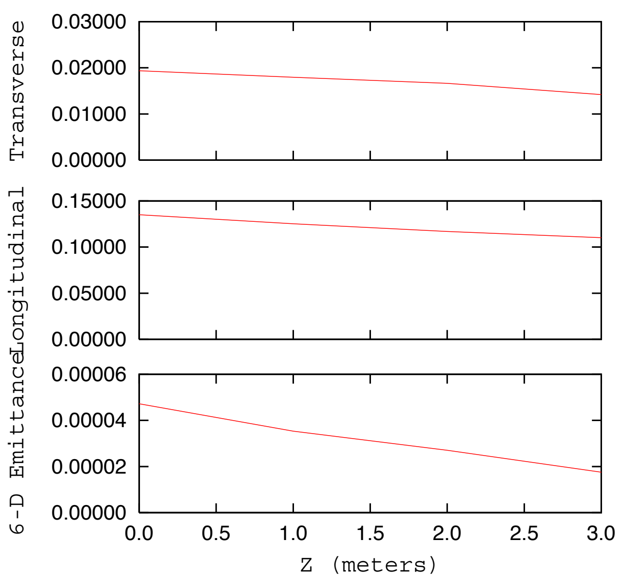

Figure 2. Emittance along the HCC, for transverse (top), longitudinal (middle), and 6d emittance (bottom). The Z axis is position along the solenoid axis.

EXPERIMENTAL CONCEPT

The basic concept of the experiment is to put a muon beam into a spectrometer upstream of the cooling channel, then through the HCC, and then into another spectrometer downstream of the cooling channel. By measuring individual muon tracks both upstream and downstream of the HCC a "virtual bunch" can be constructed offline and its emittance before and after the HCC can be computed. This then gives a direct measure of the emittance reduction actually achieved in the channel.

While there are several possibilities for implementing the experiment, at present an attractive possibility is to re-use the beamline and spectrometers being constructed for the MICE experiment. This beamline should be able to provide at least a hundred muon events per second, and the spectrometers have an acceptance and a resolution more than adequate for our needs. A preliminary layout of a helical cooling channel with the MICE spectrometers is shown in Figure 3.

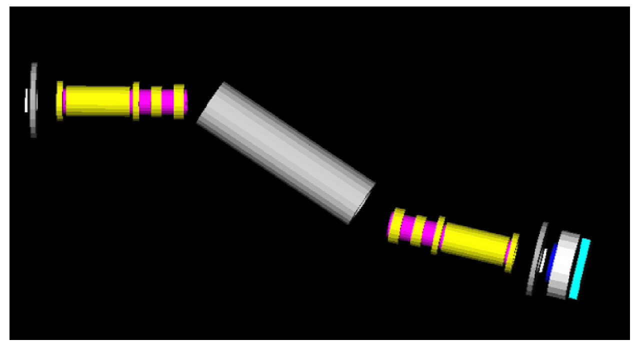

Figure 3. The MANX HCC (gray) with the MICE spectrometers and particle ID counters. The muon beam enters in the upper left. The spectrometer solenoid coils are yellow, surrounding a magenta beam pipe; at the lower right are a time-of-flight counter, a Cherenkov counter and an electron calorimeter (all for rejecting $\mu \rightarrow e$ decays).

The solenoid and HCC fringe fields are important in laying out the experiment. This is seen in Figure 4: the muon beam makes about ½ of a turn around the "bent solenoid" fringe field between the upstream spectrometer and the HCC. A similar effect will occur downstream of the HCC, but the simulation of transport into the downstream spectrometer has not yet been completed. The muon beam must of course enter the HCC at the 45° angle of its acceptance, but the fringe fields affect the beam so that the centerline of the HCC solenoid is only 32° from the centerline of the first spectrometer. The location and orientation of the HCC was determined by tracking a reference particle down the centerline of the spectrometer through the fringe fields and into the centerline of the HCC acceptance.

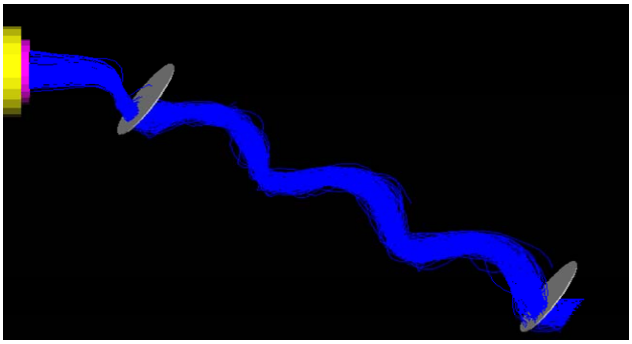

Figure 4. Muon tracks exiting the first spectrometer and traversing the Helical Cooling Channel (only its end caps are shown here for clarity). Transverse cooling occurs primarily in the angular distributions, not size of the beam, so it is not visible here.

THE ABSORBER

The energy absorber in an ionization cooling channel is a major factor in determining the cooling factor of the channel. Due to the tradeoff between energy loss (cooling) and multiple scattering (heating), there is a strong preference for the lowest-Z material possible. The nominal design discussed here uses liquid hydrogen as the energy absorber. But that requires a large volume of hydrogen (over 250 liters of liquid H_2), and safety concerns for a demonstration may make it more attractive to use liquid helium, in which case it could also be used to cool the superconducting coils of the HCC. Note that the muon energy loss is significant: this design has muons with momentum 300 MeV/c entering the HCC and 85 MeV/c exiting, which corresponds to a total energy loss of 57%, and a kinetic energy loss of 86%. In ionization cooling the overall cooling factor increases with the ratio of energy loss to incident energy, and this large fractional energy loss is what gives this channel its large cooling factor. As the muons follow helical trajectories through the absorber, their path length is $\sqrt{2}$ times the length of the HCC.

BEAM MATCHING

An important aspect of the design of this experiment is matching the beam into and out of the HCC. At present work is only beginning on this effort. It is important to demonstrate the ability to transport a muon beam through the HCC with minimal loss and with little or no emittance growth, as that will be important in any future facility. The MICE spectrometers have two matching coils at their inside ends (i.e. nearest the HCC), which should provide enough flexibility to achieve a good match at each end of the HCC.

EXPERIMENTAL MEASUREMENTS

The multifunction magnet of the HCC will be built with separate windings for the solenoid, helical dipole, and helical quadrupole fields. This will provide flexibility in tuning the channel to vary the mixing between transverse and longitudinal cooling, and a wide range of ratios will be possible. In addition, we will probably segment the coils along z so we can vary the required energy loss profile of the absorber and thus accommodate different absorber materials. This will give us the ability to configure the channel in many different ways. Using the MICE beamline and spectrometers, we should be able to achieve at least 100 good muons per second, so high statistics should be possible in a few hours of data taking for each configuration. The results will almost surely be limited by systematic errors, so a considerable fraction of the beam time will be devoted to exploring and measuring them.

CONCLUSION

A neutrino factory, and especially a muon collider, would be a powerful new facility for answering some of the major questions of particle physics today [4]. To make either one a reality requires a realistic demonstration of both the physics and engineering of an ionization cooling channel, including actual operation in a muon beam. This experiment, with its helical cooling channel, will be able to do that in ways complementary to other demonstration experiments: besides providing another demonstration of transverse cooling with a different engineering solution, MANX will verify emittance exchange and 6-d cooling in a HCC while serving as a prototype of a precooling device for a high-intensity muon beam line.

REFERENCES

[1] D. Neuffer, AIP Conference Proceedings -- January 20, 1996 -- Volume 352, Issue 1, pp. 12-18.
M. M. Alsharo'a et al., Phys. Rev. ST Accel. Beams 6, 081001 (2003)

[2] Y. Derbenev and R. P. Johnson, Phys. Rev. ST Accel. Beams 8, 041002 (2005)

[3] The MICE experiment, http://hep04.phys.iit.edu/mice/
Note that several of the authors of this paper are active members of the MICE collaboration.

[4] The most recent thoughts from a variety of authors are available from the plenary sessions of NuFact04, http://www-kuno.phys.sci.osaka-u.ac.jp/~nufact04/agenda.html
C. Albright et al, http://arxiv.org/abs/hep-ex/0008064
C. Quigg, http://arxiv.org/abs/hep-ph/9803326

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MAGNETS FOR THE MANX 6-D MUON COOLING DEMONSTRATION EXPERIMENT

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Abstract

MANX is a 6-dimensional muon ionization-cooling experiment that has been proposed to Fermilab to demonstrate the use of a Helical Cooling Channel (HCC) for future muon colliders and neutrino factories. The HCC for MANX has solenoidal, helical dipole, and helical quadrupole magnetic components which diminish as the beam loses energy as it slow down in a liquid helium absorber inside the magnets. Additional magnets that provide emittance matching between the HCC and upstream and downstream spectrometers are also described as are the results of G4Beamline simulations of the beam cooling behavior of the complete magnet and absorber system.

INTRODUCTION

MANX is a 6-dimensional muon ionization-cooling experiment which is now under design at Fermilab [1-2]. The main system of this experiment is a Helical Cooling Channel. Two HCC concepts have been proposed. The first has a large bore (~ 1 m diameter) superconducting solenoid with outer helical dipole and quadrupole coils. The second is a helical superconducting solenoid of 0.5 m diameter with the coil sections shifted in the transverse direction to simultaneously generate solenoidal, helical dipole and helical quadrupole field components. Both magnet system concepts were discussed in [3]. The comparison showed the advantage of the Helical Solenoid (HS) from a magnet system point of view. The HS has half the coil diameter and superconductor volume, seven times lower total magnetic field energy, lower peak field in the superconductor (5.7 T vs. 7.6 T), a correspondingly lower level of Lorentz forces and naturally generated helical dipole and quadrupole fields. That is why this more compact concept of HS was chosen for further investigation as discussed below.

HELICAL SOLENOID

The Helical Solenoid proposed in [3] has the general parameters and geometry shown in Table I and Fig. 1. The main concept of this approach is to use circular short coils shifted in the transverse direction to the z axis. All coil centers lay on a helical beam orbit and are equally distributed along z. Because each coil is tilted relative to the helical beam orbit direction, it simultaneously generates longitudinal and transverse field components.

The entire inner volume of the magnet system is filled with liquid helium (LHe), which is the energy absorber for the ionization-cooling experiment.

* Supported by STTR Grants DE-FG02-04ER86191 and -06ER86282
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Table 1: Helical Solenoid Parameters

Parameter	Unit	Value
Inner bore diameter	m	0.5
Helical Solenoid length	m	4.0
Helix twist pitch	m	1.6
Radius of beam reference orbit	m	0.255
Initial dipole field, B_τ	T	1.25
Dipole field gradient, $\partial B_\tau/\partial z$	T/m	-0.17
Initial quadrupole field, $\partial B_\tau/\partial r$	T/m	-0.88
Quadrupole field gradient, $\partial^2 B_\tau/\partial r/\partial z$	T/m^2	0.07
Initial field, B_z	T	-3.86
Longitudinal field gradient, $\partial B_z/\partial z$	T/m	0.54
NbTi superconductor peak field	T	5.7
Operational current	kA	10
Operating stored energy	MJ	4.4
Coil section length along Z axis	mm	20
Superconducting cable length	km	3.3

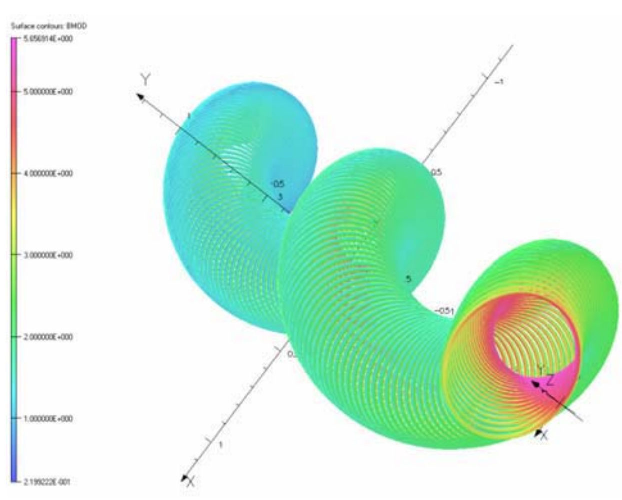

Figure 1: Helical Solenoid geometry and flux density.

The muon momentum is reduced from 300 MeV/c to 160 MeV/c in passing along the 5.6 m helical path through the LHe absorber. and the magnetic field strength must diminish with the momentum to provide a stable beam orbit. Magnetic field simulations were performed to

1-4244-0917-9/07/$25.00

investigate the behavior of the HS. Fig. 2 shows the relative field components for a model in which the current in the coils was decreased linearly as a function of the longitudinal z-coordinate with gradient -13 %/m.

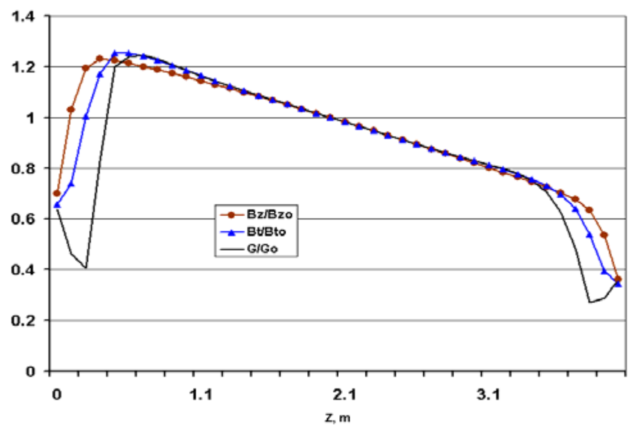

Figure 2: Field distribution related to the values at z=2 m (Bzo=-3.37 T, Bto=1.04 T, Go=-0.9 T/m).

One can see the interesting result that the three important field components, (solenoidal (Bz), helical dipole (Bt), and helical quadrupole (Gz)), scale with coil current.

Fig. 3 shows the dependence of the three field components as a function of coil radius.

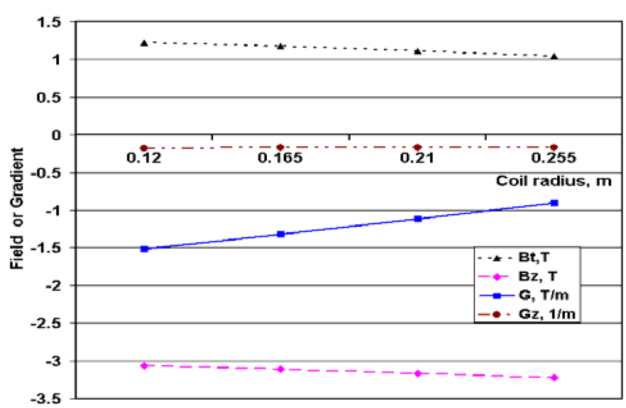

Figure 3: Field and field gradient dependence.

As follows from Fig. 3 **there is a linear dependence of field components and gradient with the coil radius change. At the same time Gz gradient is constant and defined only by coil currents**.

The HS generates complicated helical field components and corresponding Lorentz forces. These forces are intercepted by the outer collar structure. A mechanical design of a short (80 mm long) solenoid section to be used as a prototype for study is shown in Fig. 4. Coils are continuously wound with NbTi Rutherford SSC type cable on an inner support cylinder, while outer collar rings are correspondingly mounted, section by section. After assembly, the solenoid is vacuum impregnated with epoxy, forming a solid mechanical structure. Mechanical stresses at a nominal current in this cold mass assembly are less than 50 MPa.

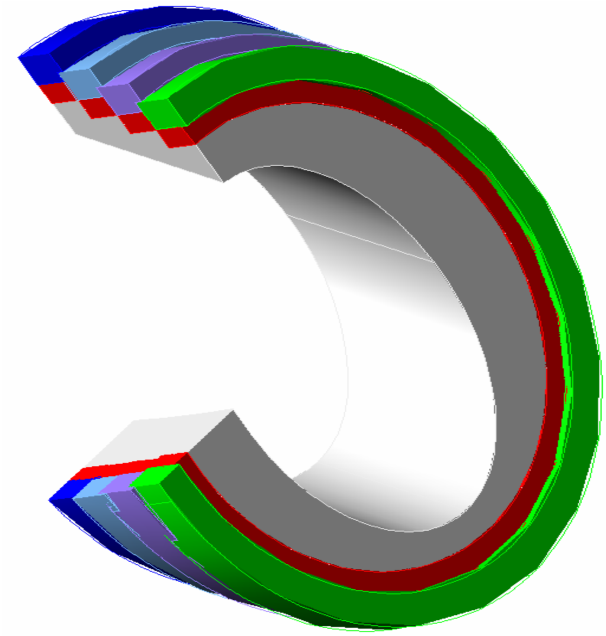

Figure 4: Helical Solenoid short section geometry. Inner support (grey), superconducting coil (red) and outer collar rings (green-blue).

HELICAL SOLENOID WITH RF CAVITIES

In the technique of ionization cooling for muon beams, the muons lose both transverse and longitudinal momentum while passing through a low-Z material. The longitudinal momentum is then restored by acceleration in RF cavities.

The proposed Helical Solenoid for future MANX experiments could be upgraded with the RF accelerating structures. Several types of RF cavities for muon accelerators [4-6] were proposed.

In the basic HCC concept, the accelerating cavities have to be placed inside the magnet system. We have slightly modified an 805 MHz cavity with thin beryllium windows [6], and have managed to fit the cavity inside an HCC using a special spiral waveguide to feed the cavity. The RF design was performed with the use of CST Microwave Studio. However, the development of practical mechanical solutions for placing the cavity inside HCC remains a challenging problem.

A good starting point for this design could be a $\pi/2$ interleaved cavity consisting of 16 pillbox-like cells [10, 11]. This 1.25 meter single coupled multi-cell accelerating cavity is designed to provide an energy gain of ≈22 MeV. The cavity is to be cooled to liquid nitrogen temperature to increase the shunt impedance by about a factor of two and reduce the large peak power requirements. The total RF peak power for the cavity is then ≈11 MW. Unfortunately, this cavity can not be used “as is” – significant design work is needed to make this cavity into a helical shape.

An accelerating cavity of any kind will be exposed in the HCC to a very strong magnetic field. In an evacuated

RF cavity the maximum accelerating gradient degrades substantially in the presence of a focusing magnetic field due to breakdowns induced presumably by well focused dark currents. The idea of filling RF cavities with high-density gas to suppress breakdowns works very well and is applicable to muons [8]. Besides suppressing breakdowns, the gas in the cavities also acts as the energy absorber needed for ionization cooling [9]. By regulating absorber gas pressure the proposed RF system is capable of exactly restoring the muon momentum loss in the absorber. But it is quite clear that this attractive concept needs a strong R&D effort, including beam tests.

IONIZATION COOLING EFFECT

The MANX cooling channel consists of upstream matching, helical cooling, and downstream matching sections, respectively [10]. The beam emittance cooling takes place in the LHe-filled helical cooling section. Figure 5 shows the field strength along the reference orbit in the whole MANX cooling channel.

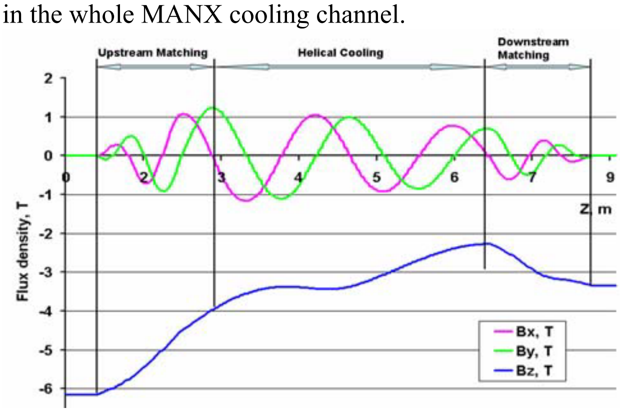

Figure 5: Field along the reference orbit.

The beam trajectory in the helical cooling section is a spiral which follows the centers of the helical solenoid coils. The reference orbit is described by the radius of the reference orbit (a) and the helical period (λ). The tangential pitch of the reference orbit (κ), is determined as $\kappa = 2\pi a/\lambda$ from these parameters. The upstream and downstream matching magnets are made of coils like the basic HS that must transform a coaxial beam with $a=0$ to match the HCC. To do this, the upstream matching coils adiabatically increase helical dipole and quadrupole components. In addition, the beam is stabilized by an adiabatic decrease of the solenoidal component. The downstream matching section has the opposite function from the upstream matching section to reduce a and κ. More detailed discussion about the design of the matching magnet is in reference [10]. Figure 6 shows the simulated normalized 6-dimensional (6D) emittance evolution in the MANX channel with and without the emittance matching sections. The red line shows the 6D emittance evolution of the beam which travels in the whole MANX channel, while the blue one shows that of the beam which passes through only in the helical cooling section. The size of the initial emittance is arbitrary in this plot because the initial condition of the beam in each channel is completely different. The essential point is that the emittance grows at the beginning of both channels since the position-momentum uncorrelated beam is injected into the strongly angular momentum dependent channel. The upstream matching section removes the mismatch with a transverse momentum kick, which is yet to be fully optimized.

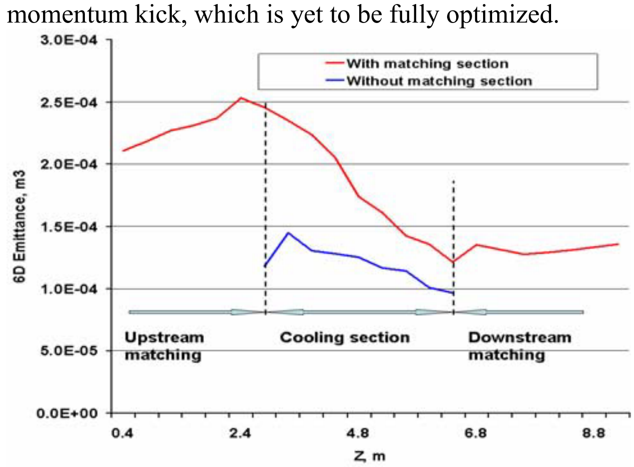

Figure 6: Emittance evolution in the whole channel (red) in only the helical cooling section (blue).

SUMMARY

- The MANX demonstration experiment should be based on the Helical Solenoid magnet system.
- The Helical Solenoid generates the longitudinal and transverse helical magnetic fields for effective ionization-cooling.
- The magnetic and mechanical analyses of the Helical Solenoid have confirmed that the magnet system can be built.
- The Helical Solenoid could be combined with a helical RF cavity to compensate muon energy loss in the absorber.

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THE MANX MUON COOLING DEMONSTRATION EXPERIMENT *

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Abstract

MANX is an experiment to prove that effective six-dimensional (6D) muon beam cooling can be achieved in a Helical Cooling Channel (HCC) using ionization-cooling with helical and solenoidal magnets in a novel configuration. The aim is to demonstrate that 6D muon beam cooling is understood well enough to plan intense neutrino factories and high-luminosity muon colliders. The experiment consists of the HCC magnet that envelops a liquid helium energy absorber, upstream and downstream instrumentation to measure the beam parameters before and after cooling, and emittance matching sections between the detectors and the HCC.

INTRODUCTION

A muon collider at the energy frontier can be used to explore physics beyond the standard model such as supersymmetry, technicolor, extra dimensions, and grand unified theories [1]. A muon collider at the Higgs mass can profit from the s-channel resonance production cross section that is 40,000 times more than an electron collider to allow the fundamental properties of the Higgs boson to be measured more precisely. A muon beam which is produced via pion decay needs fast 6D phase space emittance reduction to fit into the acceptance of the RF cavities, for instance, being developed for the ILC. The ionization cooling method is the only way to shrink muon beam transverse phase space within its short lifetime (2.2 sec in its rest frame) [2]. However, emittance exchange is required to provide longitudinal phase space cooling.

Recently, a novel cooling scheme has been proposed [3]. A HCC is used with a continuous ionization cooling absorber. The helical magnet produces helical dipole, helical quadrupole, and solenoidal field components. The muon beam in the magnet has a spiral orbit with a constant helical orbit radius and a constant helical period. The spiral orbit is generated by a repulsive radial force which is induced by the muon's longitudinal momentum with the transverse helical dipole field component and an attractive radial force which is induced by the muon's transverse momentum with the solenoidal field component. Each muon oscillates about an equilibrium orbit with an amplitude that depends on the momentum. A particle with a higher (lower) momentum than the equilibrium particle has a longer (shorter) path length, and loses more (less) kinetic energy in the continuous energy absorber. In this way emittance is exchanged from the longitudinal to the transverse phase space. For a system of multiple cooling channels, the lost kinetic energy is restored by RF cavities between channels or integrated RF cavities. The analytical treatment of this cooling scheme has shown a 6D cooling factor to be of order 10^6.

Simulations have verified the helical cooling theory [4]. For the next stage, we are planning a demonstration experiment called MANX (Muon collider And Neutrino factory eXperiment) [5]. In this paper, we discuss the concepts of the MANX experiment and describe the recent progress on designing the matching sections.

CONCEPTUAL DESIGN OF MANX CHANNEL

Figure 1 shows the conceptual picture of the MANX channel. It consists of a helical cooling channel (red) and the upstream and downstream matching section magnets (light blue). The liquid helium (LHe) ionization cooling absorber fills the cooling channel. The beam in the matching sections is assumed to be in vacuum in Figure 1. There are thin Al windows between cooling and matching magnets to separate liquid and vacuum regions.

Emittance exchange can take place without an RF cavity. Therefore, for simplicity, there are no RF cavities in the current MANX design. Hence the magnetic field strength in the cooling channel is varied to correspond to the momentum decrease along the channel. Figure 2 shows the designed field strength and gradients as a function of the length of cooling channel. In the current design, the initial and final mean momenta of the muons are 300 MeV/c and 170 MeV/c for a channel length of 3.2 m. LHe is chosen as the ionization cooling absorber material in the current design because of safety issues and its possible use as a coolant for the magnet conductors. Table 1 has a summary of the design parameters of MANX channel.

The function of the matching magnets is to match the emittance of the injected beam into the acceptance of the helical magnet. To do this, it must induce a transverse momentum kick to match the helical pitch (κ) and make a beam position offset to match the helical orbit radius (a). The first attempt adiabatically ramped the helical dipole and quadrupole components while holding the solenoid component constant. The required matching length was more than 10 m, but it makes a perfect match. The period of the betatron oscillation induced by the ramping function is found to be 1.5 λ. Hence, it was decided that the transverse momentum kick should take place during one betatron oscillation, while the beam stability is maintained by tuning the solenoid field strength. Figure 3 shows the magnetic field configuration in the 3.2 m cooling channel and 2.4 m matching sections.

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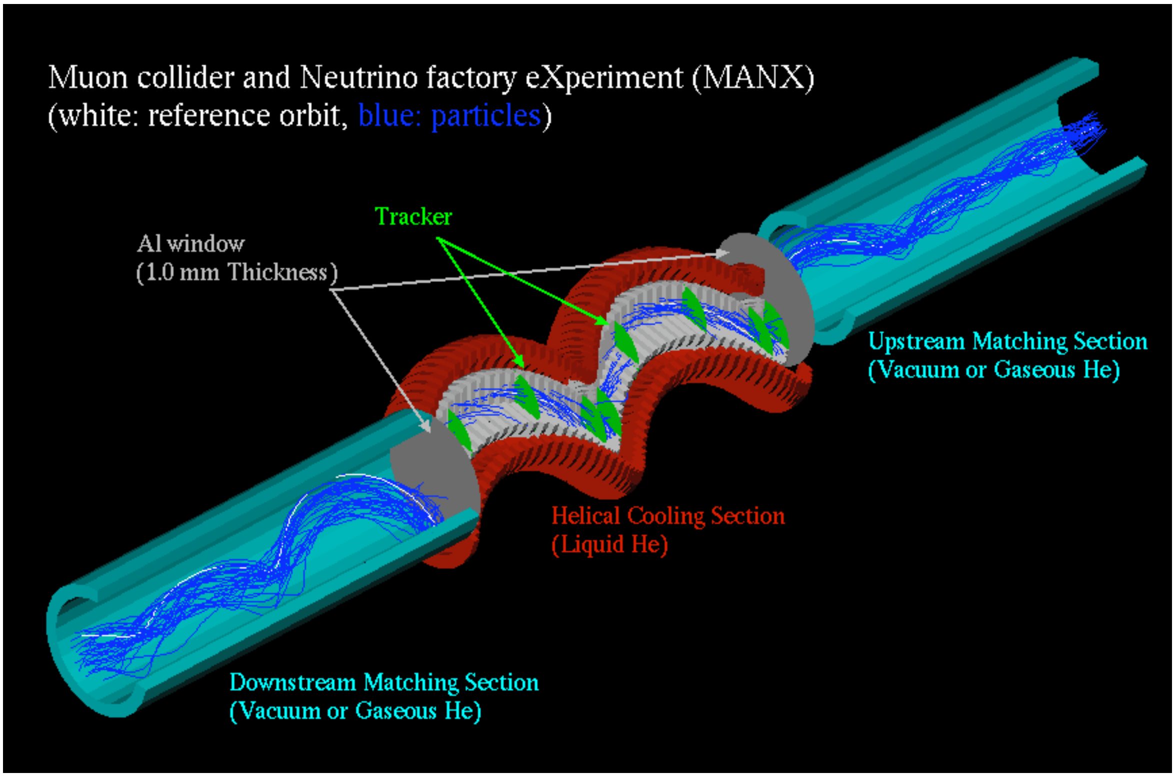

Figure 1: Conceptual picture of the helical cooling channel (red) and the two emittance matching sections (blue). The helical solenoid magnets shown in red enclose the LHe ionization energy absorber, which is separated from the vacuum of the matching sections by thin Al windows. The beam is physically larger after cooling because it has much less momentum than the incoming beam; the normalized emittance has been reduced. The total length is 9.6 meters. introduction

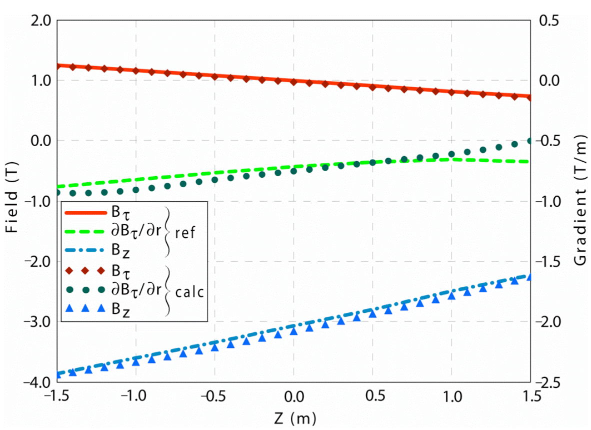

Figure 2: Field configurations along the design orbit in the cooling channel. The circle, square, and triangle points show the required analytical field components and gradients and red, green, and blue lines are calculated by finite element analysis (FEA). The conductor design is shown in Ref. [6].

As shown in Figure 4, there is emittance growth in the matching sections, which indicates there is a mismatching in the matching sections. This is caused by the beta beat. We need to improve the design of the matching magnets to make a practical matching magnet.

Table 1: Current MANX design parameters. Helical Pitch, κ, is defined as the tangent of the helical pitch angle of the reference orbit. Helical field strengths are quoted at the radius of the helical reference orbit, *a*.

Initial mean momentum: Final meam momentum	**P**	300 MeV/c 170 MeV/c
Helical pitch:	κ	1
Helical period:	λ	1.6 m
Helical ref. orbit radius:	***a***	0.255 m
Initial solenoid strength: Final solenoid strength:	**Bz**	-3.8 T -1.7 T
Initial helical dipole strength: Final helical dipole strength:	**b**	1.2 T 0.8 T
Initial helical quad. strength: Final helical quad. Strength:	**b'**	-0.9 T/m -0.5 T/m

The field parameters are slightly different from the design values because of the imperfection of the beta beat tuning in the matching magnets. The average beam position at the end of the MANX channel is ~10 mm in x and y directions.

SIMULATION RESULT

The program G4Beamline [7] was used to study the cooling behavior of the MANX experiment. Figure 1 is an example of its visual utility. Figure 4 shows the evolution of the normalized rms 6D emittance down the length of the channel. The cooling factors in the longitudinal and in each transverse direction are equally 1.3, hence the cooling factor of 6D emittance is approximately 2.1.

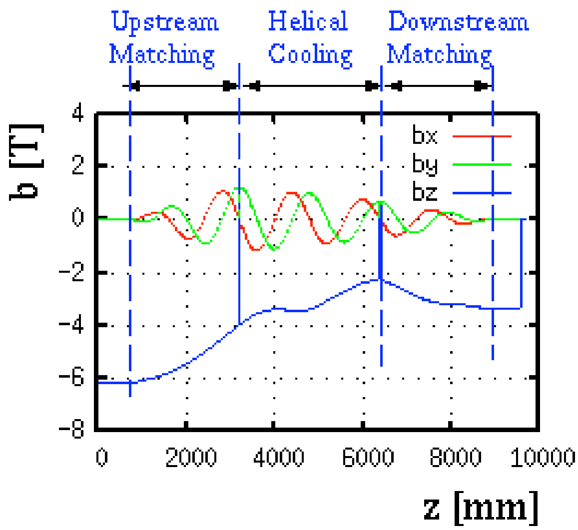

Figure 3: Field strength along the reference orbit in the MANX channel.

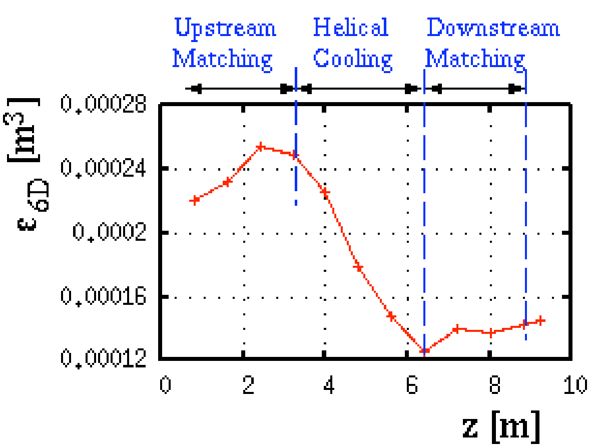

Figure 4: 6D emittance evolution in MANX.

The simulated injected beam is large to probe the acceptance of the cooling channel. The particles used for Figure 4 are those that pass through the whole cooling channel. Hence, it includes particles traversing barely stable regions of the magnet aperture. As a result, we observe 6D emittance growth in the matching magnets.

EXPERIMENTAL DESIGN CONCEPTS

We are investigating several designs for the MANX experiment. One design is similar to the MICE experiment, in which the emittances are reconstructed from ensembles of individual beam particles. Measurement of the longitudinal component of the momenta permits reconstruction of the longitudinal emittance cooling, which is essential for the proof of the emittance exchange. To determine the momentum reduction and evolution of time structure measurements through the cooling channel we are considering installing scintillating fiber detectors inside of the cooling section and the matching sections, which will be accommodated in the design of the magnets. Particle identification detectors, such as time-of-flight and Cherenkov counters are envisioned, and a range measurement downstream of the system can be used to provide additional verification of muon identity and final energy. Another design utilizes external spectrometers to measure the initial and final momenta.

Another approach, discussed in Ref. [8], called the beamlet method, uses highly collimated, small diameter beamlets to probe the behavior of the beamlets as they pass through the cooling channel. To cover the acceptance of the channel it is necessary to make a series of measurements to cover the acceptance of the channel. In this approach, with sufficient beam intensity it is possible to operate scintillating fibers in a beam profiling mode rather than in a single particle trajectory mode.

Muon Beam Line/Transport Line

Designs of the pion production target, the pion decay channel, and the beam transport system in the Fermilab MuCool Test Area are in progress [8]. We are also investigating a number of other beam lines and experimental areas at Fermilab and other laboratories that could be suitable for the MANX experiment.

CONCLUSIONS

A conceptual design study of a MANX channel consisting of a 3.2 m helical cooling magnet with 2.4 m matching magnets is presented. The matching magnet successfully produces the required transverse momentum and the position off-set from the coaxial beam. However, it does not result in a perfect match to the beam phase space. We need to improve the matching magnet design. The cooling channel reduces the 6D emittance by a factor of 2.

Two different approaches to measuring cooling are discussed; the single particle tracking and the beamlet methods. Possible instrumentation to measure the beam emittance is discussed.

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FOUR-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MUON BEAM COOLING*

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Abstract

Novel configurations of superconducting magnets for helical muon beam cooling channels and demonstration experiments are being designed at Fermilab. The magnet system for helical cooling channels has to generate longitudinal solenoidal and transverse helical dipole and helical quadrupole fields. This paper discusses the Helical Solenoid model design and manufacturing of the 4-coil model with 0.6 m diameter aimed at verifying the design concept, fabrication technology, and the magnet system performance. Details of magnetic and mechanical designs, including the 3D analysis by TOSCA and ANSYS will be presented. The model quench performance and the test setup in the FNAL Vertical Magnet Test Facility cryostat will be discussed.

INTRODUCTION

The helical field concept for muon cooling was proposed and described in [1]. That concept was realized in the Helical Solenoid (HS) configuration [2], which generates the needed solenoidal, helical dipole, and helical quadrupole magnetic fields to achieve 6-dimensional muon beam cooling in the MANX cooling demonstration experiment [3,4]. The design of straight superconducting solenoids with ~5 T field is well known. However, the transverse displacements of the HS coils generate large transverse forces, which are zero in the straight geometry. These forces require technical solutions to protect the superconductor from large stresses and deformations. A short four-coil Helical Solenoid model has been designed at FNAL and the fabrication process has been started.

HELICAL SOLENOID MODEL

The Helical Solenoid model should demonstrate the magnet system performance and match the existing FNAL Vertical Magnet Test Facility (VMTF) equipment. The model outer diameter is limited by the 640 mm diameter cryostat bore. The stand has the required cryogenics, 30 kA power supply, quench detection, protection and control systems.

Magnetic Design

The four coil geometry with flux density distribution is shown in Fig. 1. The coils centers follow the helical beam orbit with 255 mm radius and 1.6 m helix period.

*Work supported in part by DOE STTR Grant DE-FG02-06ER86282
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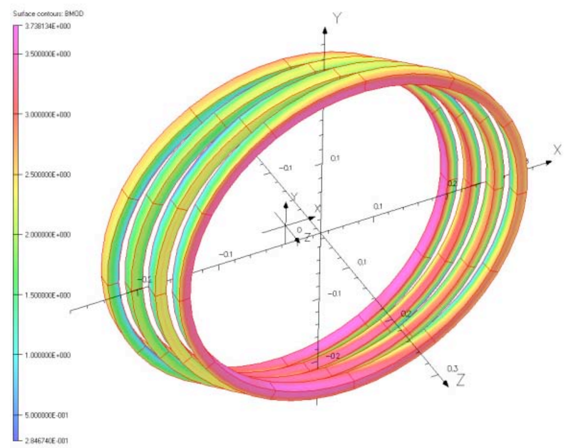

Figure 1: 4-Coil geometry and flux density.

Table 1: Solenoid Parameters

Parameter	Units	Value
Coil inner diameter	mm	426
Coil outer diameter	mm	455
NbTi superconducting cable	mm	12.34 x 1.46
Cable critical current at 7 T, 4.2 K	A	9660
Jc (non-Cu)	A/mm^2	1730
Copper to superconductor ratio		1.5:1
Strand diameter	mm	0.8
Helical orbit radius	mm	255
Number of turns per coil		10
Coil width	mm	20

The coil width of 20 mm was chosen to provide sufficiently smooth magnetic field distribution over the beam bore. The full length HS to be used for the MANX experiment is 3.2 m. The short 80 mm model should verify the design concept by reproducing the same level of fields, Lorentz forces, and corresponding stresses in the superconductor and support structures as in the long HS. Simulated magnetic design results are compared in Table 2 for the long HS design and the short HS design at two currents. Using the available margin in the cable current-carrying capacity to run the short model 46% above the nominal value, the Lorentz forces in the short model are seen to be comparable with those in the long HS.

Table 2: Magnetic Design Parameters

Parameter	Short HS Nominal	Short HS Max	Long HS
Peak superconductor field, T	3.3	4.84	5.7
Current, kA	9.6	14	9.6
Coil inner diameter, mm	426	426	510
Number of turns/section	10	10	10
Fx force/section, kN	70	149	160
Fy force/section, kN	12	25	60
Fxy force/section, kN	71	151	171
Fz force/section, kN	157	337	299

Mechanical Design

The main goal of the mechanical design was to develop the mechanical concept which could be extrapolated to the long solenoids without changing the structure. From this point of view, the solenoid assembled from identical coils is the most promising approach.

Each coil is wound from Rutherford type superconducting cable on a stainless steel bobbin. Outer stainless steel collar rings provide the coil support and intercept the radial Lorentz forces. Since the coils are shifted in the transverse plane such that their centers follow the helical path, there are transition areas where the cable can smoothly be transferred between the coils. This technique allows continuous winding of the long HS without splices.

The short model consists of four superconducting coils with support structures and end flanges. The model reproduces a short section of the long helical solenoid. By operating at higher current, it is intended to reach the fields, forces, and stresses of the long HS to verify the design concept and fabrication technology.

There are two ways to protect coils from the transverse motion under Lorentz forces. The first is to weld inner and outer support rings to each other forming a solid mechanical structure. The second is to machine steps on both sides of the inner and outer support rings locking the coil motion in the transverse direction.

The 3D mechanical structure was modeled by the ANSYS code. Since the coils are to be epoxy impregnated, the analysis was made for a solid model with all the boundaries between different materials attached to each other. Fig. 2 shows the stress distribution in superconducting coils. The peak stress at 14 kA current is only 8.8 MPa which is well below the conductor degradation limit. The maximum stress in the support structure is ~23 MPa, as follows from Fig. 3, which is also acceptable. These relatively large margins in stresses will be beneficial in the long HS design, where the side flanges can be separated by a distance of 400 mm or even 800 mm.

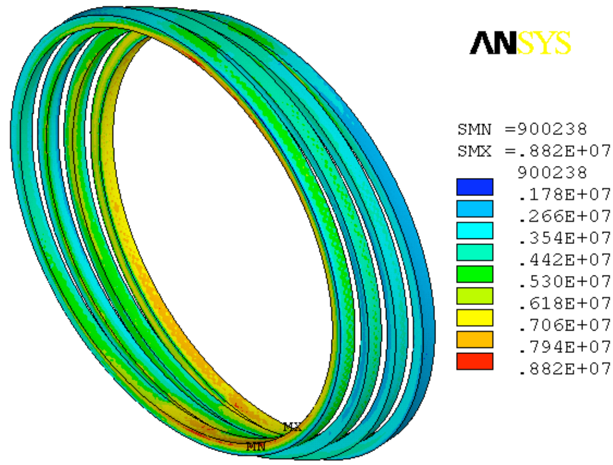

Figure 2: Coils stress at the peak current 14 kA.

The model will be attached to the cryostat by 4 rods as shown in Fig. 3.

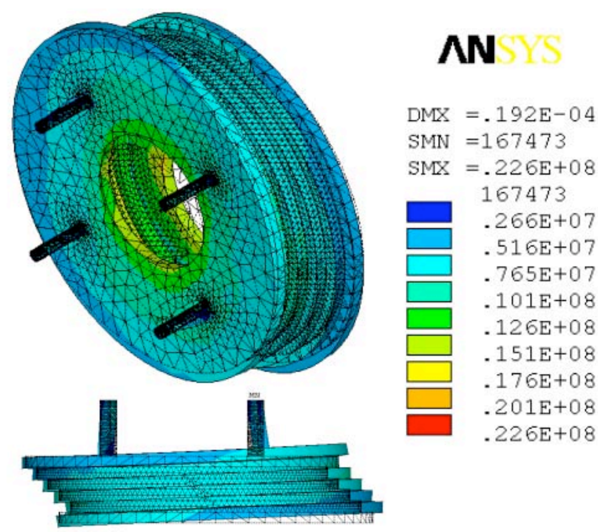

Figure 3: Stresses and deformations in the model.

The results of magnetic and mechanical modeling were verified by the 3D COMSOL code.

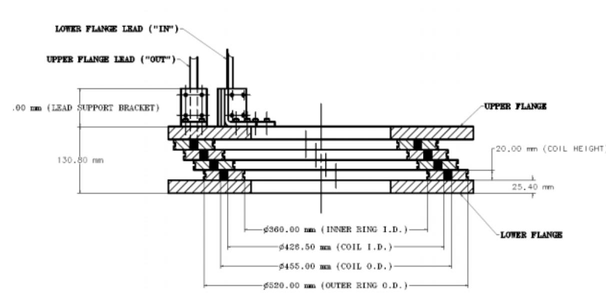

Figure 4: The model cross section.

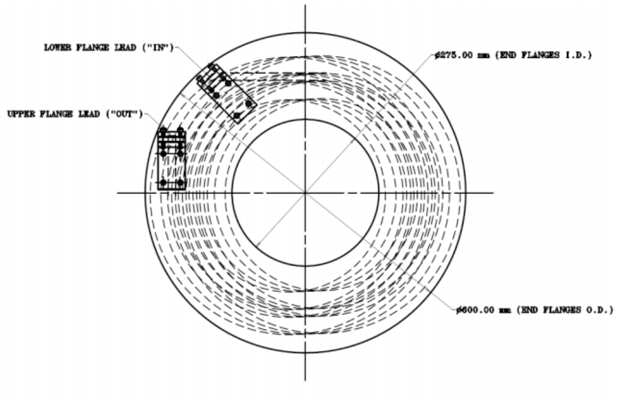

Figure 5: The model top view.

As it seen in Fig. 5, the coils have easy transition areas near the vertical axis. The transition turns will be placed in these areas during the coil winding.

Fabrication

FNAL has about 40 km of good NbTi superconducting cable left after the SSC project. It is more than enough to build the muon cooling channel demonstration experiment. The model will be wound using the FNAL horizontal winding rotational table system as shown in Fig. 6.

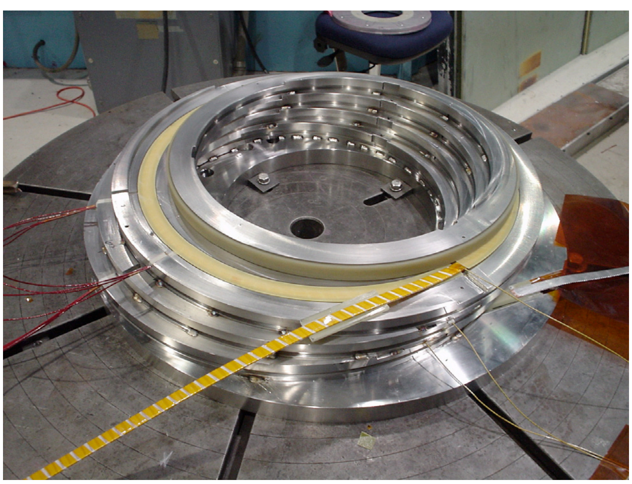

Figure 6: The model assembly view before the 4-th coil winding.

Since the available superconducting cable is keystoned, it was necessary to confirm the possibility of smooth coil winding without the loss of mechanical stability and strand separations by a winding experiment. The manufactured tooling will provide smooth continuous coil winding without splices.

The winding and magnet assembly procedure will have the following steps:

- the side flange attached to the rotating table;
- the first coil inner ring locked and fixed to the flange;
- all outer rings stocked in the space between winding table and superconductor bobbin with the cable passing through all ring bores;
- first coil lead end fixed and coil wound;
- outer ring for the first coil installed;
- inner ring for the second coil installed;
- the second coil wound;
- the outer ring for the second coil installed;

So, this process is repeated until all coils are wound. After that the upper side flange and outer support rings will be installed. All rings and flanges are fixed to each other by skip welds. Their angular position is controlled by pins. The whole assembly will be vacuum impregnated with epoxy to provide the necessary structural integrity.

Preparation for Test

The HS model will be tested in the VMTF at Fermilab. The cryostat has 640 mm inner bore diameter. The model will be attached to the top plate by 4 rods. The walls of the cryostat and surrounding space are non-magnetic, thus there will be no unbalanced forces applied to the model.

The model will be instrumented with the strip heaters, voltage taps, and strain gages. All instrumentation will be connected to the VMTF control system which will detect the quenches, measure voltages and currents, strains, etc. During a quench some part of the stored energy will be transferred from the magnet to an external dump resistor. The solenoid will be trained to the maximum current. The quench history will show the magnet system mechanical and magnetic stability

The magnetic field in the model center will be measured by a rotational coil field measurement system and a Hall probe system.

CONCLUSION

- The 4-Coil Helical Solenoid model has been designed.
- The model is capable of reproducing the same level of stresses in superconductor and support structure as in long solenoids.
- The Helical Solenoid fabrication is now in progress.
- The model test is planned for the summer of 2008.

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MAGNETS FOR THE MANX 6-D MUON COOLING DEMONSTRATION EXPERIMENT*

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Abstract

MANX is a 6-dimensional muon ionization-cooling experiment that has been proposed to Fermilab to demonstrate the use of a helical cooling channel (HCC) for muon beam emittance reduction for future muon colliders and neutrino factories. The HCC for MANX has solenoidal, helical dipole, and helical quadrupole magnetic components, which diminish as the beam loses energy as it slows down in the liquid helium absorber inside the magnet. The proposed magnet system design is comprised of coil rings positioned along a helical path, which will provide the desired solenoidal and helical dipole and quadrupole fields. Additional helical multipole coils discussed that provide matching 6D cooling conditions at short helix periods. The results of a magnetic field simulations and mechanical analysis are presented.

INTRODUCTION

MANX - a 6-dimensional muon ionization-cooling experiment was proposed to confirm the cooling efficiency of helical cooling channels described in [1].

The novel configurations of Helical Solenoids were investigated in [2] - [4]. It was shown that 0.5 m diameter superconducting Helical Solenoid with the period length of 1.6 m provides 6D cooling conditions. Nevertheless, further analysis showed that more effective cooling and the cooling channel transmission could be obtained with shorter periods: 1 m for the pre-cooling and 0.25 m for the final stage of muon cooling [5]. The goal of this paper is to investigate parameters of Helical magnet systems for the pre-cooler with the period of 1.0 m. It should be noted that the Helical Solenoid diameter should be large enough to accommodate in future the RF cavity.

HELICAL SOLENOIDS

Helical Solenoids with various parameters were investigated. There were used different magnetic field correction schemes to match optimal cooling conditions: a large bore correction solenoid, a helical multipole, and non-circular forms of Helical Solenoid coils. All these approaches are described in the sections below.

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Helical Solenoids with 1 m Helix Period

Helical Solenoids with the period 1.0 m were investigated using TOSCA code. The Helical Solenoid main parameters are shown in the Table 1.

Table 1: Helical Solenoid Parameters

Parameter	Units	Value
Coil inner diameter	mm	550
Helical reference beam orbit radius	mm	159.2
Helix period	m	1.0
Transverse field Bt on the reference orbit	T	1.64
Bz - field on the reference orbit	T	-5.35
Gradient dBz/dr on the reference orbit	T/m	9.4
Bzo – field in the magnet system center	T	-6.99
Bz = Bz/Bzo – on the reference orbit		0.765
Bt/Bz – on the beam reference orbit		-0.307

In the previous works [2], [3], when the beam orbit was about equal to the coil radius, the magnetic field was specified on orbit: Bt – transverse dipole field component, dBt/dr – transverse field gradient. Because the Bt has a 1/r dependence, it is more convenient specify the field gradient dBz/dr, which is about constant in aperture for such magnet systems but coupled with dBt/dr through Laplace equation in cylindrical coordinate system.

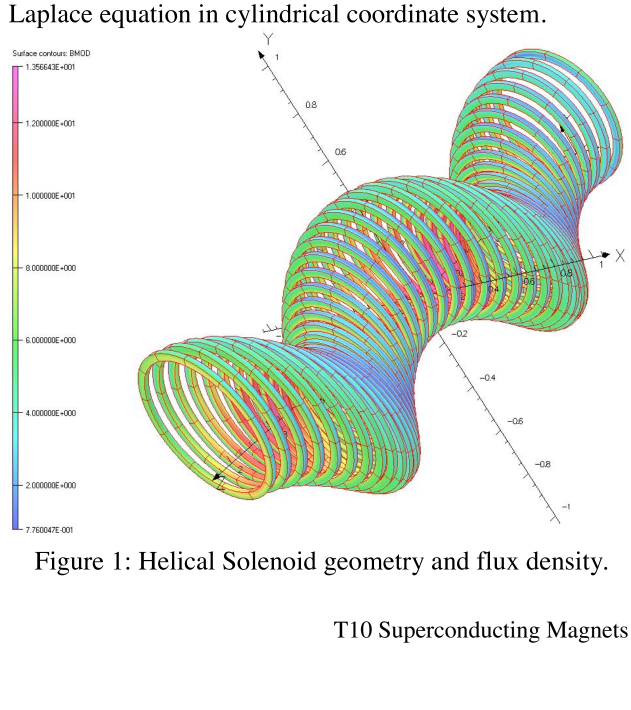

Figure 1: Helical Solenoid geometry and flux density.

The field simulation (see Fig. 1) using specified in the Table 1 parameters showed large misbalance between transverse Bt = 1.64 T and longitudinal Bz = -8.4 T field components at coil current 166.84 kA. The Bt/Bz is only -0.195 instead of -0.307. So, the relation between transverse and longitudinal field should be 57% increased. At transverse field 1.64 T the coil peak field reaches 13 T.

Helical Solenoid with Compensation Solenoid

The discrepancy between the transverse and longitudinal fields could be compensated by a straight solenoid placed outside of the Helical Solenoid. This additional solenoid should generate 2.76 T field in the opposite to the helix direction. It produces positive demagnetization effect and reduces the coil peak field from 13 T down to 9.2 T (See Fig. 2).

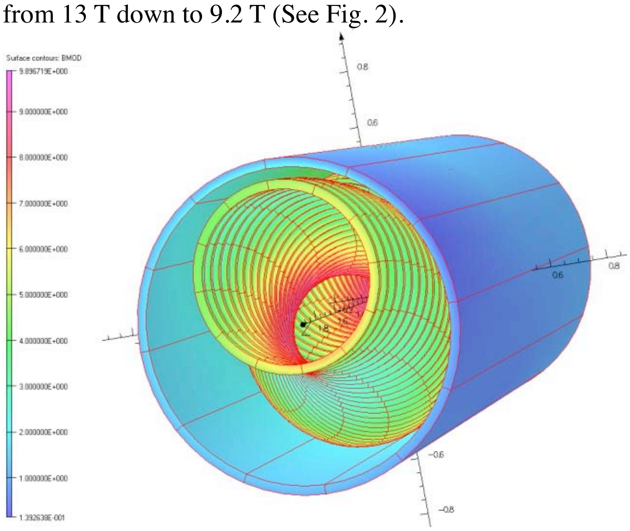

Figure 2: Helical Solenoid with Outer straight Solenoid geometry and flux density.

The Bz field component distribution in the Helical Solenoid aperture from radius -0.2 m to 0.5 m is shown in Fig. 3.

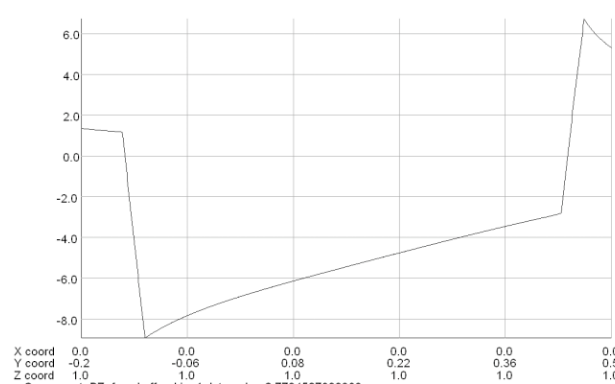

Figure 3: Bz field distribution.

One could see a linear behavior of Bz field at the beam reference orbit: the gradient dBz/dr = 9.76 T/m, Bt = 1.64 T, Bz = -5.35 T, Bt/Bz = 0.307 at 166.84 kA of Helical Solenoid coils and – 54.96 kA for the straight solenoid. All circular coils in helical and straight solenoids have the coil length of 20 mm in Z – direction.

Helical Solenoid with Helical Multipole Coils

Another way to achieve the optimal field is to use the Helical Dipole and Helical Quadrupole coils wound on the cylindrical surface. This approach was investigated in [2]. Rather large field gradients produce large peak fields, Lorentz forces and substantially increase the energy of magnetic field. It is possible to reduce these effects by placing helical windings on the surface of Helical Solenoid. The Helical Dipole wound on the outer surface of Helical Solenoid is shown in Fig. 4 and has 10 sections per pole evenly distributed in the azimuth angle 60°.

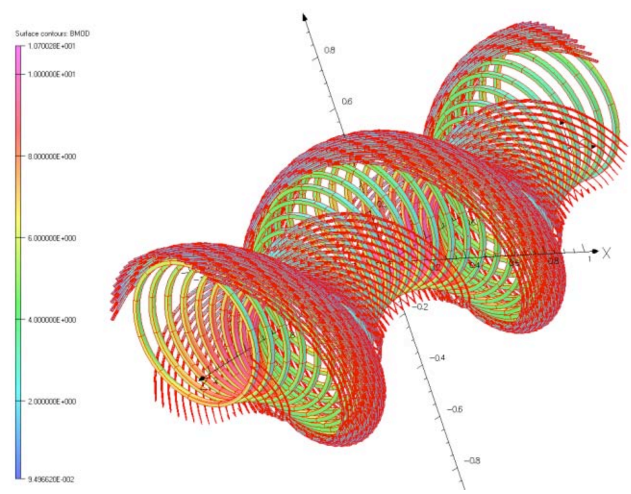

Figure 4: Helical Solenoid with Helical Dipole Coil geometry and flux density.

The coil peak field is 10.7 T on the inner surface of Helical Solenoid and 2.4 T in the Helical Dipole.

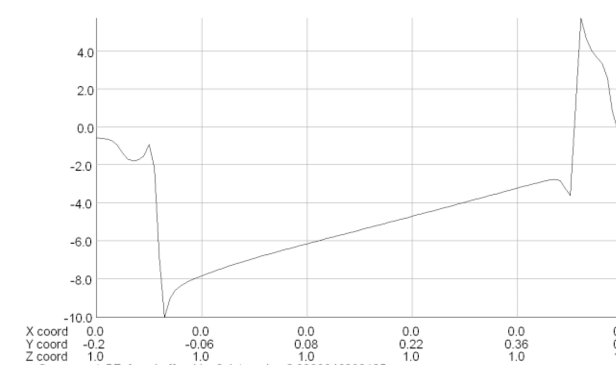

Figure 5: Helical Solenoid with Helical Dipole. Bz field distribution from radius -0.2 m to 0.5 m.

The magnet system has parameters close to the optimal: gradient dBz/dr = 10.35 T/m, Bt =1.64 T, Bz = -5.35 T, Bt/Bz = 0.307 at 230.6 kA Helical Solenoid coil current, and 665.3 kA of Helical Dipole winding total current.

The Helical Quadrupole coils wound on the surface of Helical Solenoid could correct the transverse field gradient dBt/dz. The transverse field distribution in the aperture generated by the Helical Quadrupole is shown in Fig.6.

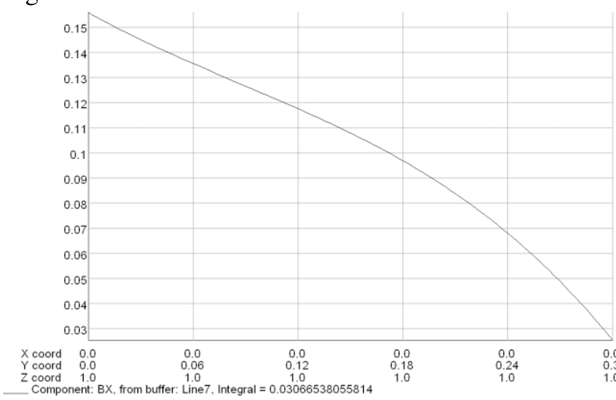

Figure 6: Helical Quadrupole transverse field Bt.

The Helical quadrupole capable correct transverse field gradient 0.6 T/m at 200 kA total Helical Quadrupole winding current.

Helical Solenoids with Non-Circular Coils

The discrepancy between transverse and longitudinal fields could be reduced by changing the form of Helical Solenoid coils. Because the field should have larger gradient than in the case of circular coils, the coil should have trapezoidal form. The maximum gradient is achieved with the triangular coils, as shown in Fig. 7.

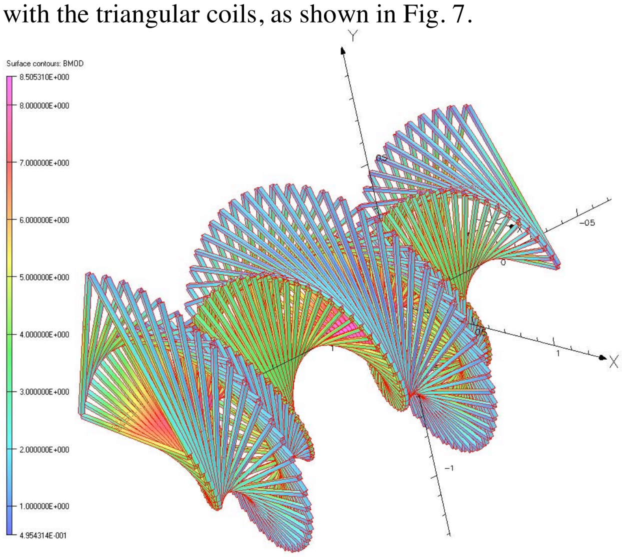

Figure 7: Helical Solenoid with triangular coils Bmax = 8.5 T.

This solenoid has large field gradient dBz/dr = 11.9 T/m, Bz = -5.35 T, Bt = 1.36 T at 136.4 kA coil current. The trapezoidal coil shape can reduce this gradient to the optimal 9.4 T/m and improve the balance between components.

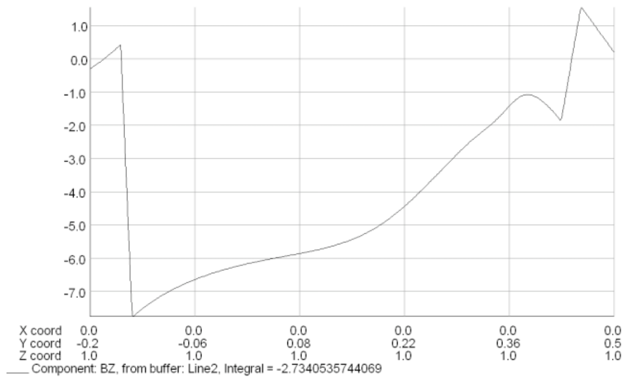

Figure 8: Helical Solenoid with triangular coils. Bz field distribution from radius -0.2 m to 0.5 m.

CONCLUSION

- Magnet systems based on the Helical Solenoids are capable of generating fields required for the optimal muon cooling even at short helix periods.
- Large bore straight solenoids, helical multipole windings or trapezoidal coils can be used for eliminating of the misbalance between transverse and longitudinal fields.
- The best type of field compensation depends on the application. Demonstration models can use helical multipole windings for greater flexibility. The final design will be more efficient with non-circular shape coils.
- The high 8.5 T - 11 T peak fields drive the design to the use of Nb_3Sn superconductors.
- The presented results could be distributed for the higher fields and smaller orbit radii which used at the cooling channel end.

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STATUS OF THE MANX MUON COOLING EXPERIMENT*

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Abstract

A demonstration experiment of six-dimensional (6D) phase space muon beam cooling is a key milestone on the roadmap toward to a real muon collider. In order to achieve this goal, we have designed the Muon collider And Neutrino factory eXperiment (MANX) channel, which consists of the Helical Cooling Channel (HCC). We discuss the status of the simulation study of the MANX in this document.

CONCEPTUAL DESIGN OF MANX

We have considered a 6D phase space cooling demonstration experiment, which we call MANX [1]. The main goals of this experiment are to prove the helical cooling theory and to demonstrate the feasibility of the HCC. The crucial advantage of the MANX experiment is that the output signal from the MANX channel is very robust. Consequently, a high-precision experiment is not required in order to demonstrate clearly the effectiveness of the beam cooling.

The current MANX channel design is shown in Figure 1. It consists of three sections; an upstream matching section, a helical cooling section, and a downstream matching section. The helical cooling section is made of the superconducting helical solenoid (HS) coil. By adjusting current distribution in each HS coil, we can generate the desired helical dipole, helical quadrupole, and solenoid components [2]. The matching section is designed to connect between the beam phase space in the straight section and the helical beam phase space. From the recent design study, the optimum matching field can be generated by the HS coil [2]. In this study, the whole MANX field is generated in the analytical field expression for simplicity.

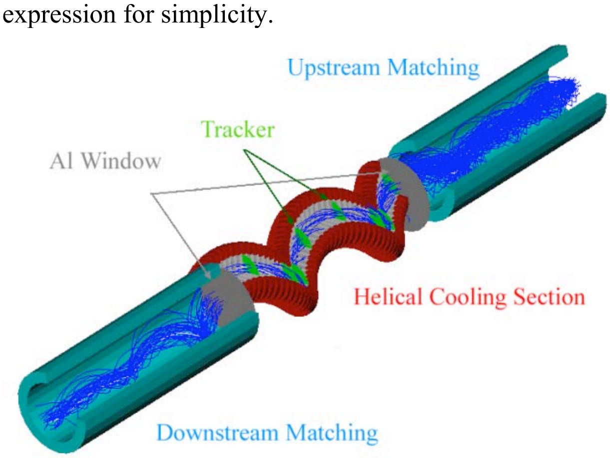

Figure 1: Whole layout of the MANX.

It is better to use a low Z (atomic number) material as a cooling absorber to reduce the heating effect caused by the stochastic process (multiple scattering and energy straggling). Liquid helium (LHe) is used as the cooling absorber in the current design since it is widely used and easy to handle without any serious safety considerations. LHe can also work as a coolant of superconducting coils.

BEST COOLING SCHEME

Figure 2 shows the field amplitude on the reference orbit in the whole MANX channel in the best cooling scheme for a muon collider. The field amplitude in the helical cooling section is ramped down along with the beam path length since the average beam momentum is degraded by the ionization energy loss with LHe. The design parameter is listed in Table 1.

Table 1: Design Parameters in Cooling Section

Initial mean momentum Final meam momentum	**p**	300 MeV/c 170 MeV/c
Helical pitch	**κ**	1
Helical period	**λ**	1.6 m
Helical ref. orbit radius	***a***	0.255 m
Initial solenoid strength Final solenoid strength	**Bz**	-3.8 T -1.7 T
Initial helical dipole strength Final helical dipole strength	**b**	1.2 T 0.8 T
Initial helical quad. Strength Final helical quad. Strength	**b’**	-0.9 T/m -0.5 T/m

In the matching section, the amplitude of helical dipole field component is adiabatically ramped up. The transverse momentum is induced in this section and the beam position is moved from the coaxial center. A detailed discussion has been done in Ref. [3].

Figure 3 shows the 6D emittance evolution in the MANX with best cooling scheme. We can observe the 6D cooling factor of 2.

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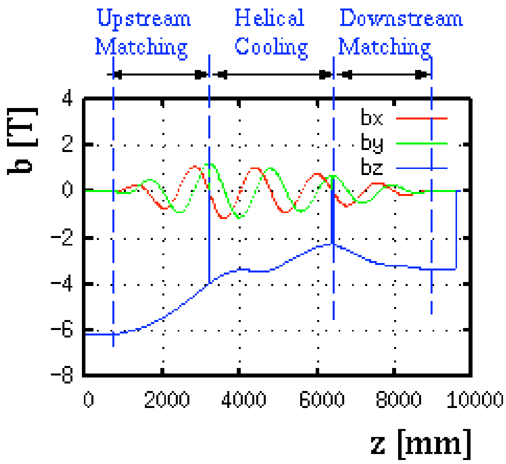

Figure 2: Magnetic field of reference particle in MANX

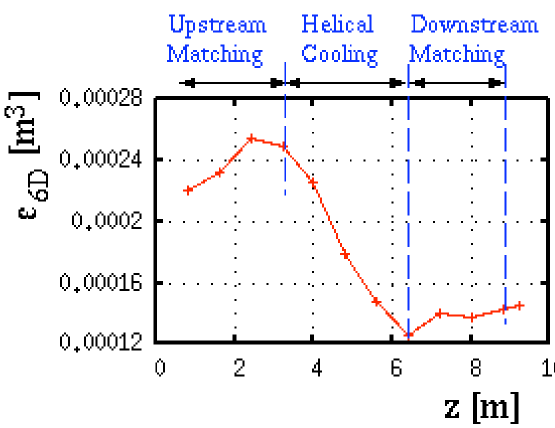

Figure 3: 6D emittance evolution in the best cooling scheme

OPTIONAL COOLING

We tested another cooling scheme in the helical cooling section in simulation; that is longitudinal only cooling. This feature is uniquely happened in the HCC. Therefore, it can be shown the verification of the helical cooling theory. This scheme can be realized with the dispersion factor [4], $\hat{D} = 2\left(1+\kappa^2\right)/\kappa^2$, where κ is the helical pitch which is the ratio between transverse and longitudinal momenta (pφ/pz).

Figure 3 shows the transverse, longitudinal, and 6D emittance evolutions with two different sets of cooling schemes. One set (red and blue lines) shows the longitudinal only cooling scheme (LOCS) and other one (green and magenta lines) shows the best cooling scheme (BCS) as discussed in previous session, respectively. One can find that the transverse emittance cooling efficiency in the BCS is ~30 % larger than that in the LOCS. On the other hand, the longitudinal emittance cooling efficiency in the LOCS is 50 % bigger than that in the BCS. It is worth to note that the 6D emittance evolutions in both schemes are identical. It means that the 6D cooling efficiency is determined by the total amount of energy loss.

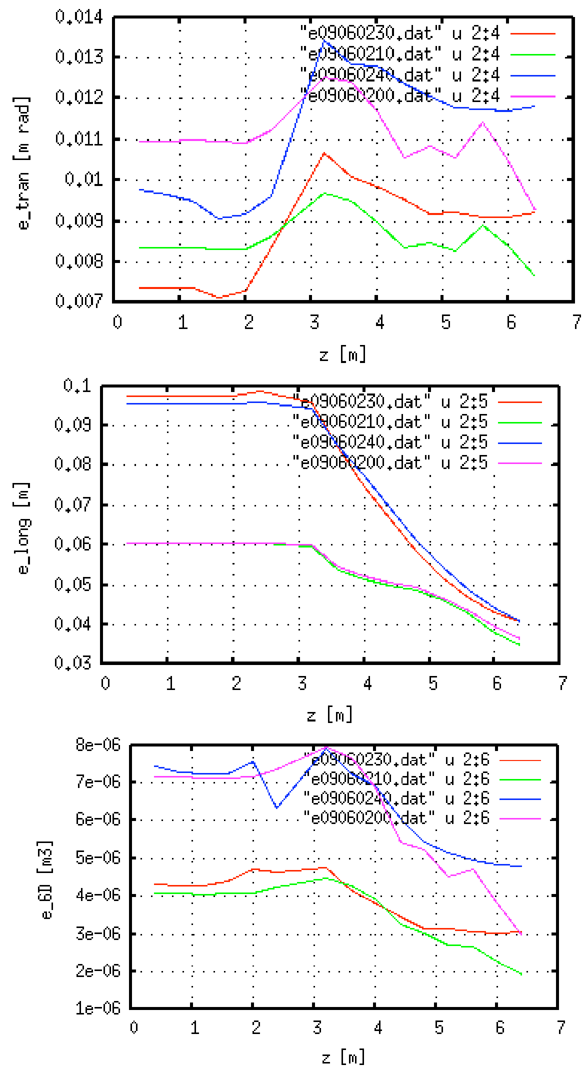

Figure 3: Transverse (top), longitudinal (middle), and 6D (bottom) emittance evolutions in the best cooling (red and blue lines) and the longitudinal only cooling (magenta and green lines) schemes.

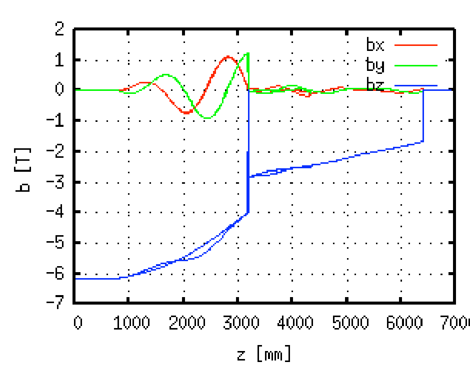

Figure 4: Field amplitude in the longitudinal only cooling decrement channel with the upstream matching magnet. The field is immediately turned off at z = 3200 mm. It is not realistic.

In order to achieve the longitudinal only cooling scheme, the helical dipole field component must be zero in the helical cooling section as shown in Figure 4. This magnet structure may be realized by superimpose the field configuration from the other HS coils as discussed in Ref. [5].

The helical magnet structure has another unique feature: It can realize the isochronous condition. It appears when the dispersion function is fulfilled $\hat{D} = \left(1+\kappa^2\right)/\gamma^2\kappa^2$, where γ is the normalized energy by the muon mass. This study is in progress [6].

FIELD QUALITY TEST

Figure 5 shows the transverse and longitudinal emittance evolutions in the helical cooling magnet with a random field error. The various rms of random field error is tested with ±2 %, ±5 %, ±7 %, and ±10 %. These fractions are randomly multiplied to three field components, bx, by, and bz. As a result, the random field error does not strongly affect on the cooling efficiency. The real field error is caused by the misplacement and disorientation of conductor and drift of the current. The realistic field error study will be done.

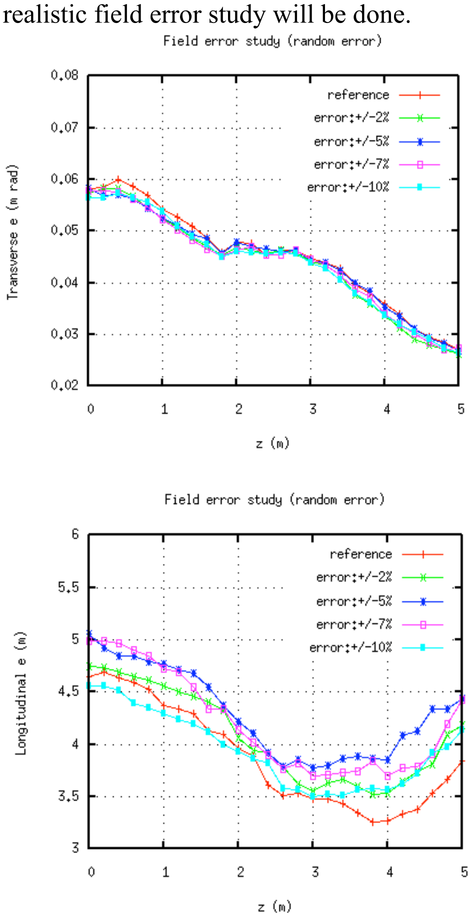

Figure 5: Transverse (top) and longitudinal (bottom) emittance evolutions in the cooling magnet with various field errors

DESIGN OF DETECTOR SYSTEM

The main spectrometers are located upstream and downstream of the MANX channel to measure the initial and final beam phase space. We expect that the MICE type spectrometer can be applied for the MANX experiment [7]. In addition, the fast signal time of flight (TOF) counter is needed for the precise longitudinal phase space measurement. We have collaborated with the University of Chicago group to develop the 2 ps TOF counter.

By putting several tracker planes in the helical cooling section, we can significantly suppress the systematic error caused by the particle loss. Those trackers can be used as the spectrometer if the quality of the field map is sufficiently good. The particle tracking and reconstruction are essential for this purpose. The source of ambiguity is caused by the multiple scattering and energy straggling in the interaction with the absorber. The Kalman filter can deal with this stochastic process as a noise [8]. The tracker detector in the cryostat will be made of a scintillation fiber (SciFi) detector. The feasibility study of SciFi tracker in the cryogenic temperature is in progress.

It will not be critical to determine the particle id in this experiment to remove as a background signal since background particles, like protons and pions, can be absorbed in LHe absorber. But an electron generated from a muon decay after the helical cooling section cannot be separated. The electromagnetic calorimeter which is located at the end of MANX channel can identify a signal of the electron from real signal. The quantitative study of the spectrometer design is on going.

CONCLUSIONS

We have designed the MANX channel to demonstrate the 6D helical cooling concept by comparing experimental result with the simulation results. We discussed two possible cooling options; the best cooling and the longitudinal only cooling schemes. Those tests can be clear evidence that the helical cooling theory is valid.

The output signal from the spectrometer must be sufficiently precise to compare with the simulation result. We have started the design study of the spectrometer system. The design of the fast TOF counter is being optimized for a precision measurement of the longitudinal phase space.

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4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MANX*

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Abstract

Magnets for the proposed muon cooling demonstration experiment MANX (**M**uon collider **A**nd **N**eutrino factory e**X**periment) have to generate longitudinal solenoid and transverse helical dipole and helical quadrupole fields. This paper discusses the 0.4 M diameter 4-coil Helical Solenoid (HS) model design, manufacturing, and testing that has been done to verify the design concept, fabrication technology, and the magnet system performance. The model quench performance in the FNAL Vertical Magnet Test Facility (VMTF) will be discussed.

INTRODUCTION

Effective emittance cooling is a major challenge in utilizing muons in high energy lepton colliders. An efficient scheme utilizing a Helical Cooling Channel (HCC) has been proposed for 6-D beam cooling [1]. It requires a solenoid field with superimposed helical dipole and helical quadrupole fields, along with a low Z energy-loss media and RF cavities for momentum regeneration. A cooling experiment has been proposed (MANX) using the HCC without RF cavities to demonstrate the concept.

The Helical Solenoid (HS) is a novel approach for generating the required HCC fields by using thin solenoid rings, offset transversely in a helical pattern [2]. Further design considerations for this thin ring approach are discussed elsewhere [3,4]. This helical solenoid approach has an important advantage over a more conventional straight wide aperture solenoid with superimposed dipole and quadrupole windings. It requires much smaller coils resulting in smaller stored energy and less field on the conductor.

As part of a DOE sponsored STTR project, Muons Inc. and Fermilab have built and tested a "4 coil" demonstration magnet (HSM01) to validate the design concept and gain experience in this novel magnet technology. The design and construction are summarized here and reported in detail elsewhere [5]. This paper focuses on newly acquired test results.

MAGNET DESIGN AND CONSTRUCTION

The magnet demonstration goal was to reproduce, as much as possible, the field and mechanical forces expected in a full length magnet within facility constraints. The SC cable to be used for both MANX and this 4-coil magnet is SSC inner cable[2], insulated with Kapton over glass tape.

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Table 1: Parameters for full scale vs. 4 coil HS.

Parameter	Long HS	4-Coil HS
Peak Field (T)	5.7	4.4
Operating Current (kA)	9.6	13.6
Coil ID (mm)	510	420
Number of turns/section	10	9 (see text)
Fx force/section (kN)	160	119
Fy force/section (kN)	60	21
Fxy force/section (kN)	171	121
Fz force/section (kN)	299	273

Table 1 shows the 4-coil and baseline MANX magnet design parameters. For the demonstration magnet, we chose the individual coil apertures so that a 4-coil helical magnet system would fit into the Fermilab VMTF Dewar of 600 mm diameter. The fields of this 4 coil system would be approximately half that of a full scale HS, however, the lower field on conductor makes it possible to operate at a much higher transport current. As shown in Table 1, the fields (generated from Tosca simulation) as well of as the forces (generated from ANSYS simulation) of the 4 coil model are comparable to the full scale magnet, with both magnets operating at 85 percent of the predicted short sample conductor limit.

Fig. 1 shows schematically the coil layout while Fig. 2 shows the coil winding near completion. Coils are wound on a horizontal winding table. The insulated cable is wound with a "hard way" bend around a G-10 insulated inner stainless steel (SS) support ring and supported axially with a bottom SS flange. There are nominally 9 turns/coil. As shown in Fig. 2, the spiral Kapton wrap is not overlapped. This was done to facilitate the epoxy impregnation into the coil. Once the coil is wound, a Kapton encapsulated quench protection heater is wound circumferentially on the 9 turn package. The coil with heater is held in place by an SS outer support ring. Once a coil is completed, the next inner support ring is mechanically locked in place with the correct helical geometry. The package is designed so that the leads from one coil transition smoothly into the next coil with adequate mechanical support. This pattern continues through the fourth coil, whose axial support is completed with a matching flange. The rings and flanges are welded together for structural support. Voltage taps are soldered onto the power leads as well as the transition region between coils. The coil volume is then vacuum-impregnated to provide the necessary mechanical support of the conductor.

While the construction proceeded well, there were two significant fabrication issues. First, it was determined through resistance and inductance measurements that one of the four coils had an extra number of turns (10 vs. 9). This was later verified during the post-test magnet autopsy. This extra turn had a small effect on the predicted field and quench performance.

A more serious problem was from the insulation. During the room temperature insulation hipot tests, the magnet could withstand no more than 250 V to ground without a discharge. In liquid helium, a 15 kΩ short to ground developed. The exact location of the insulation failure was not determined, although a post mortem examination points to a likely coil-to -coil transition area insulation weakness. Because of the very small amount of stored energy in these coils, the magnet could be safely operated at full field. However, the ground current was closely monitored during the entire test. Furthermore, we decided to limit our quench protection heater studies to a few quenches, since these studies by their nature generate voltage imbalances in the coil.

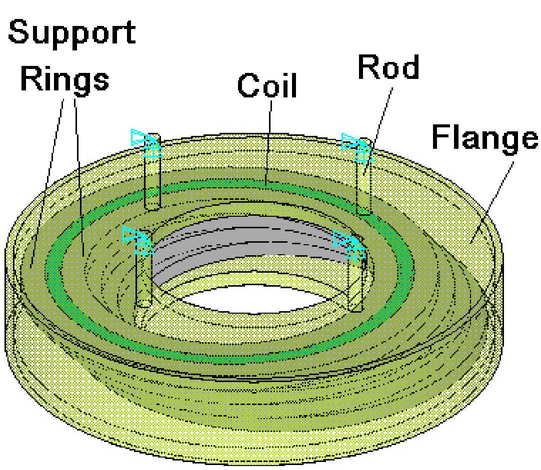

Figure 1: HSM01 Coil Layout

TEST PROGRAM

Tests were performed in the Fermilab VMTF. The Dewar can accommodate magnets up to 600 mm in diameter and 3.5 M in length, in temperatures in liquid helium from 1.7K to the nominal 4.5K. An anti-cryostat "warm finger" was inserted into the magnet for room temperature magnetic field probe measurements.

The test plan consisted of magnetic measurements at room temperature as well as in liquid helium, quench training, and quench protection studies. The strain gauges mounted on the magnet shell were monitored during the test. The results of these studies, summarized in the magnet test report [6], show that the strain changes during cool down or excitation are consistent with the ANSYS mechanical model predictions.

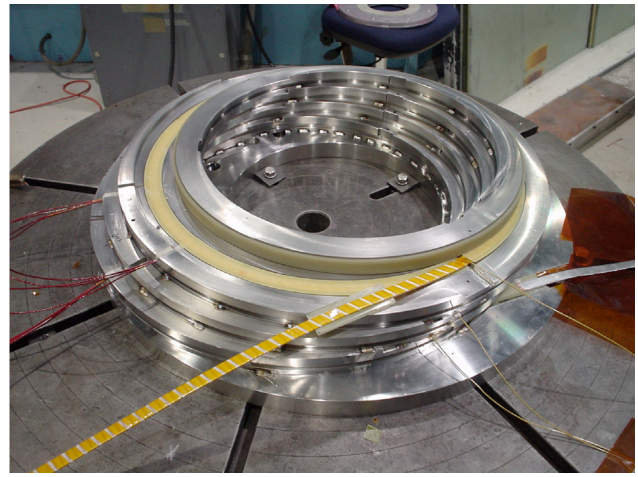

Figure 2: HSM01 During Assembly

Quench Performance

Fig. 3 is a summary of the HSM01 quench performance. The nominal ramp rate was 50 A/sec. After approximately 20 quenches, the magnet reached its quench plateau of approximately 13 kA which is approximately 85 percent of the predicted short sample. While training quenches are observed in all four coils, the quenches in the plateau were limited to coils Q1 and Q2. The exact location of the quench was not possible to determine due to lack of instrumentation. Quenches at lower temperature (3.0 K) were performed at ramp rates from 20 – 300 A/sec including nominal 50 A/sec with no significant changes in quench performance. We conclude that the mechanical support within each coil, provided primarily by the epoxy potting material, was probably not sufficient.

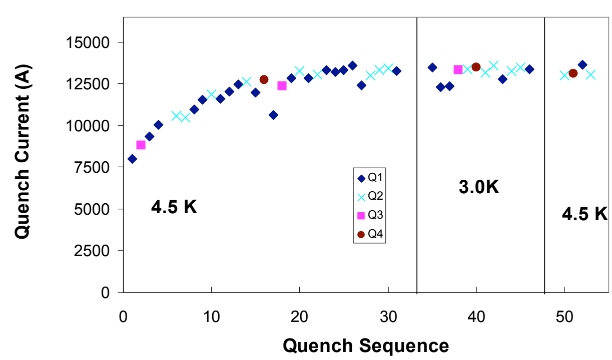

Figure 3: Quench Performance of HSM01. Coils are designation Q1-Q4 with Q1 closest to the positive lead.

Magnetic Field Measurements

Field measurements were taken with a 3-axis Hall probe at room temperature at ±10 A as well as in liquid helium at 2000 A. The field coordinate system was defined as follows: the "z" direction is normal to the lead end coil; "x and y" directions are in the plane of the lead end coil; x=y=0 is the approximate geometric center of the 4-coil magnet system; and z=0 is on the lead end coil front face. At room temperature, scans were performed longitudinally along the z axis at approximately x=y=0. There were also parallel scans at large radius in 45 degree increments. Cold measurements were performed with a Hall probe at room temperature using the anti-cryostat "warm finger" placed in the x=y=0 location.

The results are shown in Fig. 4 and Fig. 5. Due to a lack of accurately determined coil center positions, there was an uncertainty lining up the coordinates systems from the warm to cold as well as to the calculated fields. Thus in Fig. 4, the peaks of the measured warm and cold fields as well as the Tosca prediction are adjusted longitudinally to match. Because of the lack of magnetic material and the small thermal contraction in a larger aperture coil, it was expected and confirmed by measurement that the shape and normalization of the cold and warm room temperature transfer functions both agree well with the Tosca model calculation.

Fig. 5 show a representative warm By distribution as compared to calculation. The discrepancy in the shape and normalization is likely related to the uncertainties in the accurately determining the coil center coordinates.

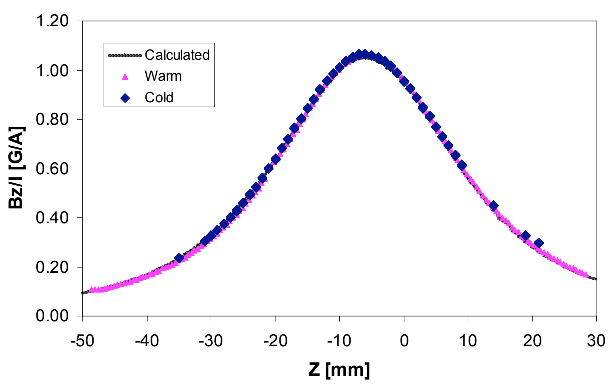

Figure 4: Longitudinal Field on axis vs. Calculation

Quench Protection

The quench heater studies were curtailed because of the 15 kΩ short to ground. Heaters in two coils were connected in series to a quench protection heater firing unit. Using the minimum unit setting of 50 V, and capacitor settings of 4.8 mF and 9.6 mF, the magnet was successfully quenched at 12 kA with a delay time of 150 ms and 120 ms respectively.

RRR measurements of the conductor were performed during the post test warmup. Values in the range of 140 were recorded.

RESULTS AND FUTURE PLANS

Our immediate goal is to build a nearly identical magnet with improved conductor insulation, potting procedure and mechanical support. There is evidence from the post mortem autopsy that there are voids in the epoxy impregnation which likely limited the quench performance. Finally the SS outer support ring will be replaced with aluminum to provide larger cold prestress.

Even if the coil reaches its full short sample limit, it is believed that these magnets will need a larger quench operating margin. A full scale HS would require over one hundred coils in series; thus quench stabilization needs to be considered. Both features call for a larger critical current density in the superconductor or a larger number of amp-turns. Thus we are looking into designs with wider conductor, "easy way" bend which would allow us to stack more amp turns, and Nb3Sn conductor.

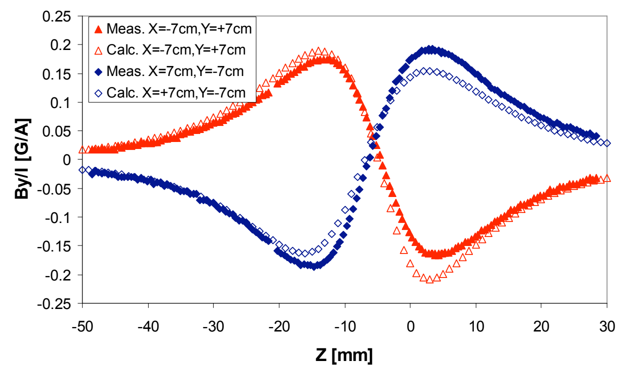

Figure 5: Representative Transverse Field/Current vs. Calculation

CONCLUSION

A 4-coil model of a Helical cooling channel solenoid has been successfully built and tested. The magnet reached 85 percent of short sample, the approximate level of design operation. It also reached a considerably higher current than the design current, albeit in a lower field. The field distributions agree well with predictions. Further care will be taken on subsequent magnets to fiducialize the coil geometry to facilitate field comparisons.

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RF INTEGRATION INTO HELICAL MAGNET FOR MUON 6-DIMENSIONAL BEAM COOLING*

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Abstract

The helical cooling channel is proposed to make a quick muon beam phase space cooling in a short channel length. The challenging part of the helical cooling channel magnet design is how to integrate the RF cavity into the compact helical cooling magnet. This report shows the possibility of the integration of the system.

INTRODUCTION

The helical cooling channel (HCC) is proposed to obtain the exceptional cooling performance in a short channel length [1]. It consists of a helical dipole and a solenoid magnet to generate a continuous dispersion. A helical quadrupole component is superimposed to increase the beam acceptance. A high pressurizing hydrogen gas filled RF cavity [2] is incorporated into the HCC magnet to make an ionization cooling and an energy loss compensation at the same time. Because the HCC makes a continuous emittance exchange it generates the six-dimensional phase space cooling.

The HCC simulation has been demonstrated by using the realistic helical magnet. The helical magnetic field is generated from the helical solenoid (HS) coils [3]. The helical magnet is a series of simple coil rings with each ring center located along with the helical beam path. The RF cavity is located in the center of the HS coil. There must be a gap between the RF cavity and the HS coil for a pressure wall, a thermal isolation, and a space for a cooling pipe of the RF cavity and for an RF power transport cable. In this document, we will discuss what is the required gap and how the HCC will preserve the cooling performance with the realistic geometry configuration.

DESIGN REALISTIC HELICAL MAGNET

Required Gap between RF Cavity and HS Coil

In the current HCC design, the RF cavity is operated under liquid nitrogen (LN2) temperature. The density of a 50 atm gaseous hydrogen absorber in the HCC is, therefore, 1/8 of the liquid hydrogen density. The pressure wall is designed by using the ANSYS mechanical analysis package. A typical result is shown in Figure 1. The helical tangential pitch is 1.0 and the helical period is 1.6 m. These geometric parameters are close to the first and second HCC segments (shown in Figure 5). SS316, Inconel625, and Inconel718 were tested as wall materials. The inner diameter of the helical tube is 0.5 m. The required thicknesses for these wall materials are 0.75, 0.5, and 0.35 inches, respectively, using a safety factor 4 based on the ASME code. From the mechanical analysis, 10 mm thickness wall with Inconel718 will be sufficient for the pressure barrier.

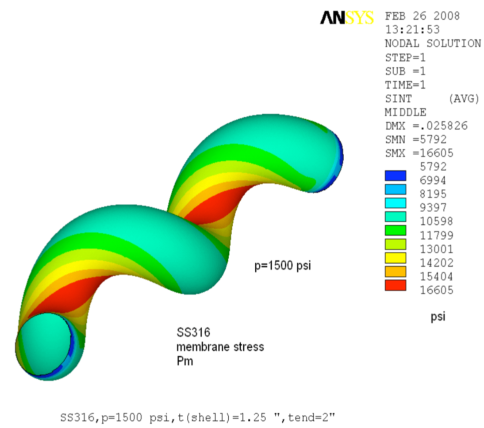

Figure 1: Mechanical analysis of high pressurized helical tube.

There is a liquid nitrogen (LN2) jacket outside the pressure wall to operate the RF cavity at LN2 temperature. The thickness of LN2 will be strongly dependent on the RF power loss on the wall. A LN2 will use convection flow to remove the heat effectively for high heat deposition. We assume that 10 mm LN2 jacket would be sufficient to keep the temperature of RF cavity. There must be a vacuum gap between the LN2 and the liquid helium (LHe) layers for thermal insulation. An RF power transport cable will be stretched in this gap. We assume that 1 inch diameter coaxial cable will be sufficient for the RF power transportation. Hence, the vacuum gap is designed to be 40 mm.

The helical magnet will be made of a superconducting (SC) cable. The magnet is in an LHe bath. There must be a SC support and a super insulator to avoid the radiation heating from the LN2 jacket. We expect that a 20 mm gap will be sufficient for those layers.

Figure 2 shows the schematic picture of the required thickness for each layer. The gap in the vacuum layer seems to be larger than the requirement. This overestimated space will be absorbed by some unknown factor in some layer. In the current design, the total gap between the HS coil and the helical RF cavity is designed to be 80 mm.

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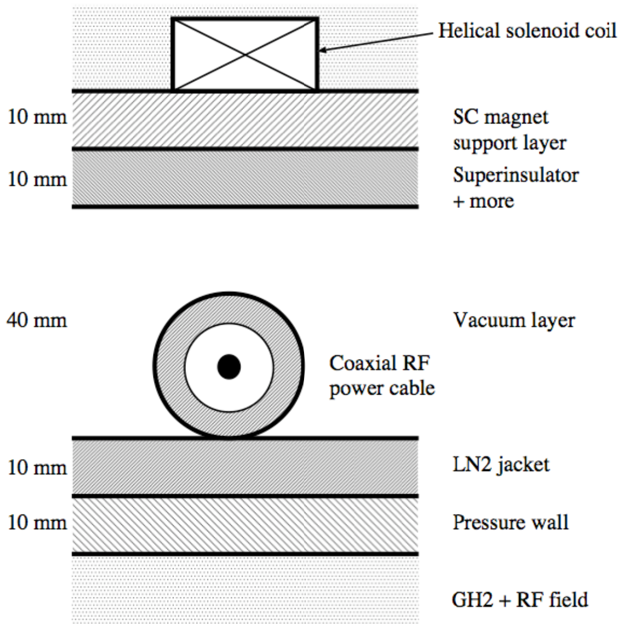

Figure 2: Schematic draw of layers between the HS coil and the high pressurizing hydrogen filled RF cavity.

Generate Helical Field by Helical Solenoid Coil

The HS coil has a geometric approach to aid in the tuning of the required helical dipole and solenoid fields. Figure 3 is a schematic drawing to show how to tune the dipole and solenoid field strengths on the reference orbit. The drawing shows the reference orbit from the end view of HCC. Three thick circles show the schematic HS coils. Let us find out the field on “Coil-2” center. The solenoid field is dominantly generated by the “Coil-2”. On the other hand, the helical dipole field (Bφ) is dominantly generated by “Coil-1” and “Coil-3”, those are upstream and downstream of the “Coil-2”, respectively.

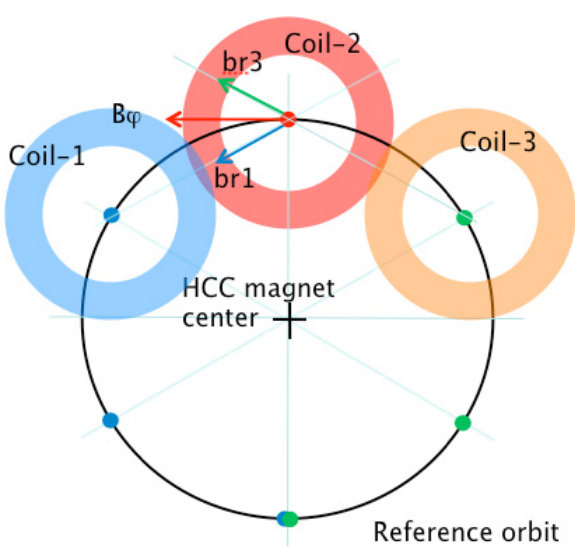

Figure 3: Schematic view of the HS coil from the end of HCC.

The coil diameter is additional degree of freedom to adjust the helical field gradient. However, this geometric effect is too weak to optimize the field gradient. Besides, an 80 mm gap requirement limits the maximum field gradient.

Add Correction Helical Solenoid Coil to Generate Proper Helical Quadrupole Component

In order to reduce the geometrical limitation of the HCC field, a correction coil is introduced. Figure 4 shows the modified configuration of the helical magnet by adding the correction HS coils. The red circle is a 200 MHz pillbox RF cavity. Blue and green circles are the primary and correction HS coils, respectively. There is an 80 mm gap between the RF cavity and the primary HS coil. A large green ring is a pure straight solenoid conductor. The tuning process of the helical magnet is as following.

The optimum helical dipole and helical field gradient are realized by tuning the position, size, and current of the primary and correction HS coils. Then, the solenoid component is tuned by adjusting a large solenoid conductor current.

The cooling simulation has been made in this configuration and shown that the field quality is well for muon collider application. However, there are two problematic issues in this design. First, the correction HS coil generates a large wasted energy since no beam path through it. Second, the field strength on the correction HS coil is quite large near the primary HS coil.

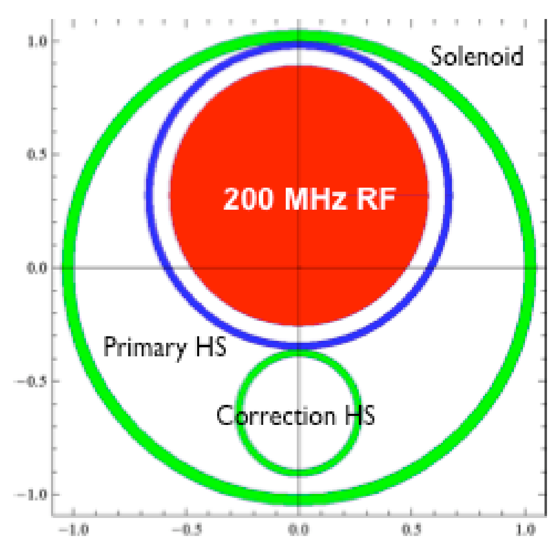

Figure 4: Schematic view of modified helical magnet with correction coils. The unit is meter. The origin is the helical magnet center.

Add Helical Coil to Generate Proper Helical Quadrupole Component

In order to increase the efficiency of the magnet system, a new HCC magnet has been designed. As shown in Figure 5, the correction HS coil is replaced with four helical quadrupole conductors. The quadruple conductor will wind around the primary HS followed by the helical pitch. The field quality on the reference is almost identical as the previous design.

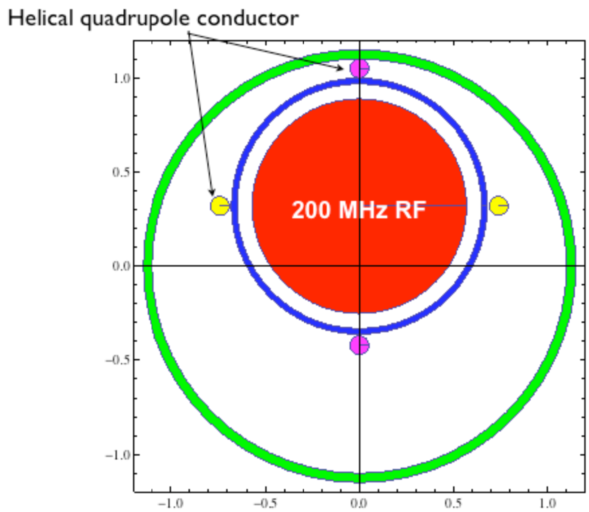

Figure 5: Schematic view of a new HS configuration with a helical quadrupole conductor.

Figure 6 shows the transverse and longitudinal phase space evolutions in a series of HCCs with the helical quadrupole conductor as shown in Figure 5. The RF frequency is shifted from 200 to 1600 MHz following the beam size reduction as a function of path length. The field optimization in a 1600 MHz HCC is on going.

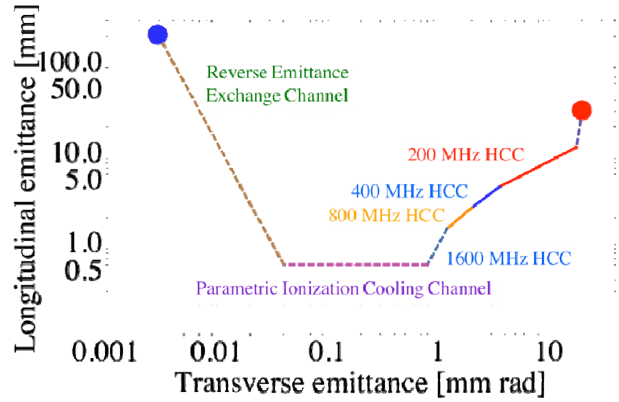

Figure 6: Transverse and longitudinal phase space evolutions in a series of HCCs.

CONCLUSION

The realistic HCC magnet system has been designed by taking into account the spacing between the HS coil and the RF cavity. The cooling performance in the HCC has been investigated. So far, the RF cavity size is determined from the pillbox structure. However, the cavity size can be made smaller by changing the shape of the cavity and by introducing dielectric loaded RF cavities [4]. The phase space matching will be the next issue. To fix it, we will introduce the adiabatic ramping frequency RF as a function of the channel length. We also plan to fine tune the HCC field quality to reduce the mismatching.

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MANX, A 6-D MUON BEAM COOLING EXPERIMENT FOR RAL*

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Abstract

MANX is a six-dimensional muon ionization cooling demonstration experiment based on the concept of a helical cooling channel in which a beam of muons loses energy in a continuous helium or hydrogen absorber while passing through a special superconducting magnet called a helical solenoid. The goals of the experiment include tests of the theory of the helical cooling channel and the helical solenoid implementation of it, verification of the simulation programs, and a demonstration of effective six-dimensional cooling of a muon beam. We report the status of the experiment and in particular, the proposal to have MANX follow MICE at the Rutherford-Appleton Laboratory (RAL) as an extension of the MICE experimental program. We describe the economies of such an approach which allow the MICE beam line and much of the MICE apparatus and expertise to be reused.

INTRODUCTION

The P5 committee reported prospective future projects for HEP activity in May, 2008. According to their road map, a muon collider will be an appropriate long term project if progress is made on the necessary breakthrough technologies. There are two immediate challenges for muon colliders. First, muons should be accelerated within their short lifetime. Second, quick six-dimensional (6D) phase space cooling of the beam is required to achieve effective muon acceleration. Therefore, a compact muon accelerating and cooling system is required. Because high-gradient high-power RF is preferable for quick acceleration, using SRF is a desirable solution. To this end, the beam phase space needs to be cooled down to the acceptance of the SRF system.

Recently, a novel 6D phase space cooling channel based on ionization cooling called a helical cooling channel (HCC) was proposed [1]. It consists of helical dipole, helical quadrupole, and solenoid magnetic components that confine the beam in a helical path filled with dense hydrogen gas. To compensate for ionization energy loss, a continuous RF acceleration field is needed. In order to simultaneously provide low-Z absorber and high-gradient RF, a high pressure hydrogen gas filled RF (HPRF) cavity was designed. It has been successfully tested and investigated for cooling applications [2]. By integrating the HPRF into the HCC, the HCC can be the most compact muon cooling channel.

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The HCC has been studied in simulation and shows exceptional cooling performance [3]. We proposed the demonstration experiment to verify the helical cooling theory and to test a special helical solenoid (HS) magnet technology [3] that can provide the required HCC field components. The project is named MANX (Muon collider And Neutrino factory demonstration eXperiment). MANX has been designed as an extension of MICE (Muon Ionization Cooling Experiment) at RAL. The concept of this demonstration experiment will be discussed in this paper.

LAYOUT OF MANX CHANNEL AT RAL

The MICE experiment is now being installed in a beam line at ISIS, an 800 MeV proton synchrotron. As shown in Figure 1, the proton beam hits a titanium target to generate pions that are then focused, momentum-selected, and transported to a decay solenoid to decay into muons. The muons are momentum-selected and transported into the MICE hall. Figure 1 shows the hoped-for configuration that will follow the successful completion of MICE, where the magnets and RF of that experiment are replaced by the MANX cooling channel (HCC) [4]. In the figure, the HS of MANX is shown placed between the MICE solenoid spectrometers, which will be reused.

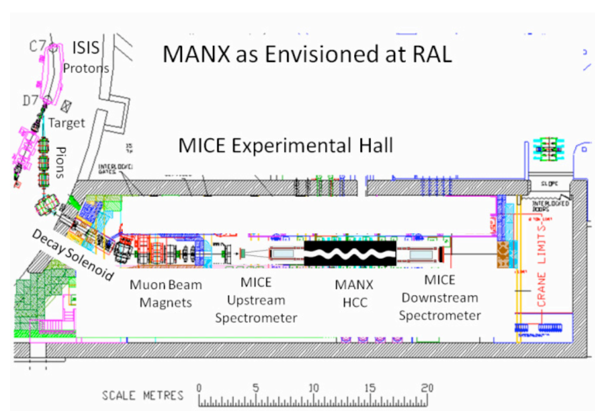

Figure 1: Layout of MANX in the MICE beam line at RAL. In addition to the MICE spectrometers there are MICE beam counters and particle identification detectors that will be reused for MANX.

Figure 2 shows the MANX HCC in more detail, including proposed tracking detectors inside the HCC [5]. The HCC is comprised of a central liquid-helium-filled helical solenoid (HS) and 2 matching sections to provide smooth transitions between the HS and the MICE spectrometers. Five sets of detectors are shown, three within the HS and two sets between the HS and the matching sections.

To avoid complications and to reduce costs, there is no RF in the MANX channel and helium is used instead of hydrogen. Hence, the magnetic field in the cooling section is reduced to correspond to the reduction of the reference momentum as the beam loses energy by ionizing the liquid helium. The detailed field parameters for MANX have been reported previously [6].

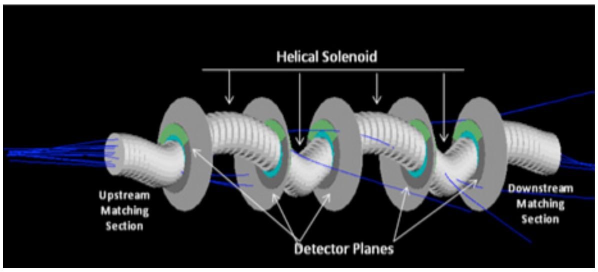

Figure 2: The helical cooling channel, with helical solenoid, matching sections and internal tracker units shown.

The key feature of 6D phase space cooling is emittance exchange. This process takes place by manipulating the path length of a particle as a function of its momentum in an ionization cooling absorber. Hence, magnetic dispersion is required. With the proper dispersion, particles with higher momentum traverse longer path lengths in a cooling absorber while lower momentum particles have shorter path lengths. This process causes the beam to become more monoenergetic at the expense of having larger transverse size generated by the dispersion. Consequently, transverse phase space is swapped with longitudinal phase space via this coupling between transverse and longitudinal momenta. A period of the coupling oscillation in the HCC is typically 1.5λ, where λ is one helical period. Hence, the length of cooling section in MANX is chosen 2λ to observe the coupling oscillation. In case of using liquid helium as a cooling absorber, the expected cooling factor per one plane is equally 1.3, yielding a 6D cooling factor of 2.0 in a 2 m MANX channel [4].

The MANX spectrometer yields six measurements {x, y, x' (or p_x), y' (or p_y), E (from p_x, p_y, and p_z), t (or s)} for each particle, where s is the path length of particle. These quantities are used to compute the 6-D emittance. Data will be taken with and without absorber. Without absorber, there is no interference between variables due to the stochastic aspects of Coulomb scattering. Hence, the clear correlation between path length (s) and particle momentum (p) will be observable. This will be direct evidence of the coupling oscillation in the dispersive magnet field, which will characterize the emittance exchange process. The path length measurement, however, will have ambiguity in the reconstruction of particle tracking. To address this, time of flight measured in the helical magnet will be used to resolve the ambiguity between path length and momentum. Fast timing resolution from devices that are available today is sufficient to meet the requirements.

Figure 3 shows the correlation between path length (s) and channel length (z) for various momenta from 200 to 300 MeV/c. Figure 4 shows the transit times versus momentum for a 3.2 m channel. The time of flight plot indicates that 1 MeV/c momentum differences can be measured with a pair of TOF counters 3.2 m apart with 50 ps timing resolution located upstream and downstream of the helical cooling channel. Time of flight counters are presently being developed with a resolution goal of better than 10 ps using micro-channel plates [7], which is applicable if better than 1 MeV/c resolution is required.

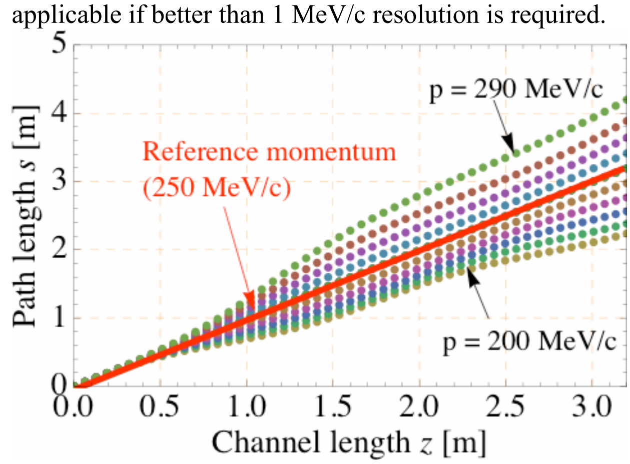

Figure 3: Dependence of path length for momenta in the range (250 MeV/c ± 20 %) as a function of HCC length z. The blue points are for the highest momentum.

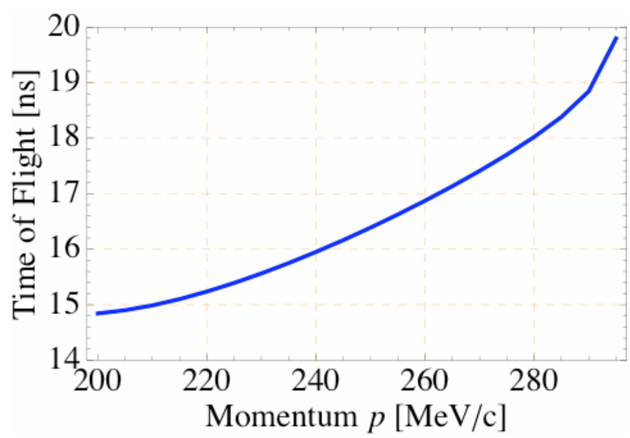

Figure 4: Time-of-flight versus momentum for a 3.2 m long HCC. This shows that the time difference per 10 MeV/c is approximately 500 psec.

The detector system must be well calibrated without absorber. The calibration will allow particle track reconstruction with sufficient precision to study stochastic processes by adding the time of flight information.

RESOLUTION ANALYSIS IN COLLECTIVE MODE

Single particle events can be aggregated to approximate collections of particles. In a 3.2 m HCC filled with LHe absorber 300 MeV/c muons are degraded to less than 170 MeV/c. Figures 5 and 6 show the RMS deviations of the transverse phase space parameters, r and p_r, in the HCC as a function of distance along the HCC length. The RMS of the spatial distribution is almost constant in the HCC. Hence, 50 mm position resolution must be sufficient for the position resolution of the detector in the HCC magnet. On the other hand, the transverse momentum is changing as a function of the HCC length. The RMS of momentum drops by 10 MeV/c. Hence, the required transverse momentum resolution of the detector is less than 10 MeV/c. The study of momentum resolution is ongoing and it requires development of reconstruction methods.

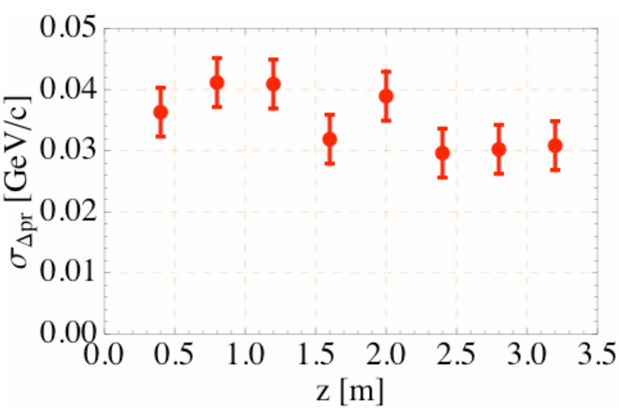

Figure 5: RMS of radial beam distribution in the HCC.

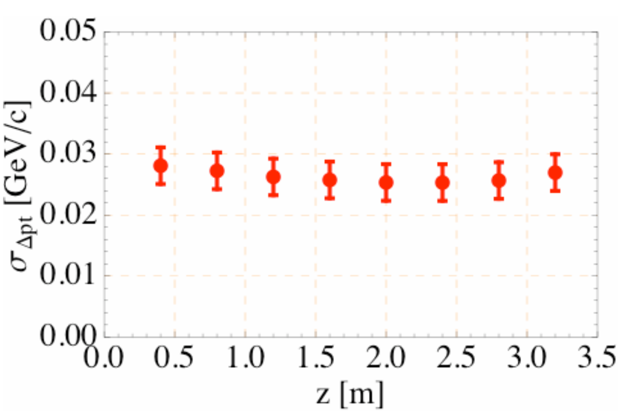

Figure 6: RMS of transverse momentum distribution in the HCC.

Figures 7 and 8 show the time and total momentum phase space parameters. The RMS of the time spread seems to be constant. This means that we do not need a fast timing detector in the HCC. The RMS of total momentum is changing as a function of the HCC length. The required resolution of the total momentum is 1 MeV/c. This measurement seems to be the most challenging in the HCC detector system.

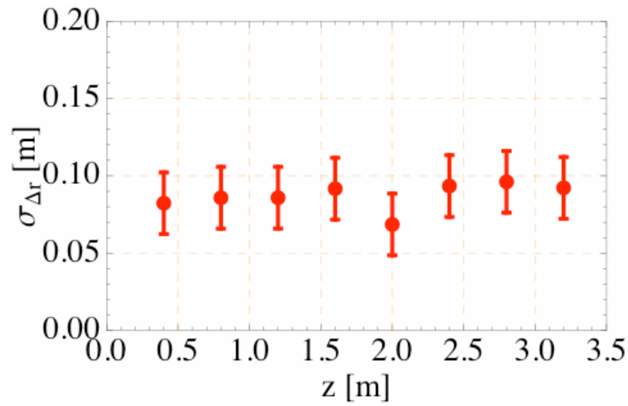

Figure 7: RMS of time spread in the HCC.

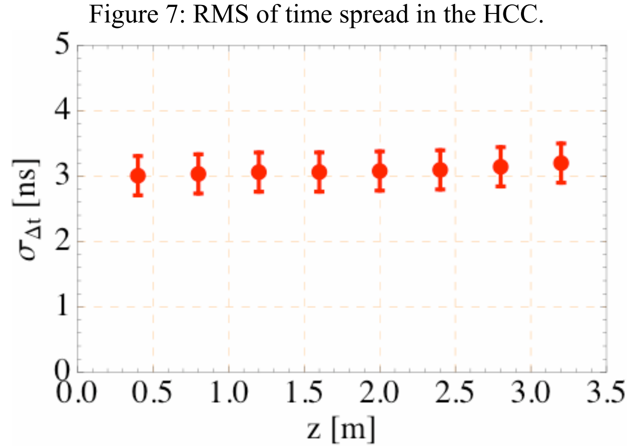

Figure 8: RMS of total momentum distribution in the HCC.

CONCLUSION

The MANX experiment is proposed to demonstrate 6-D muon ionization cooling in a helical cooling channel. The concept of the MANX experiment is discussed. Two measurement modes are shown. By observing the momentum dependent time of flight without absorber in the HCC, the essential features of the HCC will be determined. In addition, the required resolution for the 6-D parameters is discussed. The most challenging measurement is the total momentum. This resolution will be determined by reconstruction in the particle tracking system.

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INTEGRATING THE MANX 6-D MUON COOLING EXPERIMENT WITH THE MICE SPECTROMETERS*

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Abstract

The MANX experiment is to demonstrate the reduction of 6D muon phase space emittance using a continuous liquid absorber to provide ionization cooling in a helical solenoid magnetic channel. The experiment involves the construction of a short two-period long helical cooling channel (HCC) to reduce the muon invariant emittance by a factor of two. The HCC would replace the current cooling section of the MICE experiment now being setup at the Rutherford Appleton Laboratory. The MANX experiment would use the existing MICE spectrometers and muon beam line. This paper shall consider the various approaches to integrate MANX into the RAL hall using the MICE spectrometers. This study shall discuss the matching schemes used to minimize losses and prevent emittance growth between the MICE spectrometers and the MANX HCC. Also the placement of additional detection planes in the matching region and the HCC to improve the resolution will be examined.

INTRODUCTION

The MANX experiment is being proposed to test the theory of using a Helical Cooling Channel (HCC) to reduce the 6D phase space of a muon beam. The HCC cooling scheme uses a continuous absorber to provide ionization cooling in a helical solenoid channel [1]. The HCC will have an application in providing the six orders of magnitude in 6D muon phase space reduction that will be necessary for a muon collider. The HCC combines a solenoid field with helical dipole and helical quadrupole fields to provide a large acceptance channel. The most efficient approach to create the magnetic lattice for the HCC is to construct it from short solenoid coils arranged along the helical path as shown in figure 1. This has been shown to produce the desired field without an undesirably large magnetic field at the superconducting coils [2, 3]. The HCC proposed for a muon collider would use 400 atm. (room temperature equivalent) pressurized H_2 gas as the absorber. A muon traversing the channel would lose energy with dE/dx=14.3 MeV/m along the path. RF cavities would be inserted into the channel to replace the energy lost in the absorber. The RF requirements are substantial and would not allow much free space in the lattice without RF cavities. In the MANX demonstration experiment liquid helium is chosen as the absorber and there will be no RF cavities to replace the lost energy. These choices are made to both control costs and reduce the timeline to mount the experiment.*

* Work supported by U.S. DOE contract DE-AC02-07CH11359
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The experiment has been proposed to be performed at the Rutherford-Appleton laboratory in the MICE hall at ISIS. The experiment would make use of the MICE muon beam with the magnets configured for a muon momentum of 350 MeV/c in the upstream MICE spectrometer. The muon beam line is shown in figure 1a. The upstream part of this beam line consists of two bending dipoles with a focusing solenoid magnet for a decay channel in between. Table 1 summarizes the beam parameters after the second bend and after the beam diffuser just before entering the upstream spectrometer. The pion contamination in the muon beam after the second bend is estimated to be 0.65%. MANX will use the upstream and downstream tracking spectrometers from MICE. The existing Cherenkov detector should be able to tag the residual pions in threshold mode. The downstream EM calorimeter or similar device will be used to tag decay electrons and give a muon momentum measurement to a certain precision. The MICE H_2 absorbers and RF cavities will not be used. They will be replaced with a short HCC channel and matching sections.

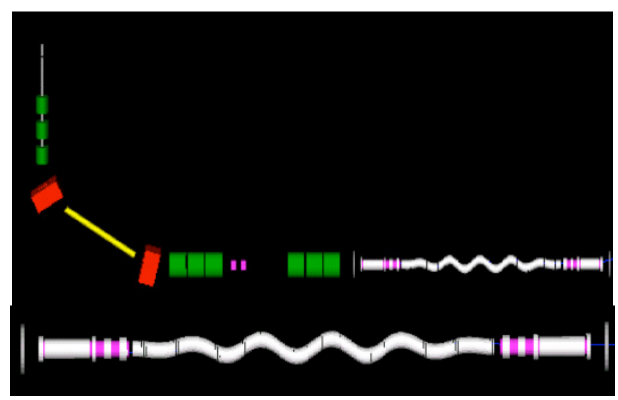

Figure 1: MANX baseline matching design. (a) MANX layout including beam line. (b) Enlarged MANX HCC with baseline matching sections.

Table 1: Parameters Describing the MICE Beam Adjusted for 350 MeV/c Muons

Parameter	*After 2nd Bend*	*After Diffuser*
P, MeV/c	375	341
σ_P, MeV/c	44	36
σ_X, mm	102	55
σ_Y, mm	56	41
σ_{Px}, mm	11	32
σ_{Py}, mm	7	30
σ_T, ns	0.29	0.47

HCC AND MATCHING SECTIONS

The experiment will incorporate a 4 m long HCC filled with liquid helium. The field is provided by a helical arrangement of solenoid coils which will provide B_Z=4.5 T and B_ϕ=1 T at the beginning of the channel. The field profile will fall off along the channel to match the energy loss from the absorber so that the beam maintains the helical geometry. Table 2 displays the parameters used to describe channel. The cooling performance is shown in figure 2, which gives the 6D emittance expected in the HCC. This is described in refs [4, 5].

Table 2: Parameters Describing the MANX HCC

Parameter	*Value*
Helical Period	2 meters
Pitch Tangent: $\kappa = P_\perp/P_\parallel$	0.8
Channel Length	4 meters
Reference Radius	0.255 meters
Initial Solenoid Field	4.5 T
Initial Helical Dipole Field	1 T
Initial Mean Muon Momentum	350 MeV/c
Solenoid Coil Inner Radius	0.25 meters

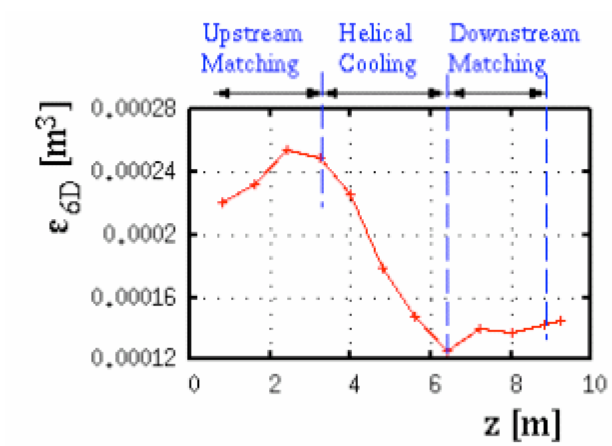

Figure 2: The 6D emittance is shown in the HCC and upstream and downstream matching regions. (This figure uses slightly different parameters than in Table 2).

The beam must be inserted into the channel at the reference radius and with the angular incline of the pitch. We have looked at a scheme where upstream and downstream of the HCC cryostat solenoid coils are place so as to gradually guide the beam from the orbit in the MICE spectrometers to reference orbit in the HCC. This matching transition uses 1.5 helical periods with fields approaching more than 6 T. Figure 1b shows the HCC with the 1.5 period long gradual matching sections. An attempt to shorten the transition distance requires a significant increase of the field which becomes impractical. The HCC plus matching section is 10.4 meters long which is 4 meters longer than the planned MICE cooling section. There exists enough space in the MICE hall to move the downstream spectrometer to accommodate the MANX cooling channel. Simulations show that, for a beam described by parameters in Table 2, 70% of the non-decaying muons in the upstream spectrometer will traverse the HCC cooling channel. The downside to this scheme is that the cost of the magnetic structure for the matching section will exceed that of the HCC cooling channel itself.

An alternate approach to the previously described matching scheme is to position the HCC off axis to the MICE spectrometers as shown in figure 3. In this scheme the HCC is positioned at 45° with respect to the MICE spectrometers so that muon beam from the spectrometer will enter properly oriented into the HCC. If no further beam matching is performed only 39% of the non-decaying muons will survive to the end of the HCC channel. Figure 4 shows that increasing the current in the MICE matching coils can improve this transmission somewhat. The figure gives the fraction of muons seen in the upstream spectrometer that survive to the end of the HCC as a function of the MICE matching coil current (shown as a scale factor times the nominal current). As the nominal MICE matching currents are near their current limits, some modification of these coils would be necessary for this improvement.

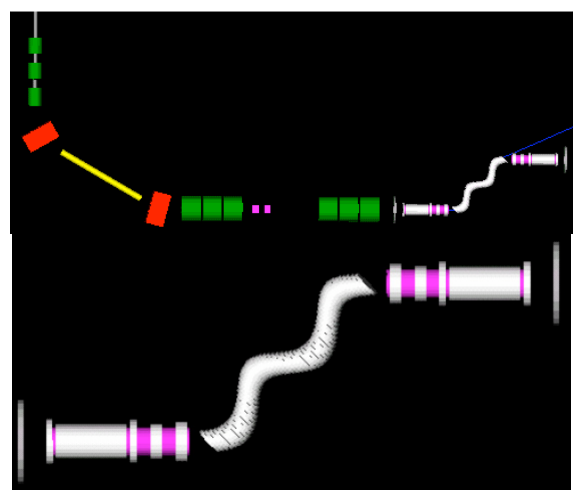

Figure 3: The HCC channel (lower) is shown positioned between the two MICE spectrometers. Also shown (upper) is the off axis HCC channel positioned with the entire MICE beam line.

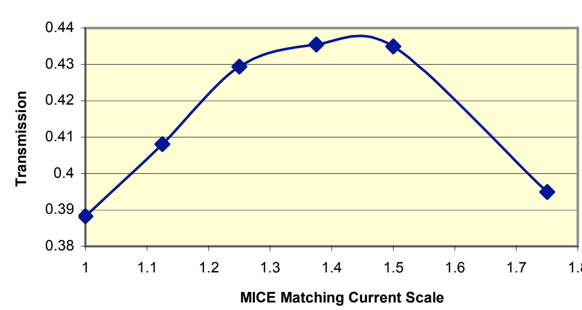

Figure 4: Muon transmission in the HCC channel as a function of the MICE matching coil current. The current is shown as a scale factor to be applied to the nominal MICE matching coil current.

Additional improvement can be achieved by also increasing the current in the first several HCC coils. Figure 5 shows the transmission as a function of a current scale factor applied to the first two HCC short solenoid coils. The several curves are for different scale factors applied also to the MICE matching coils. This off axis configuration can achieve a transmission of 55%. There is a concern that there will be large transverse magnetic forces between the HCC coils and the MICE spectrometer magnets with the off axis configuration that would have to be accommodated.

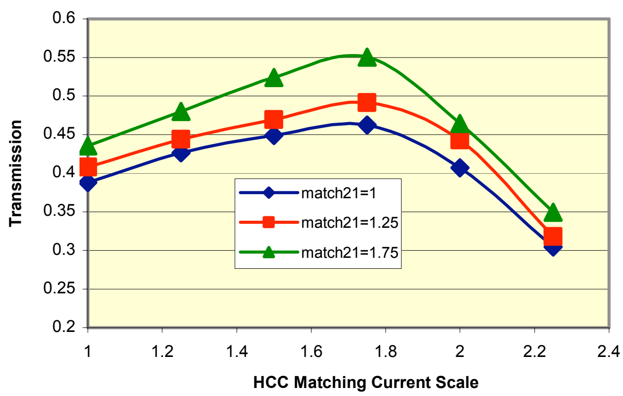

Figure 5: Muon transmission in the HCC channel as a function of the current in the first two HCC short solenoids. The current is shown as a scale factor to be applied to the nominal current in those solenoids. The different curves shown correspond to different currents in the MICE matching coils.

DETECTOR RESOLUTION

The MANX experiment will use the MICE spectrometer scintillating fiber (SciFi) planes which have an effective wire spacing of 1.65 mm when seven fibers are ganged together for the electronic readout. Timing measurements in MICE are provided by time-of-flight detectors with a resolution of 50 ps. The MANX experiment will add an additional two SciFi planes in each of the matching sections and four planes inside the HCC itself. The detector arrangement is described elsewhere [6, 7]. In a simulation study where a muon track first passes through the detector planes creating simulated detector hits. In a second pass the parameters describing the track are fit to these hits to reconstruct the track. This procedure provides the errors to the track parameters. Table 3 shows the errors that were found using the MICE planes alone and the MICE planes in conjunction with additional planes in the matching region. These errors are from measurement alone. They do not include errors related to the uncertainties of the field which are currently being studied. The errors quoted for the MICE SciFi tracker alone are valid for the center of that detector. When the variables are extrapolated to HCC the errors in those variables grow significantly. This is the justification for putting additional detection planes in the matching region. The errors shown for the Mice SciFi plus matching planes are calculated for the beam variables as seen in the matching region just before the entrance to the HCC cryostat. Using these track measurement errors one can obtain the expected error in the determination of the emittance. Table 4 shows the relative measurement errors of transverse and 6D emittance for these cases. In order to calculate the 6D emittance we have assumed that the incoming beam has a 0.8 ns time structure that would be representative of 200 MHz RF of an upstream phase rotation or pre-cooling section. These errors are more than adequate for the anticipated physics of the MANX program.

Table 3: Measurement Errors Expected from SciFi Detection Planes in MANX

Case	σ_X	σ_{Px}	σ_{Pz}
	mm	MeV/c	MeV/c
Upstream Mice SiFi Alone	0.74	1.3	1.0
Downstr. Mice SiFi Alone	0.95	0.94	0.4
Mice plus Matching Planes	2.4	3.0	1.7

Table 4: Relative Measurement Errors for Transverse and 6D Emittance

Case	$\Delta\varepsilon_{TR}/\varepsilon_{TR}$	$\Delta\varepsilon_{6D}/\varepsilon_{6D}$
Upstream Mice SiFi Alone	0.10%	1.44%
Downstream Mice SiFi Alone	0.32%	0.77%
Mice plus Matching Planes	0.28%	1.58%

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MANX: A 6D Ionization-Cooling Experiment[1]

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Abstract. Six-dimensional ionization cooling of muons is essential for muon colliders and possibly beneficial for neutrino factories. An experiment to demonstrate six-dimensional ionization cooling using practical apparatus is presented. It exploits recent innovative ideas that may lead to six-dimensional muon-cooling channels with emittance reduction approaching that needed for high-luminosity muon colliders.

Keywords: Muon cooling, muon collider, neutrino factory, helical cooling channel.
PACS: 29.27.-a, 29.20.-c, 14.60.Ef, 41.85.Lc

INTRODUCTION

Ionization cooling [1], in which a beam is cooled by energy loss in an absorber medium, is a key technique for future muon accelerator facilities, e.g., a neutrino factory [2] or muon collider [3]. It is unique in its ability to cool an intense beam of muons before a substantial fraction of them have decayed. Ionization cooling is essentially a transverse effect but can be made to cool the longitudinal degrees of freedom as well via emittance exchange [4]. An experiment to demonstrate transverse ionization cooling (the Muon Ionization Cooling Experiment, MICE) [5] is in progress. We describe a possible six-dimensional (6D) cooling experiment: the Muon-collider And Neutrino-factory eXperiment, MANX [6].

SIX-DIMENSIONAL MUON COOLING

Several approaches to six-dimensional muon cooling have been devised. The first design shown to work in simulation was the Balbekov ring cooler [7]. Since then, several ring cooler designs have been studied, based on solenoid-focused "RFOFO" cells [8] and quadrupole- [9] or dipole-edge-field-focused [10] cells. All can produce useful levels of 6D cooling, but injection and extraction are problematic. This problem is eliminated (at the expense of greater hardware cost) by extending an RFOFO ring into the third dimension, giving a helical, "Guggenheim" cooling channel [11].[2] This can also alleviate problematic RF loading and absorber heating, and it allows the focusing strength at each step along the device to be tailored to the emittance at that point, enhancing the cooling efficacy. In all of these designs, bending magnets introduce the dispersion needed for longitudinal–transverse emittance exchange.

Helical Cooling Channel

A more recent development is the Helical Cooling Channel (HCC) [12], employing a helical dipole field superimposed on a solenoid field. The helical dipole, known from "Siberian Snake" magnets used to control spin resonances in synchrotrons, provides the dispersion needed for emittance exchange. The solenoid field provides focusing, and helical quadrupole magnets are added for beam stability and larger acceptance. Figure 1 illustrates the beam motion, as well as two possible magnet configurations: a conventional one with three separate windings generating the required field components, and the recent "Helical Solenoid" invention [13], which achieves the same field components and acceptance using simple circular coils of half the radius, about one-quarter the stored energy, and smaller fields at the conductors. The equilibrium beam orbit follows the centers of the coils. (The theory of the HCC, based on a Hamiltonian formalism that starts with the opposing radial forces shown in Fig. 1, is derived in [12].)

Continuous Absorber

Six-dimensional muon coolers were first formulated with emittance exchange via wedge absorbers located at dispersive points in the lattice. The same effect may be achieved more simply by use of a continuous absorber [12, 14] (Fig. 2). This approach may be synergistic with the idea of maximizing the operating gradient of copper RF cavities in high magnetic fields by filling them with pressurized hydrogen [15]; the absorber needed for ionization cooling can thus be combined with the muon

[1] To appear in *Proc. NuFact07 Workshop*, Okayama, Japan (2007).
[2] The allusion is to the Guggenheim Museum in New York, rather than, say, that in Bilbao.

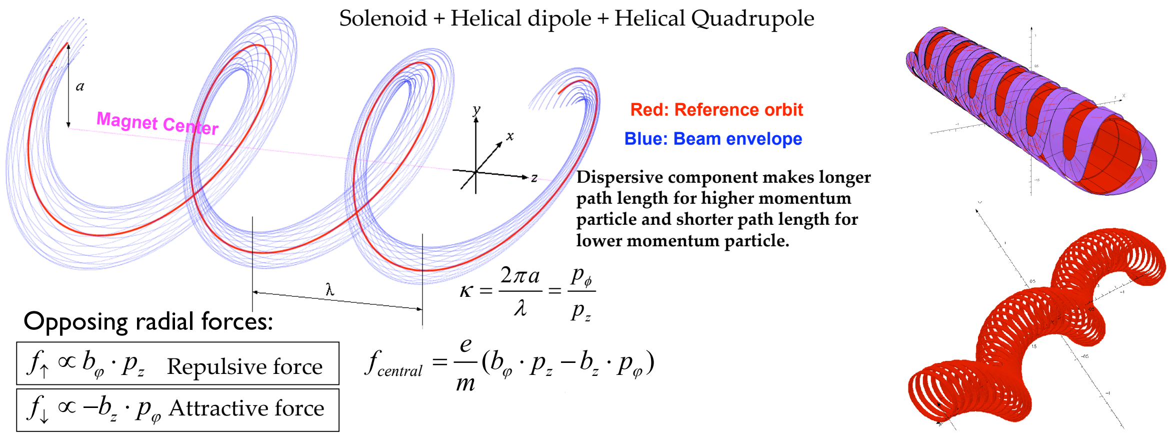

FIGURE 1. (left) Helical-channel principle; (top-right) conventional "Siberian snake" solution with individual windings providing the required solenoidal, helical dipole, and helical quadrupole fields; (bottom-right) Helical Solenoid implementation with the same acceptance and the three required fields produced using simple offset coils only half the diameter of the conventional magnet.

re-acceleration, giving a shorter and more adiabatic channel. Another possibility is a "separated-function" cooling channel in which pressurized-gas- or liquid-filled HCC segments are separated by linear-accelerator sections; in such an arrangement, the fields of each HCC segment can be graded [14], so as to maintain constant focusing strength as the beam momentum is reduced by energy loss in the absorber medium. Such an arrangement may be advantageous in that the acceleration could then be done using superconducting RF cavities, reducing instantaneous-power requirements.

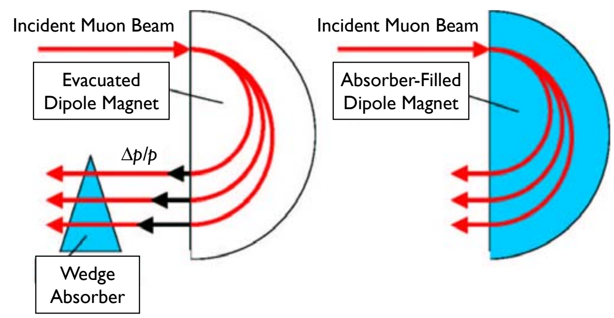

FIGURE 2. (left) Emittance exchange via dispersion and wedge absorber; (right) emittance exchange via continuous absorber.

HCC Example

Figure 3 shows the results of a G4beamline [16] simulation of a 160 m, 4-section HCC carried out by K. Yonehara [14]. The 6D emittance reduction factor of 5×10^4 is a big step towards the $\sim 10^6$ required for a high-luminosity muon collider. Cooling approaches capable of providing the additional factor of 10–100 needed are under development [14].

MANX

These innovative muon-cooling approaches will require experimental demonstration before a facility employing them can be approved for construction. Since such demonstrations are potentially expensive (typically comparable in cost to medium-scale HEP experiments), which aspects to demonstrate, and how best to do so, must be considered with care.

A proposal for a 6D HCC demonstration experiment is under development by a collaboration among Muons, Inc. [17], Fermilab, and university groups [6]. The approach taken is to design a separated-function, graded-HCC segment of modest length which nevertheless delivers an impressive ($\approx$ 3–5) 6D cooling factor. Such a device might be suitable for use as a precooler to a combined-function HCC incorporating pressurized RF cavities, or as a first segment in a separated-function HCC. It may also be capable of increasing substantially the rate of muons stopping in a thin target, e.g., in a muon-to-electron-conversion experiment [18].

By eliminating the RF cavities, the cost is substantially reduced and the attention is focused on the dynamics and engineering issues of the HCC magnet itself. While this is not the only approach that might be taken in such a demonstration experiment, it may be a sensible one in that it "factorizes" the engineering challenges: with hydrogen-absorber operation in close proximity to RF cavities and high-field solenoids already being tackled by MICE, arguably this need not be demonstrated again before a full muon accelerator facility is engineered.

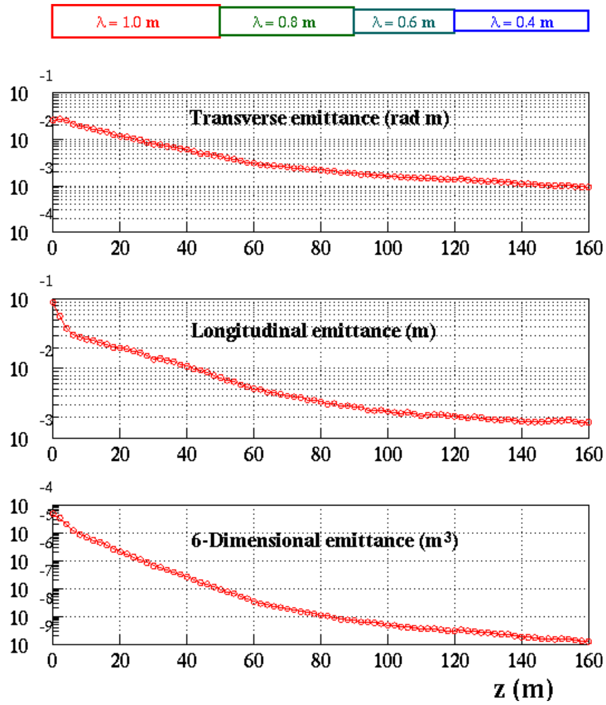

FIGURE 3. Simulation of emittance reduction in a 4-segment, 160 m HCC filled with high-pressure hydrogen gas.

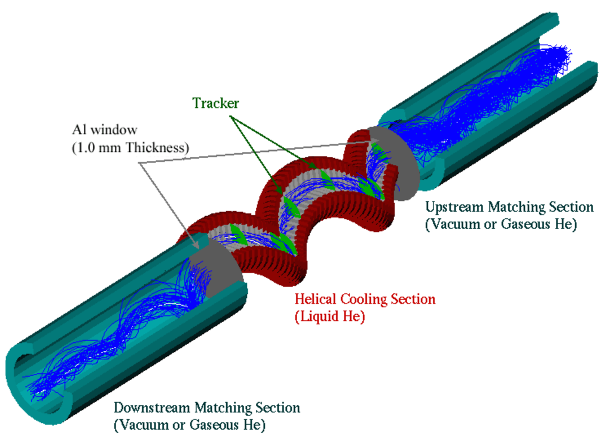

FIGURE 4. Simulation of possible MANX HCC section between matching sections. The solenoid and rotating-dipole fields gradually turn on (off) in the upstream (downstream) matching section. The overall length in this example is 12 m.

The MANX apparatus will include muon-measurement sections and (Fig. 4) matching sections into and out of the cooling section; it may also be possible to operate thin tracking detectors within the HCC section as indicated in Fig. 4.

Various venues for MANX are being explored. The MICE muon beamline and detectors might be re-usable for MANX; options involving a new muon beam at Fermilab are also under consideration. It is hoped to carry out the experiment within the next $\lesssim 5$ years.

ACKNOWLEDGMENTS

I thank my collaborators at Muons, Inc., who devised many of the innovations discussed here. This work is supported by the US Dept. of Energy. The G4beamline program is in ongoing development by IIT and Muons, Inc. under STTR grant DE-FG02-06ER86281.

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MECHANICAL ANALYSIS AND TEST RESULTS OF 4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL

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ABSTRACT

Novel configurations of helical superconducting magnets for muon beam 6D phase space cooling channels and demonstration experiments are being designed at Fermilab. Operating as needed for the beam cooling in a cryogenic environment, the helical solenoid generates longitudinal and transverse magnetic fields; meanwhile, large Lorentz forces are produced, so rigid coil support structures need to be designed. A short model of a helical solenoid (HS), consisting of four coils and supporting structures, was designed, built and tested at Fermilab. The magnetic and mechanical designs were analyzed using TOSCA and ANSYS. The supporting structures were fabricated and assembled using SSC NbTi cable. Strain gauges were utilized to monitor the deformation of the structures due to both thermal contraction and Lorentz forces. The superconducting coils were trained during the test. The model should prove the design concept, fabrication technology, and the magnet system performance.

KEYWORDS: Superconducting magnet, Muon beam cooling, Helical cooling channel, Four-coil helical solenoid.

INTRODUCTION

The Large Hadron Collider (LHC) construction was finished at CERN and the first protons were fired around the entire tunnel circuit in September 2008. Soon LHC will be operated to study hadron-hadron collisions. Nowadays, physicists are carrying out complementary studies of lepton-lepton collisions, and one plan is to design a Muon Collider [1]. Muons are much heavier than electrons, so very high energy muon beams can be bent in beam lines and recirculated in an accelerator with much less energy loss. However muons are unstable particles with a very short lifetime and muon beams have large emittances. To meet the requirement of the Muon Collider, one of the extremely difficult challenges is to reduce the muon beam size in a very short time before muons decay away. For this purpose, the Helical Cooling Channel (HCC) concept for the six-dimensional muon beam cooling was suggested in [2]. The Helical Solenoid configuration [3] generates the needed solenoidal, helical dipole and helical quadrupole magnetic fields [4, 5] to realize the beam size reduction in a helical ionization cooling channel.

It is well known that hoop stress and axial compression are the dominant stress components for the straight solenoids. However, in a helical solenoid, much more complicated stress patterns are generated due to the magnetic field components and the structure configuration. It is important to develop the proper design and technology to protect the superconductor coils from large stresses and displacements during cool down and magnet excitation. A four-coil helical solenoid model, named HSM01, was designed, fabricated and tested at Fermi National Accelerator Laboratory (FNAL) to develop the manufacturing technology and demonstrate the magnet system performance. This paper will present the model design and the simulation results, and show the test results of magnet training, as well as strain gauge readings. The post-test model autopsy was finished to observe the inner mechanical structure, and the improvements for the next model were discussed.

DESIGN AND SIMULATION

To fit within the Vertical Magnet Test Facility (VMTF) at FNAL, HSM01 was designed with 640 mm outer diameter, limited by the cryostat bore diameter. The stand has all the cryogenics, 30 kA power supply, quench detection, protection and control systems. Simulations for both magnetic and mechanical design were executed to have a better understanding of the model performance before fabrication and test.

Magnetic Design and Simulation

HSM01 consists of four coils with the centers shifted along an arc corresponding to the helical orbit. The basic model parameters are listed in TABLE 1. Cable Ic(B) dependence and load lines for long HS and for HS 4-coil model are shown in FIGURE 1. For the long helical solenoid at 4.5 K, with cable current 9660 A, the peak superconductor magnetic flux density B reaches 5.7 T. To produce this same level of magnetic field and Lorentz force in the four-coil model, the cable current has to be raised up to 14 kA, and the peak magnetic flux density B in the superconductor is 4.84 T. Study and comparison of the magnetic field and forces between the four-coil model and the long helical solenoid model were made in [6]. The four-coil geometry and the simulated flux density distribution in ANSYS are shown in FIGURE 2.

TABLE 1. Solenoid Parameters.

Parameter	Units	Value
Coil inner diameter	mm	426
Coil outer diameter	mm	455
NbTi cable dimensions	mm	12.34 x 1.46
Cable critical current at 5.3 T, 4.5 K	kA	16.4
Strand diameter	mm	0.8
Helical orbit radius	mm	255
Helix period	mm	1600
Number of turns per coil		10
Coil height	mm	20

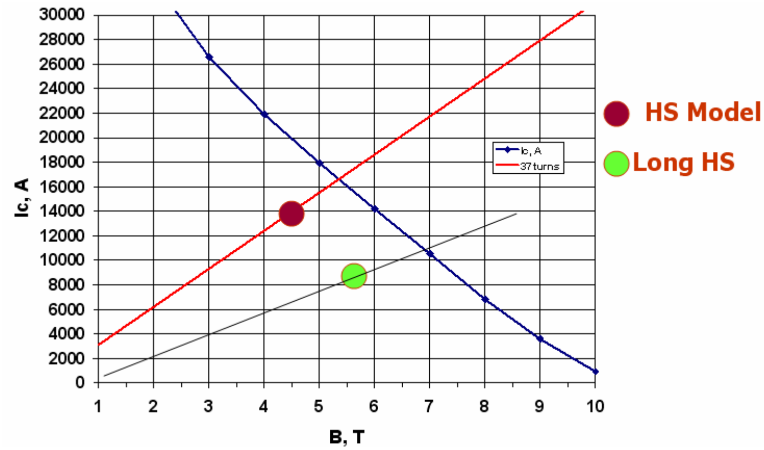


FIGURE 1. Cable Ic(B) Dependence and Load Lines for Long HS and for HS Four-Coil Model.

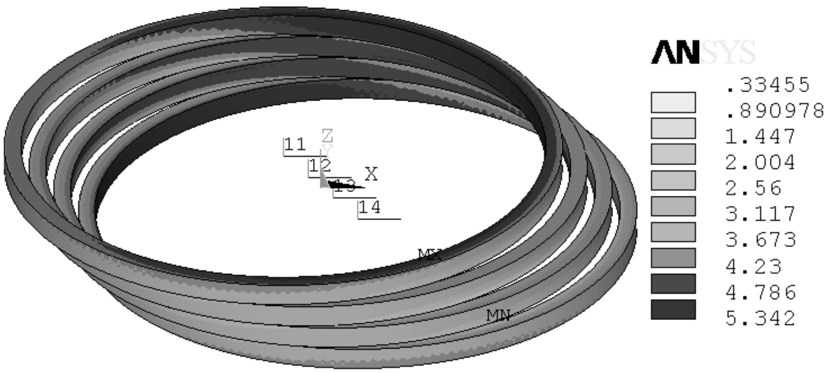


FIGURE 2. Four-Coil Geometry and Magnetic Flux Density Distribution (Values in T) at 14 kA.

Mechanical Design and Simulation

The helical solenoid generates solenoidal, helical dipole and helical quadrupole magnetic fields; meanwhile, it produces large radial and longitudinal forces, as well as bending, so solid mechanical structures are needed to intercept the forces and support the coils [6]. FIGURE 3 shows the design sketch in cross section view. The material is stainless steel for the supporting structures, including inner rings, outer rings, and end flanges, etc. Steps are machined on both sides of the inner and outer rings to lock the coil from moving in the transverse direction. The inner rings, as well as the outer rings, are welded together with the end flanges to strengthen the whole structure. Due to the magnetic forces and the helical structure configuration, complex stress patterns exist, including hoop stress, radial compression, axial compression, and shear stress.

The 3D mechanical model is built in ANSYS, shown in FIGURE 4. Since the model is simplified (for instance, there are no steps modeled in the support rings), for the boundary conditions all the structure components are glued to each other, and the model is attached to VMTF by 4 rods for the test.

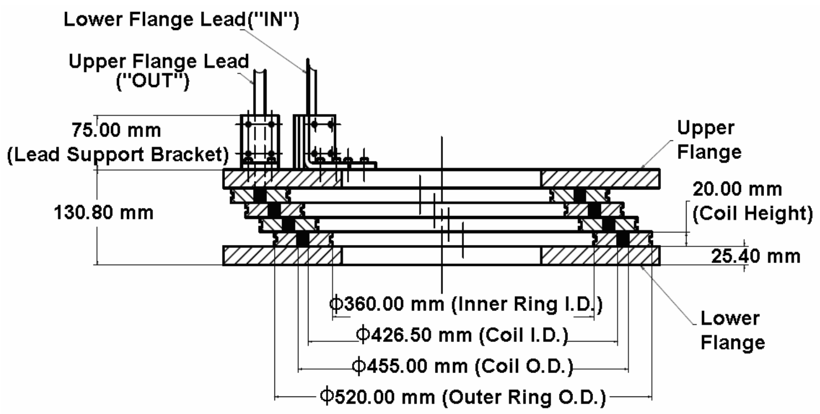


FIGURE 3. The Model Design Sketch in Cross Section View.

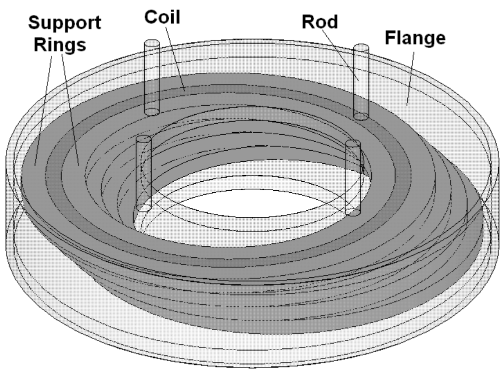


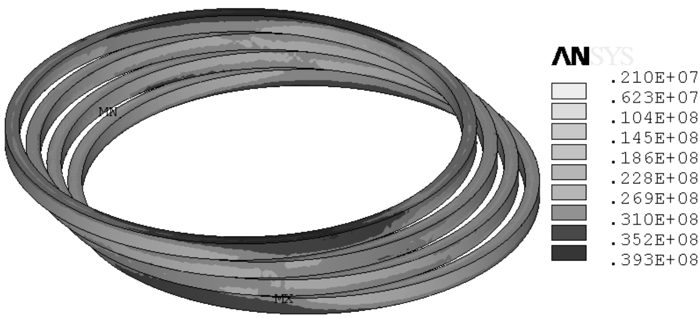
FIGURE 4. 3D Mechanical Model in ANSYS.

The magnetic forces are calculated based on the Lorentz Force Law on a current-carrying wire, and the results are consistent with the results from TOSCA. The forces are then applied on the nodes of each coil. The accumulated force for each coil is considerably large, for instance, in the top coil, the accumulated radial force is about 150 KN and the accumulated axial force is about 320 KN. The forces are trying to straighten the helical coils, and compress the superconductors in both radial and axial direction, so the support rings not only have to provide the coil support, but also have to prevent coil motions. Besides the magnetic forces, thermal contractions of the helical structure during cool down, from room temperature to 4.5 K, also causes big stresses in the superconducting coils, especially in the axial direction.

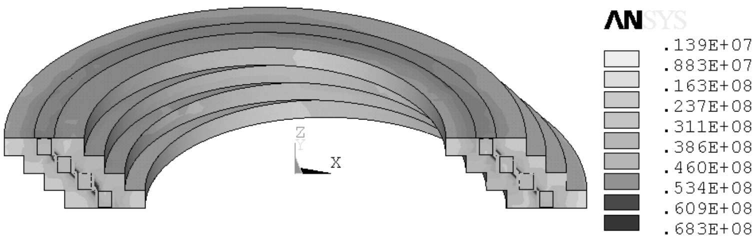
The stress distributions in the coils and the support rings are shown in FIGURE 5 (a) and (b). The maximum stress is 39.3 MPa in the coils and 68.3 MPa in the support rings, which is well below the conductor degradation limit stress 150 MPa and the stainless steel yield stress 550 MPa. The relatively large margins in stress will be beneficial for the long HS design.

FABRICATION AND TEST

HSM01 was fabricated and tested at FNAL. Heaters were installed in the gap outside of the outer coil radius to provide quench protection. Strain gauges were glued in the outer surface of the support rings to monitor the deformation of the structure.



(a). Stress in Coils.



(b). Stress in Coils and Support Rings from Cross Section View.

FIGURE 5. Stress Distribution (Value in Pascal) at the Peak Current 14 kA.

Fabrication

The horizontal winding rotational table system was used to wind NbTi cable, shown in FIGURE 6. The side flange was attached to the table, and then the first coil inner support ring was locked and welded to the flange. The cable, passing through all the outer support rings, was wound around the first inner ring, and the first outer support ring was locked. The other three coils were wound and assembled with the similar procedure. Welding was made at certain spots on the support rings and the other side flange. Since the coil centers are shifted, the hard-bend winding way was adopted to provide continuous winding without any splices; however from coil to coil, the transition turns shown in FIGURE 7 should be well insulated and arranged. Extra pieces of G-10 insulation were used, and pressure was applied to make the transition turns fit inside the support rings. The long solenoid can also be wound and assembled in the same way as the short model.

There were two significant fabrication issues. First, due to the limited winding space, one of the four coils has 10 turns, while the other three coils have only 9 turns, but it did not have a big effect on the magnet performance. Second, during the room temperature insulation hipot tests, the magnet could withstand no more than 250 V to ground without a discharge. In liquid helium, a 15 kΩ short to ground developed [7]. A post-test inspection points to a likely coil-to-coil transition area insulation weakness which was probably caused by the insulation bending under the pressure to fit the transition turns.

Test

HSM01 was suspended in the VMTF cryostat, with an insulated warm bore tube passing through the aperture to measure the magnetic field components near the center. Because there are only 9 turns in three coils, an update model was built and simulated in TOSCA. The model

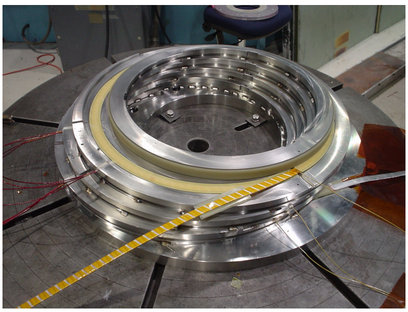


FIGURE 6. The Model Winding and Assembly Process.

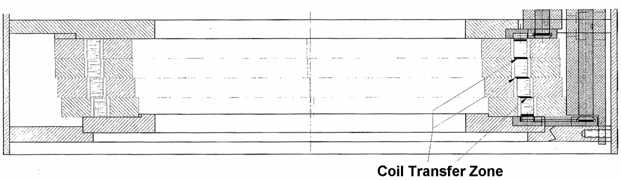


FIGURE 7. Cross Section of the Transition Turns.

predicts shapes and strengths that are very similar to the measured ones [7]. Quench performance and temperature dependence were also studied, and the results are shown in FIGURE 8. The magnet reached quench plateau of about 13 kA, 85% of the predicted maximum current at 4.5 K, and lack of improvement at lower temperature indicated that it was mechanically limited.

From the readings on compensation gauges shown in FIGURE 9(a), as the magnetic field increases, the magnetic field effect on the strain gauges increases in a very small range. The readings on active gauges changed slightly with maximum around 0.003% shown in FIGURE 9(b), while the simulation gives about 0.007%. Compared to the 0.2~0.3 % strain from cool down, the Lorentz force strains are relatively small and very consistent with prediction. The radial thickness of the inner and outer support rings were designed far beyond the safety requirement for this magnet with around 70% safety margin. For the future model with higher magnetic field obtained by using different superconductors such as Nb_3Sn, the thickness of the rings is still sufficient with an estimated safety margin 30%.

The model was cut after the test to find out if there is any mechanical defect around the coil, which may help to better understand the quench performance, etc. From the photos taken on the cutting surfaces, shown in FIGURE 10, there are some imperfections, such as the voids and thick epoxy which may easily cause epoxy to break at low temperature. G10 bending may

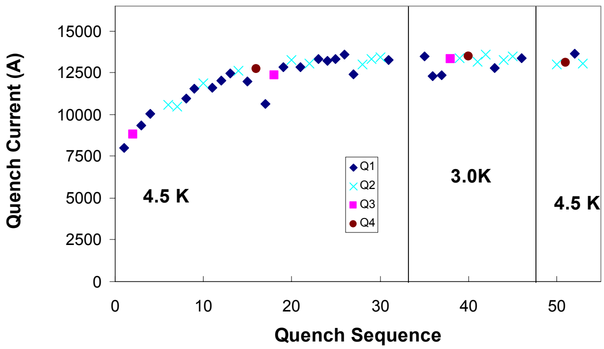
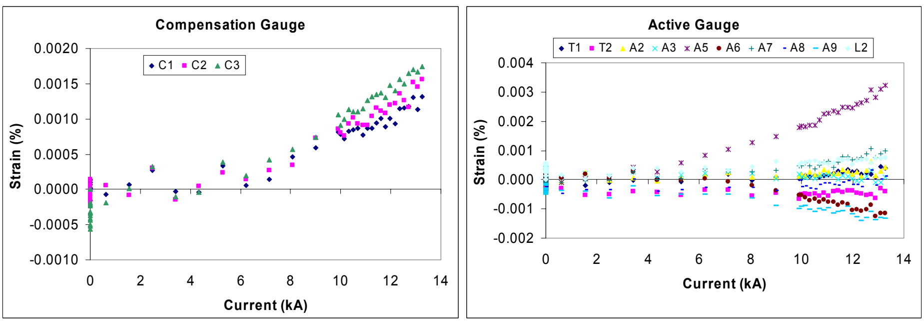


FIGURE 8. Magnet Quench Performance.



(a). Compensation Gauge Readings. **(b).** Active Gauge Readings.

FIGURE 9. Strain Gauge Monitor during Magnet Excitation.

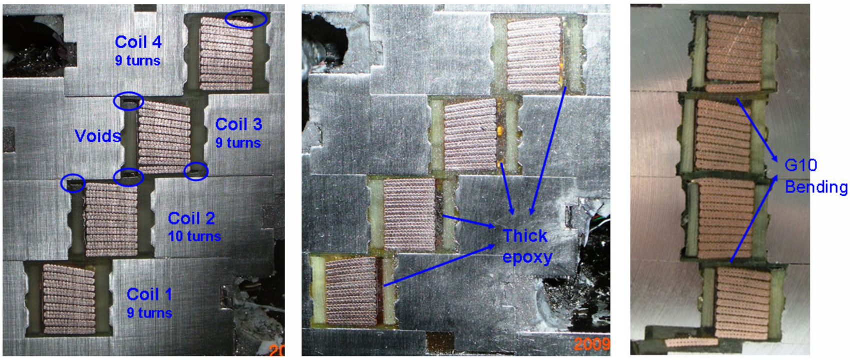


FIGURE 10. Post-Test Autopsy and Inspection.

cause the weakness of the insulation and make coil short to ground in the liquid helium. Some design improvements for the next model are: (a). The support rings will be 2 mm more in axial thickness to increase the thickness of G-10 spacers covering the coils; (b). Additional slots will be made in G-10 layers to fill the epoxy evenly; (c). The outer support rings will be furnished with a copper cooling tube to check the efficiency of the solenoid indirect cooling system.

CONCLUSION

HSM01 has been successfully fabricated and tested. Both the magnetic field measurement and strain gauge readings were consistent with the simulation predictions. The magnet reached 85% of the maximum current. The outer structures can provide sufficient support to the coils. The fabrication technology of building such a helical-configuration model was developed and the imperfections of the model will be improved for the next model which will be fabricated and tested in late 2009.

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MANX following MICE at RAL

A Proposal to Fermilab for an Accelerator Experiment to Study Muon Beam Cooling Techniques for Muon Colliders, Neutrino Factories, and Stopping Muon Beams

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1 Executive Summary

The Muon Collider and Neutrino Factory Ionization Cooling Experiment (MANX) is proposed to test the theory of ionization cooling in a helical cooling channel (HCC), to demonstrate an example useful for stopping muon beams, and to verify simulations of a 6-D ionization cooling configuration. A helical solenoid (HS) magnet will be constructed and installed at the Rutherford-Appleton Laboratory (RAL) as a continuation of the current international Muon Ionization Cooling Experiment (MICE) program.

Because of its potential importance to Fermilab for muon cooling applications, including muon colliders, neutrino factories, and stopping muon beams, it is proposed that MANX be organized as a joint Fermilab-RAL project, where Fermilab is responsible for the magnet and detector upgrades and RAL provides the MICE beam line, where much of the MICE apparatus can be reused.

MANX will test the HCC concept in its momentum-dependent incarnation, where a muon beam will lose about half of its energy in a continuous absorber, the HS field strength will scale with the muon momentum, and no RF energy replacement is required. This approach has advantages in that the experiment will be less expensive and more timely for not needing about 150 MeV of RF and in that there is a proposed upgrade to the mu2e experiment for the Project-X era that could use the same HS magnet.

The momentum-independent incarnation of the HCC, where RF is used to keep the momentum nearly constant, is not tested directly in this version of MANX. However, the theory of the HCC, the technology of the HS, and simulations that involve 150 MeV of absorber will be tested to give confidence that the effectiveness of new muon cooling techniques, especially for collider use, can be accurately predicted. MANX is an appropriate $10M intermediate step toward a $100M useful muon cooling channel.

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2 Introduction and Motivation

MANX is an experiment to test the theory [1], an implementation example [2], and numerical modeling [3] of a helical cooling channel (HCC), which has several potential applications for the capture, ionization cooling, and manipulation of large-emittance muon beams.

The HCC theory, inspired by the Siberian Snake [4], combines a solenoid field with helical dipole and helical quadrupole field components to provide a large acceptance channel with nearly homogeneous fields. The field uniformity in a long cooling channel is particularly advantageous because the very large emittances of muon beams generate large resonance driving terms that can interact with periodic magnetic variations.

Emittance exchange in a HCC, which is required to achieve 6-dimensional cooling, can be achieved using wedge absorbers and/or a continuous homogeneous absorber. MANX also tests this newer method, where dispersion-generated path length dependence on momentum provides the required correlation between momentum and energy loss.

There are two versions of the HCC that have applications to cooling of muon beams – 1) momentum dependent, where the magnet field strengths scale with diminishing muon momentum as energy is lost in an absorber and 2) momentum or z-independent, where energy lost in the absorber is almost constantly replenished by RF cavities so that the magnet strengths are constant.

MANX will test the HCC concept in its momentum-dependent version, where a muon beam will lose about half of its energy in a continuous absorber, the HS field strength will scale with the muon momentum, and no RF energy replacement is required. This approach has advantages in that the experiment will be less expensive and more timely for not needing about 150 MeV of RF and in that there is a proposed upgrade to the mu2e experiment for the Project-X era that could use the same HS magnet.

The momentum-independent version of the HCC, where RF is used to keep the momentum nearly constant, is not tested directly in this version of MANX. However, the theory of the HCC, the technology of the HS, and simulations that involve about 150 MeV of absorber will be tested to give confidence that the effectiveness of new muon cooling techniques, especially for collider use, can be accurately predicted.

Both versions have applications to muon colliders and neutrino factories. Momentum-dependent cooling channels like MANX can be used for a pre-cooler, as discussed later, in which the initial muon beam energy is higher than required for subsequent coolers. The emergent energy is reduced to a value that is low enough for the next stage. The most efficient method for the next stage and six orders of magnitude of 6d cooling is with a momentum independent channel with high pressure RF acting as the continuous energy absorber, energy replacer, and breakdown suppressor. However, if for some reason the pressurized RF cavities do not work as hoped, a MANX-like approach is another possibility, where momentum-dependent HCC segments are alternated with linac sections. A momentum-dependent cooling channel can also be used as a final cooling section to take advantage of very high fields made available by the latest generation of superconductors [5]. A momentum dependent channel can also be used to increase the intensity of stopping muon beams and can be important for the mu2e experiment upgrade for the Project-X era at Fermilab. The MANX HS magnet is very similar to the one that has been used for simulations of this mu2e improvement concept [6].

The possibility to have MANX sited at RAL as part of the MICE program [7] is very attractive with potential improvements to each experiment. The RAL infrastructure and MICE developments can expedite MANX in many ways. MANX can benefit by gaining a well understood beam line, detectors and single particle measurement/reconstruction techniques along with the expertise and experience of a talented and dedicated group of scientists. MICE should also gain by having more access to participation from a larger part of the physics and accelerator communities who have an interest in muon beams for muon colliders and stopping muon beams. Single particle measurement techniques such as used in MICE and MANX are based more on high energy physics experience than traditional accelerator experiments and so offer opportunities for particle physics experimenters to contribute.

Some of the differences and their consequences between the two experiments are discussed in later sections of this proposal. For example, going from 4d to 6d cooling implies greater required precision on longitudinal momentum measurements. This is discussed later in the section on time of flight counters with improved resolution. The total momentum precision is also relevant because MANX does not use RF cavities to replenish lost energy and will rely on measurement of invariant emittance to characterize cooling. Another important difference is that MANX will have considerably more absorber than MICE and a correspondingly larger cooling signal, even though in its initial configuration it will use liquid helium as an absorber instead of hydrogen as used by MICE.

Several simulation efforts [8] have confirmed the utility of the HCC approach to six-dimensional cooling of the muon beams. These simulations have involved the use of pressurized RF cavities that continuously replace the energy lost in the ionization cooling process. The ultimate HCC will involve new technologies now under development, namely high-pressure RF cavities and high-temperature superconductor used to produce very high magnetic fields at low temperature. However, we believe that a strong case has already been made that the HCC will be an essential component of any future muon cooling effort and that an experimental demonstration of 6D cooling using a HCC with a continuous absorber is the next logical step.

The MANX experiment being proposed is to make a HCC without RF to measure the reduction of the 6D invariant beam phase space in a HCC filled with a continuous liquid helium absorber. Without RF cavities or the high-pressure hydrogen gas that would normally fill them, MANX is a simpler experiment that can be done relatively quickly and inexpensively. In parallel to the MANX program, we are supporting an effort to incorporate RF cavities into HCC designs for cooling channels where the muon beam momentum is almost constant, and we have an active R&D program for high pressure gas-filled RF cavities. A summary of activities related to this proposal is included as Appendix A of this document

One plan is to build the HCC and new detectors at Fermilab and then transport them to Rutherford Appleton Laboratory in the UK, where they would be employed in the existing MICE beam as a later phase of the MICE experiment. By using the MICE beam line and spectrometer elements the cost and time to prepare the experiment will be reduced. We have already received technical support from Fermilab in developing the 4-coil model of the HS and we are seeking approval of this proposal to build a longer version at Fermilab for the MANX experiment.

A Letter of Intent was submitted to the Fermilab AAC in May, 2006 for a six-dimensional muon cooling experiment, and an Updated Letter of Intent was subsequently submitted in July, 2007. The development of the MANX concept has largely been funded through SBIR and STTR [9] awards by Muons, Inc. with Fermilab as a research partner. At present there is funding to complete another year of work on the MANX proposal. In addition, Muons, Inc. has received another $650,000 for the next two years to study ways to upgrade the mu2e experiment to take advantage of a larger proton flux that the Project-X would enable. This program is based on the use of a HCC magnet that is effectively the same as the MANX magnet.

Working under the Phase I MANX STTR grant and the Phase II funding of another grant with the Fermilab Technical Division, a very novel and strikingly simple design for a momentum-dependent HCC magnet was invented, based on a helical solenoid (HS). A paper comparing the new design with the conventional approach to such a magnet was presented at the 2006 Applied Superconductivity Conference [10].

This new HS design based on displaced coils also works well for the original HCC concept, where RF imbedded in the HCC keeps the beam energy relatively constant. Engineering studies are now underway to investigate how to feed the RF wave guides through the HCC coils. Subsequent work on this novel magnet design and additional advances on the MANX matching magnets and the incorporation of RF cavities in the design was reported at PAC07 [11]. A scheme to match the optics of upstream and downstream spectrometers to the HCC optics was also developed and reported at PAC07 [12].

Significant progress has been made recently in the development of HCC schemes.

- The high-pressure RF cavity experiment had good results, showing no maximum gradient degradation even in a strong magnetic field [13]. Recent calculations and simulations indicate that dense muon beams in a gaseous hydrogen cooling channel may require techniques to remove the electrons produced by ionization. First tests of the use of electron absorbing dopants in hydrogen gas have been made [14].
- The MuCool Test Area (MTA) beam line that will allow radiation testing of the high-pressure RF cavity has been funded and is expected to be installed by the end of 2008 and operational in the first quarter of 2009.
- The design of a series of HCC segments has been improved to operate with less stringent requirements on the magnetic and RF fields
- A new use of a HCC (which is very similar to the MANX design itself) is being developed to enhance the stopping beam for a muon to electron conversion experiment [15].
- Another new use of a HCC involves superimposing two periods to develop a varying dispersion function that is appropriate for extreme cooling schemes like Parametric-resonance Ionization Cooling (PIC) and Reverse Emittance Exchange (REMEX) [16].
- To address a major challenge to fit RF cavities inside the HCC magnets, an innovation of a dielectric loaded pillbox that reduces the physical dimensions of RF cavities, while maintaining RF properties of a larger cavity has recently been developed by a Fermilab-Muons, Inc. team [17].

3 Helical Cooling Channel

3.1 Principle of a Helical Cooling Channel

3.1.1 Motion in a Helical Cooling Channel

The motion of particles in a helical cooling channel is illustrated in Figure 1. 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 solenoid 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 solenoid 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 [1].

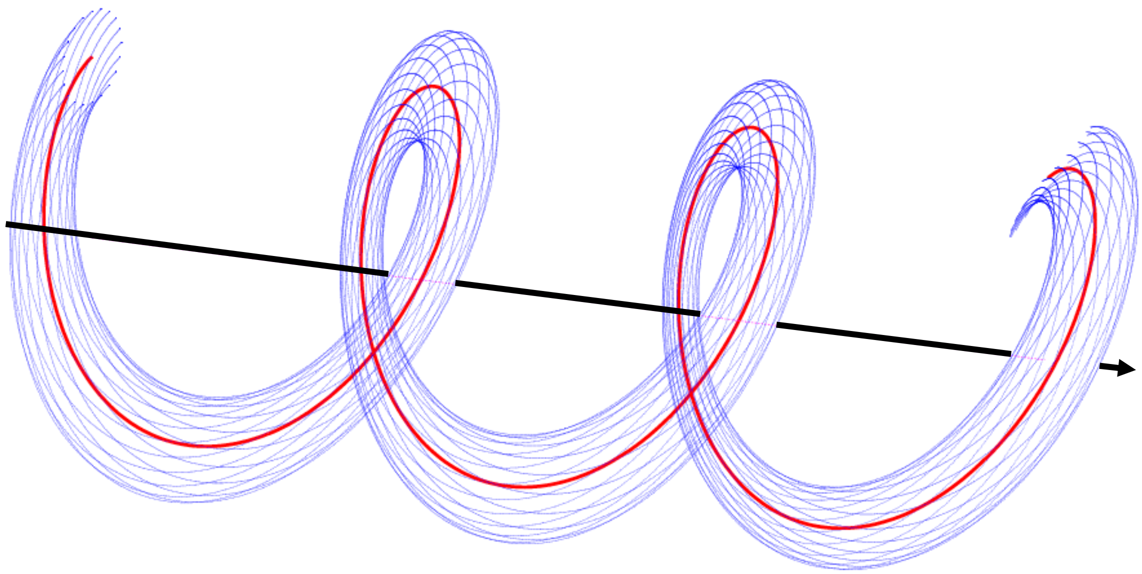

Figure 1 *Illustration of motion of the beam about the z-axis (black), which coincides with the solenoid center. For a given momentum, muons (blue) oscillate about the periodic equilibrium orbit (red). This view in perspective shows 20 muons as they oscillate about the equilibrium orbit for three helix periods.*

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. In continuous energy loss channels the strength of the solenoid field decreases along the length of the channel such that the radius of the equilibrium orbit remains constant. In energy replacement channels, RF cavities 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, including explicit expressions for cooling decrements and equilibrium emittances.

Some of the actual theoretical development of this cooling channel was worked out some years ago by Derbenev [18]. In that work, the absorber was seen as composed of a homogeneous part and a part with a density gradient. Since the thinking at the time was that the wedge absorber scheme shown in Figure 2(a) should be dominant, especially in that discrete absorbers were always envisioned, the contributions from the homogeneous absorber were not considered as significant. The ideas and mathematical descriptions become more transparent in the case of a continuous homogeneous absorber. Much of the conceptual simplicity is lost in the case of discrete absorbers that must be carefully placed between magnetic coils and between RF cavities.

For a given beam momentum, one can vary the solenoid field and the strength and period of the helical dipole field. (The hydrogen gas energy-absorber density is also a free parameter provided the density is sufficient to suppress RF breakdown at the required level.) The helical field that must be superimposed on the solenoid field must have a quadrupole component in addition to the dipole component in order to give the beam additional stability. This component could be added with "$\cos 2\theta$" quadrupole magnets having the same twist period as, and superimposed on, the helical dipole coils. Or, as we have learned in the last year, all three components can be provided by a helical solenoid magnet.

It is important to note that the direction of the solenoid field does not change in the cooling channel described below. This is an essential difference between the helical dipole method and the solenoid schemes with alternating field directions that have been envisioned up to now. This may also be some technical advantage to the extent that the large magnetic forces on the superconducting coils at the field reversal regions can be eliminated. Although a discussion of technical issues should follow the complete analysis of beam dynamics and cooling, we note that the use of continuous (or long) solenoids inherent in the helical concept should allow a higher maximum effective longitudinal field than that of schemes with alternating solenoid field directions. Consequently, the helical scheme will achieve a smaller equilibrium emittance, faster cooling rate, and decreased particle loss from decay.

A 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 a HCC filled with liquid helium, without RF, is suitable for studying emittance exchange and reduction, and measurement of transmission and losses in the HCC, particularly in the regions at the limits of the acceptance of the HCC.

Parametric-resonance Ionization Cooling and Reverse Emittance Exchange [19], new techniques for muon beams to get transverse emittances that are as small as those used in proton-antiproton colliders, are being investigated. In these schemes, a linear channel of dipoles and quadrupole or solenoid 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 with respect to the MANX 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 [20].

3.1.2 Continuous, Homogeneous Absorber in a Dispersive Magnetic Field

Figure 2(a) is a conceptual picture of the usual mechanism for reducing the energy spread in a muon beam. The dispersion of the beam generated by the dipole magnet in Figure 2(a) creates an energy-position correlation at a wedge-shaped absorber. Higher energy particles pass through thicker parts of the absorber and so have more energy loss than particles of less energy. After the absorber the beam becomes more mono-energetic.

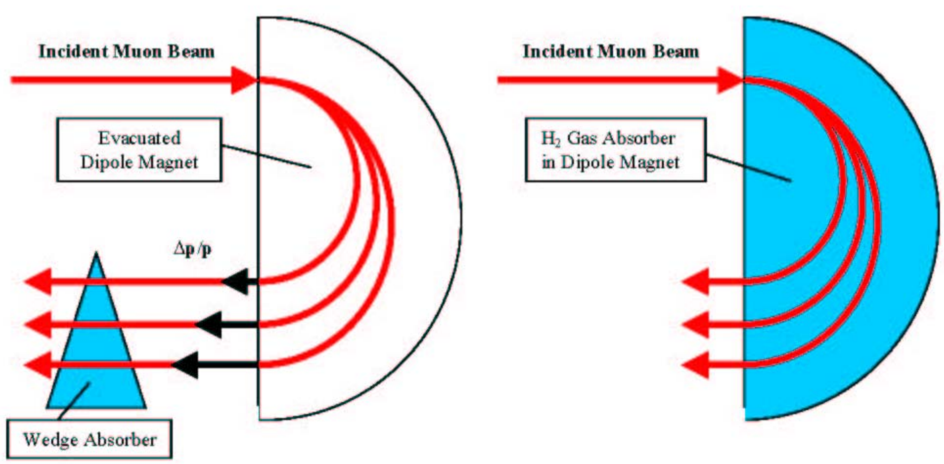

Figure 2 a) Wedge Absorber Technique b) Homogeneous Absorber Technique.

This process is called emittance exchange, because the transverse emittance must grow to allow the longitudinal emittance to be reduced. In Figure 2(a), the beam is in vacuum except in the wedge absorber. The process is limited by multiple scattering in the absorber and the high-Z windows that isolate the evacuated magnetic field region and the absorbers. For energy replacement type schemes, RF cavities, also in vacuum, replace the energy lost in the absorber.

In previous cooling plans, both the emittance exchange process and the transverse ionization beam cooling processes have been implemented by sequentially alternating absorbers and evacuated RF cavities.

The principle of emittance exchange by a continuous absorber in a dispersive magnetic field is shown in Figure 2(b). In this case the energy loss depends on the dE/dx of the continuous absorber, where the longer path length of the higher momentum particles results in a greater energy loss than the shorter trajectories of the lower momentum particles. Thus the continuous absorber performs the same function as the wedge in Figure 2(a). The same concept applies to pressurized RF cavities in which (hydrogen) gas filling the cavity acts both as the energy absorber for ionization cooling and as a breakdown suppressor to allow higher accelerating gradients.

3.1.3 Characterization of a Momentum-Dependent Cooling Channel

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 an equilibrium orbit at a given radius, a, and magnetic field parameters is derived in reference [1], above:

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

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.

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 coordinates and the longitudinal one:

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

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:

$$\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2} \text{ and } q = 0 .$$

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 variations on the original HCC concept 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. This device is discussed in the next section.

2) A device similar to a pre-cooler, but used as a full 6-dimensional muon cooling demonstration experiment (this MANX 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.

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.

5) A means to increase the rate of stopping muons for the Mu2e experiment.

6) A pion decay/muon capture channel. The HCC can be looked at as comparable to a synchrotron in that it has an effective gamma-t such that a momentum compaction factor is one of its characteristics. Studies that have just begun are aimed at taking advantage of this to limit the time spread of the muons at the end of a decay channel to improve the capture rate for muons that can be eventually gathered into a single bunch for a muon collider.

7) A new invention is being developed as a channel for extreme muon cooling in which a HCC is used with two superimposed periodicities. By using two periods, the dispersion function can be made to change as a function of z such that the dispersion can be small at positions of the wedge absorbers needed for PIC or REMEX yet large where sextupole fields can be added for chromaticity correction.

3.1.4 HCC Pre-Cooler Simulation Example

Figure 3 shows the G4Beamline simulation of a combination vacuum decay section (40 m) and pre-cooler (5 m) HCC section. 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 pre-cooler has been avoided. Simulation studies of various pre-cooler dimensions and magnet strengths have been done. Figure 4 shows an expanded view of the upstream end of the decay channel, and Figure 5 shows an expanded view of the pre-cooler. One can see that there are predominantly pions entering the decay channel and muons exiting the decay channel.

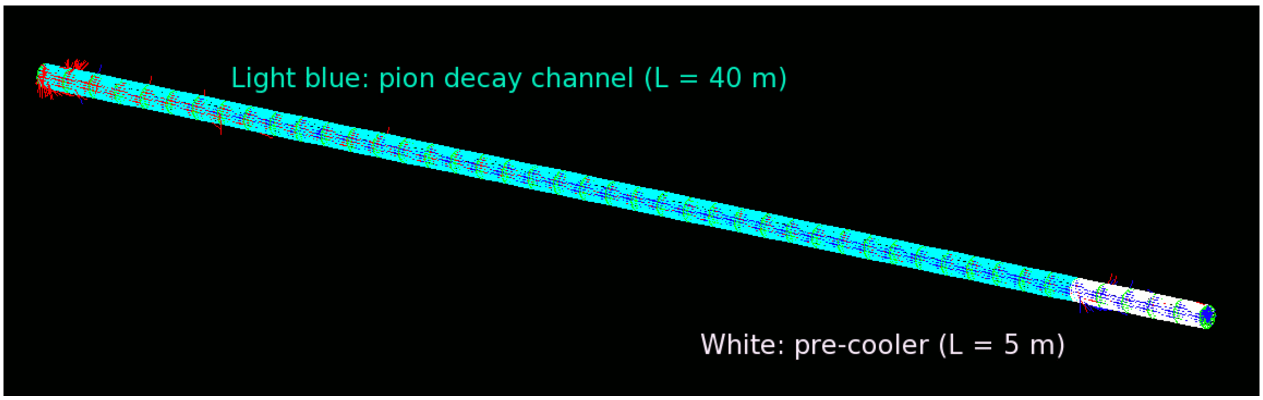

Figure 1 *G4Beamline display of a 40 m pion decay channel (light blue) followed by a 5 m pre-cooling HCC (white). The red and blue lines show the pion and muon trajectories, respectively.*

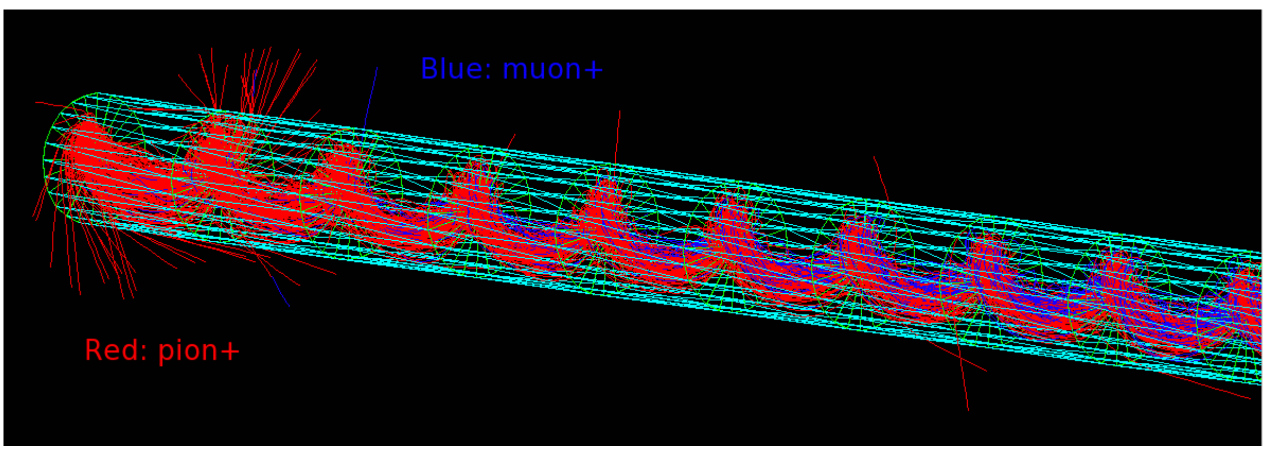

Figure 2 *Detail of beginning of decay channel, pions are shown in red, muons in blue*

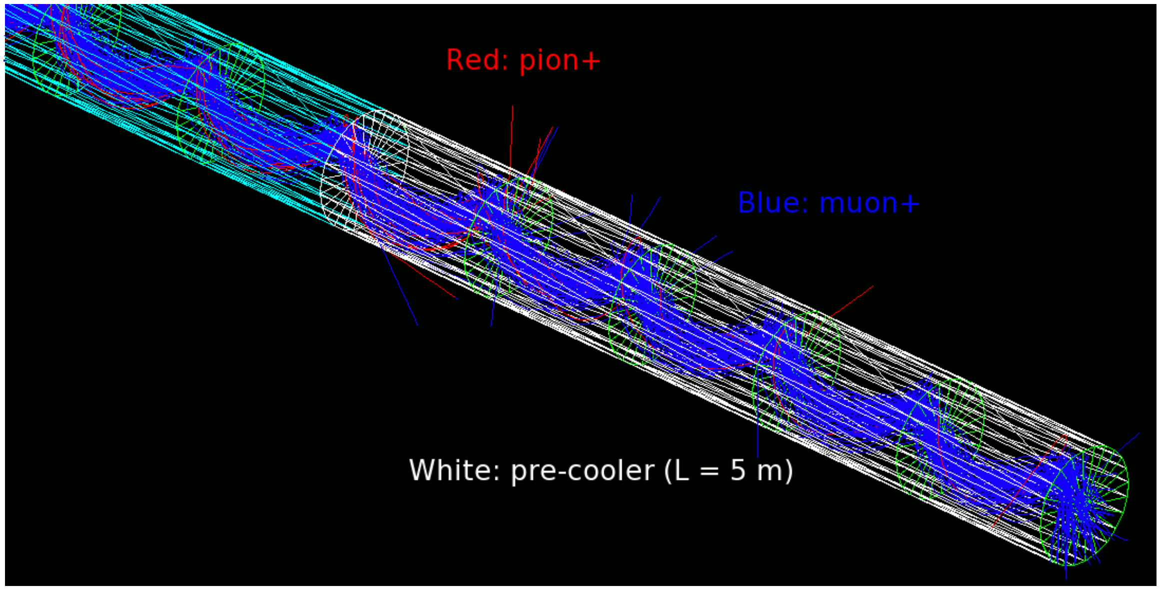

Figure 3 *Details of trajectories in a pre-cooler. The helix period is 1 meter.*

Figure 6 shows the normalized average emittance evolution of a muon beam produced by a decay channel as in Figure 5 as a function of the distance down a 6 m long HCC pre-cooler that is filled with liquid hydrogen or liquid helium and the effects of the aluminum containment windows. 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 above the equilibrium emittances the cooling with liquid helium absorber is almost as good as with liquid hydrogen and the aluminum windows do not significantly degrade the cooling.

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 pre-cooler design are negligible in their heating effect compared to the length of the liquid absorber. This pre-cooling 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 pre-cooler prototype.

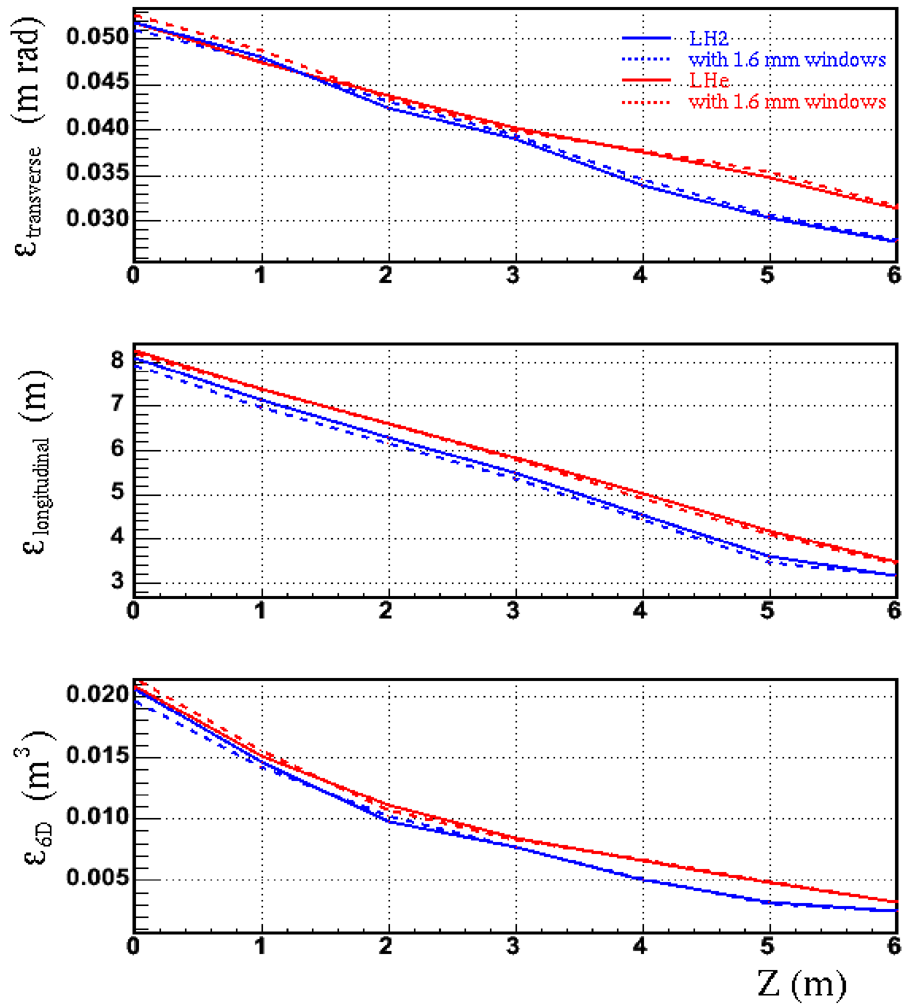

Figure 4 *Simulations showing normalized emittance evolution for particles that survive to 6 m for a HCC pre-cooler filled with liquid hydrogen (blue) or liquid helium (red), with (dashed) and without (solid) 1.6 mm thick aluminum windows on each end.*

The reduced cooling factors of MANX designs discussed later relative to this pre-cooling example reflect compromises in parameters such as initial momentum and length of the HCC and also less than perfect emittance matching.

3.2 Emittance Reduction and Matching with the MANX HCC

Typically, helical multipole fields that are used as Siberian Snake magnets for spin manipulation have fields that vary with the imaginary Bessel function $I_n(nkr)$. This function grows exponentially at moderately large radius. For the relatively modest field requirements on the HCC orbit, the field at the multipole coils would not be easily realized. A new magnetic coil arrangement, with only one quarter the field volume of the original HCC concept, has been invented, which is practical and designed to be readily built. This design can be applied to all HCC types, including MANX with its z-dependent field strengths. The simple scheme shown in Figure 7 is sufficient to create the three essential HCC magnetic field components: solenoid, helical dipole (as in the Siberian Snake), and helical quadrupole. (Although we have added a helical sextupole in some of the simulations, the sextupole typically improves the acceptance by only 10% and is not needed for MANX.) The fields at the coils for this new arrangement are modestly higher than that seen at the reference orbit, making this helical solenoid feasible to implement.

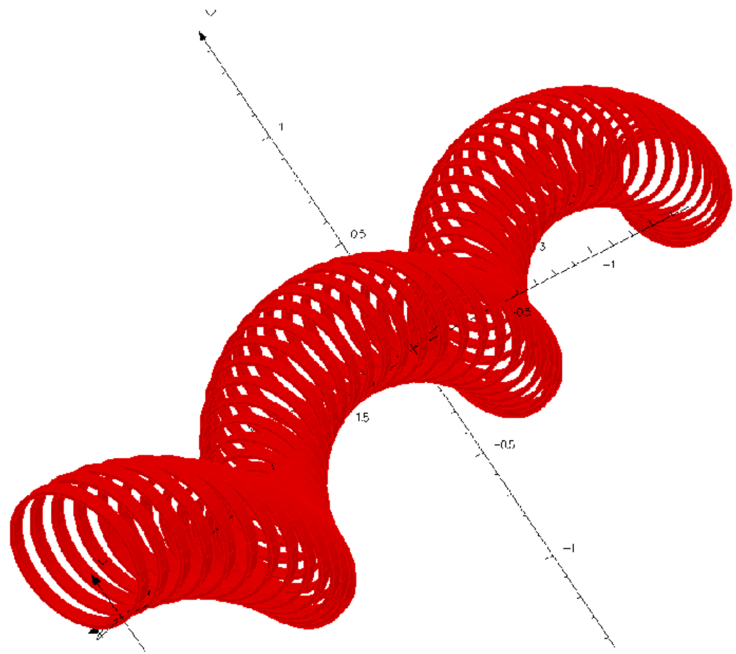

Figure 5 *Conceptual picture of a HCC segment using the helical solenoid, which provides solenoid, helical dipole, and helical quadrupole fields. Although at first glance it looks like a child's "slinky" toy, the coils are independent rings. For the MANX simulation shown in the next figures below, each ring diameter is 0.5 m and ~60 coils are used for the 3.2 m long HCC.*

3.2.1 Emittance Matching to the Helical Solenoid

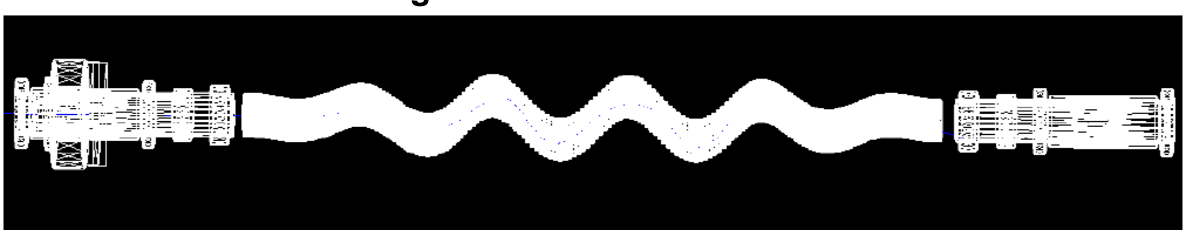

Figure 6 *G4beamline representation of MANX HCC with 1.5 period long matching sections positioned between the MICE spectrometers*

We are studying the matching of the MANX HCC to the existing MICE spectrometers. The most effective scheme to match the optics of the MANX HCC to MICE spectrometers is shown in Figure 8. This figure shows a 1.5 period long matching section before and after the 2 period long HCC. In the matching regions, the radial displacement from the solenoid axis of each coil is varied linearly between the HCC and the start or end of the matching section while keeping the same helix wave number. This causes the helical dipole field to increase linearly from zero to that of the HCC in the upstream matching section and decrease to zero in the downstream section. The field profiles for the combined matching and HCC section from one of the studies is shown in Figure 9. The 6D cooling performance for this configuration is shown in Figure 10, which results in a reduction in emittance by factor of two. This factor is less than the factor of 8.3 for the hydrogen-filled or 6.5 of the helium-filled pre-cooling examples discussed above which have perfect matching since they follow a HCC decay section. The 6D cooling factor shown below is also less than the 3.7 of earlier studies because the length of the HCC has been reduced to fit in a smaller space and the matching is not completely optimized.

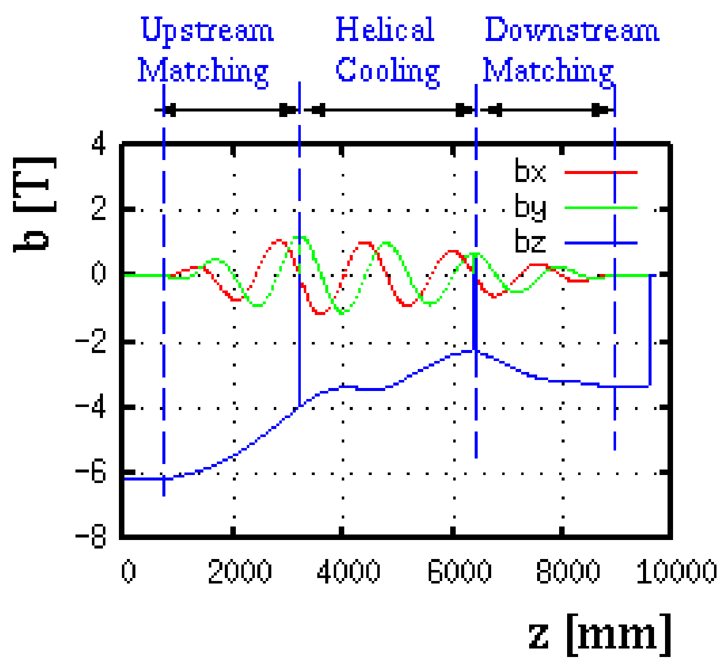

Figure 7 *Field strength components along the reference orbit used in MANX cooling simulations.*

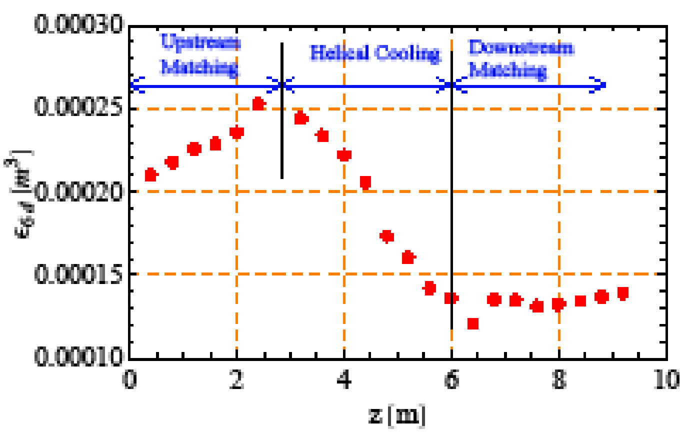

Figure 8 *Emittance evolution in the MANX emittance matching and cooling sections as simulated in G4Beamline.*

Alternative matching designs under study Although this matching scheme with a 1.5 period long phased-in helical channel is effective, it requires an additional 150% increase in the number of solenoid rings and infrastructure to mount them. There are two additional matching approaches that are currently being pursued as less expensive alternatives: The first is not to match at all and orient the HCC channel so the beam from the MICE solenoids goes into the HCC at the 45º offset reference orbit. This configuration is shown in Figure 11. There are no losses upon entering the HCC from the upstream spectrometer since the acceptance of the HCC is 50% larger than the MICE spectrometer. There are significant losses upon exit from the HCC into the downstream spectrometer. The design is currently being optimized to reduce these losses. The second approach is to have a short 0.5 period matching section upstream and downstream of the HCC instead of the previously described 1.5 period matching section. This configuration shows no losses entering the HCC from the upstream spectrometer and loses only ~5% exit the HCC downstream. The latter may be a promising compromise with acceptable losses. Another possible alternative is to eliminate the upstream matching section and to employ a matching section at the downstream interface. These possible configurations are under study at this time.

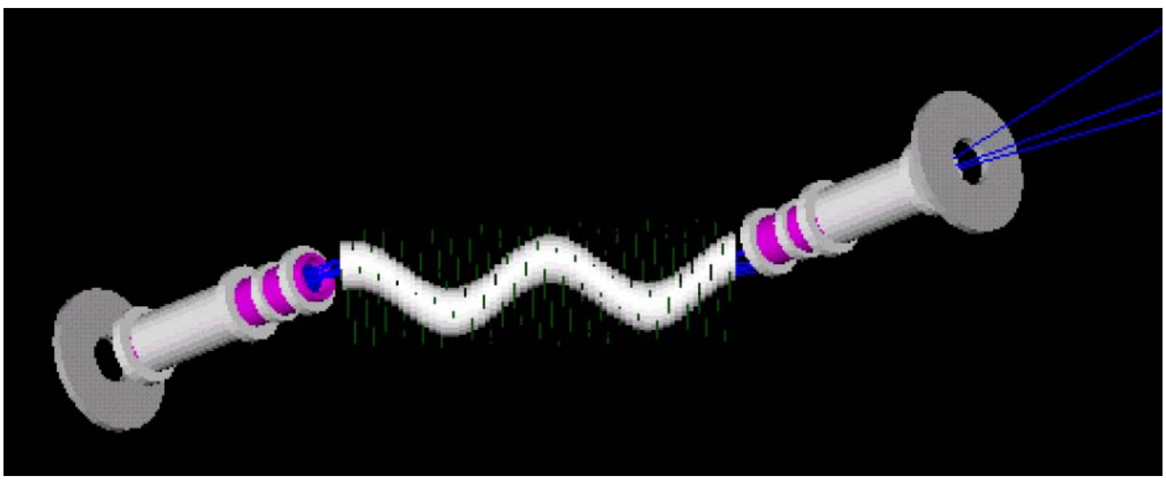

Figure 9 *A G4beamline representation of the off-axis matching configuration where the HCC is placed at a 45º orientation to the MICE spectrometer so that the beam is oriented along the reference path at entrance into the HCC.*

4 Experimental Method

MANX uses the same experimental method as MICE in that tracks are measured and emittances are reconstructed from ensembles of tracks. Much of the reconstruction and analysis software as well as the MICE spectrometers and other hardware can be used for MANX. The main differences between the two experiments are that MANX requires more precise measurement of the longitudinal momentum to determine the 6-d emittance and also desires measurement of the trajectories between the spectrometers to test the theory of the HCC and to understand losses. Also the initial beam momentum and energy loss in the channel are greater for MANX.

Studies of event reconstruction, selection and analysis strategies are in progress. We expect to benefit greatly from the experience that is acquired throughout the MICE phases, and we look forward to joining forces with the MICE collaboration to eliminate as much redundant effort as possible in analyzing the MANX data.

By measuring trajectories inside the HCC we will be able to reconstruct the emittance at a number of positions inside the HCC, and therefore be able to observe the evolution of the emittance reduction, and not just the overall emittance reduction. With a long cooling channel such as the HCC, there should be significant reductions of emittance at intermediate positions within the HCC. Studies have shown that the phase space projections evolve in shape as well as in size along the helical channel. It will be an important result to show that the evolution of the phase space patterns can be understood within the context of the Derbenev-Johnson theory.

As described in the following sections we plan to use state-of-the-art fast timing techniques to determine the longitudinal component of the momentum. Detectors inside the HCC also present technical challenges. We are considering two approaches – both using planes of scintillating fibers similar to those used for MICE. In one approach we would connect the scintillating fibers to clear fibers and bring the clear fibers out of the HCC to photon detectors, much as is done in MICE. The other approach is to interface SiPMs or other solid state photon counters directly to the scintillating fibers and possibly the readout electronics and bring electrical signals out of the HCC.

4.1 Definition of Baseline Configuration

The baseline configuration for MANX consists of all the elements of the MICE spectrometer reused, with the HCC replacing the cooling H_2 absorbers and RF sections of the MICE layout. In addition, the downstream spectrometer elements are moved further downstream to accommodate the longer length of the HCC, with its matching sections. We shall examine the individual elements of the MICE beam line and detectors to identify those elements that must be replaced or modified to meet the specific requirements of MANX. The baseline configuration includes matching sections upstream and downstream of the HCC. Another configuration, without matching sections (the off-axis configuration), is being studied with G4beamline simulations. The possible installation of the configurations is described in section 8.2.

4.1.1 Conceptual View of Experiment Components

A generic diagram of the MANX experiment is shown in Figure 12. An incident beam of muons with momentum around 350 MeV/c passes through an upstream spectrometer where the trajectory, time, and momentum of each particle are measured. A matching section, which may 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 ~200 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.

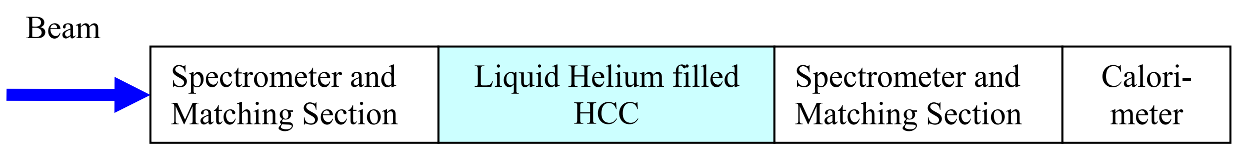

Figure 10 *Generic diagram of the MANX experiment*

The baseline spectrometer is based on solenoid geometry as is done in MICE. The matching sections then are designed for the MICE spectrometer type.

A more detailed diagram of the beam and spectrometer at RAL is shown in Figure 13.

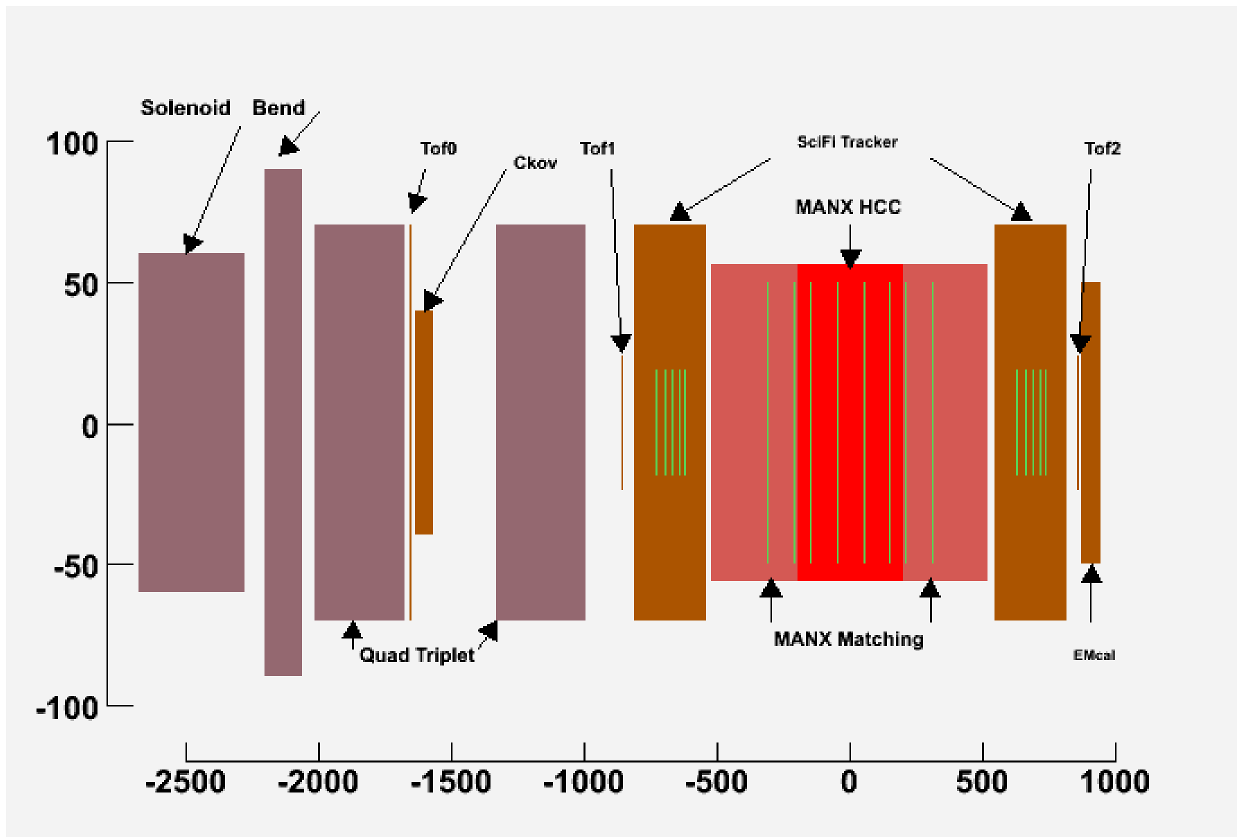

Figure 11 *Sketch of RAL MICE muon beam line elements (violet) with MANX LHe-filled helical cooling channel (red) and evacuated matching sections (salmon) positioned between MICE spectrometers (brown). The decay solenoid is at the left. The dimensions are in cm.*

The solenoid shown at the left is the decay solenoid, where pions decay into muons. (The upstream part of the beam from the internal target in the ISIS machine to the decay solenoid is not shown in the Figure 13.) The beam of muons then passes through a bending magnet for momentum analysis and two quadrupole triplets for focusing and beam shaping. Muon identification and rejection of pions and electrons in the beam is accomplished by the Cerenkov counter and a pair of time-of flight counters (TOF0 and TOF1).

4.2 Differences between MANX and MICE

The following is a list of differences between MANX and MICE. Details are provided in sections below.

- The incident muon beam momentum is higher: 350MeV/c vs 250 MeV/c in MICE. This impacts the beam tune, the muon rate, the pion to muon ratio, the identification of pions in the beam, and other areas. The higher momentum is required due to the amount of energy loss in the HCC.

- MANX requires a more precise longitudinal momentum resolution than in MICE. MANX is a 6D cooling experiment , whereas MICE is a 4D experiment, so MANX needs to measure the longitudinal emittance in addition to the transverse emittance. One approach is to determine the longitudinal momentum by means of improved time-of- flight measurements.
- The MICE Cherenkov counters are designed for 250 MeV/c. For MANX the Cherenkov counters must be able to identify muons and reject beam pions and electrons at 350 MeV/c.
- MANX requires the measurement of the emittance at a number of positions within the cooling channel. To be able to test the theory of cooling in the HCC it is important to measure the particle trajectories inside the HCC. It will also aid in identifying trajectories that are near the outer boundaries of the channel.
- There may be differences in triggering and/or DAQ.
- The MICE layout must be reconfigured to accommodate the MANX HCC and possibly MANX-specific detectors (and matching sections). In the MANX configuration in which matching sections are used, the MICE cooling and RF elements are removed and the downstream spectrometer and associated detectors are moved downstream to make room for the MANX HCC and matching sections. In the MANX "off-axis" configuration in which the matching sections are not present the downstream MICE elements must also be moved transversely.

We are currently reviewing and evaluating the MICE detectors in relation to the needs of the MANX experiment to determine which MICE elements need to be modified or replaced, and new detectors that are needed. The following sections treat specific technical areas that we have identified.

4.2.1 Beam Composition and Rates at 350MeV/c

The MICE beam line needs to be tuned for 350 MeV/c, the desired muon momentum. At this momentum the ratio of muons to pions is expected to be lower than at the MICE momentum of ~200-250 MeV/c. Work is in progress to calculate the beam characteristics at 350 MeV/c.

4.2.2 Improved Time-of-Flight Detectors

The time-of-flight counters in the MICE experiment, TOF0 and TOF1, have a time resolution of about 70 ps and are separated by 10 m. The resulting time-of–flight measurement is used for triggering on muons and rejection of pions in the beam, and for synchronizing with the RF phase, but is not precise enough to provide an accurate measurement of the longitudinal component of the momentum.

The momentum range of interest for MANX is from 150 to 350 MeV/c, where the dE/dx heating and the length of the cooling channel are acceptable. A sufficiently good velocity measurement could determine the momentum without the need for a magnetic spectrometer or it could aid the determination of total momentum for spectrometers designed to measure transverse momentum. For example, 3.8 ps (13.2ps) change in the transit time of a 300 MeV/c (150 MeV/c) muon between two detectors separated by 1 meter corresponds to a one percent momentum difference.

The MICE spectrometers are based on solenoid fields, which match a 4D experiment, where transverse momenta are measured well. However, MANX requires that longitudinal momenta also be well measured. Simulations using G4MICE modified for MANX are just starting, to see if the present MICE spectrometers will work for a 6D experiment.

An innovative approach to improve the MICE spectrometers for a 6D measurement is to add very fast timing counters to measure the muon velocity. The University of Chicago (UC) and Argonne National Laboratory (ANL) groups are developing Time of Flight (TOF) counters with the goal of resolution better than 1 ps based on micro-channel plates with innovative anodes and electronics. A resolution of 5 ps may be sufficient for the total momentum measurement for the momentum range in which we are interested.

There are two interesting aspects of this idea that make it attractive to us. First, the UC effort is in need of help to simulate these devices using Geant4, a particular strength of Muons, Inc. Second, the UC effort is looking for a meaningful intermediate-sized project to develop the techniques of ps-resolution timing. Their ultimate goal is to make the measurement of 4-vectors, rather than 3-vectors, standard in large collider detectors, such as a next-generation 'CDF-III' detector at Fermilab, an upgrade to Atlas at the LHC, or a detector like the 4th Detector at the ILC. While that goal may require tens of square meters of fast timing detectors, a MANX application at RAL might need only one square meter. In November, 2008, Muons, Inc. and UC submitted a proposal for funding for development of fast timing counters.

4.2.2.1 Basic Concept of the Fast Counters

The exciting aspects of these fast counters are based on some recent innovations:

- The invention of a new method of making micro-channel plates that promises to yield better resolution and be considerably less expensive than current techniques.
- The ability to develop high-speed ASICs containing multiple channels of 40 GHz analog waveform sampling using switched capacitor arrays, thus greatly reducing electronics cost, power, and size.
- Simulations and tests of a strip-line readout that indicate an entire row of pixels can be read out with just two channels of electronics – this is a well-known technique, but applying it with bandwidths well in excess of 1 GHz is new, and permits a great reduction in electronics channel count, cost, complexity, and power.

The basic concept is shown in Figure 14.

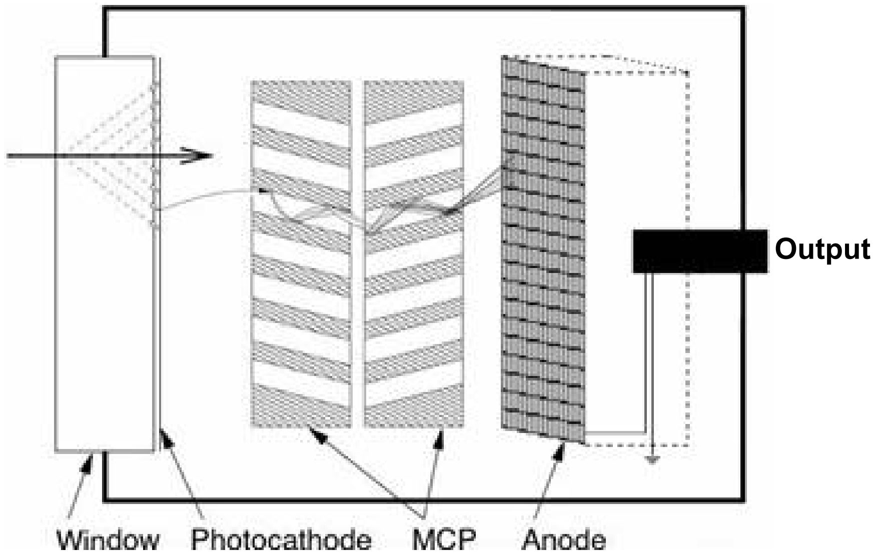

Figure 12 *Cross-section of the fast timing detector. A relativistic charged particle produces Cherenkov radiation in the window. This radiation is converted into electrons by a photocathode at negative voltage. The electrons are accelerated into and produce a shower in the micro-channel plates (MCP), and the shower is deposited on the segmented anode to be detected. Naturally this device is sensitive to photons as well (no Cherenkov radiator is needed); for high-energy photons a converter in front of the radiator can be used. Not shown: the anode has equal-time connections from each segment (pixel) to a transmission line, which has waveform-sampling channels on each end, giving both time and space positions. The drawing is not to scale.*

The entire package shown in Figure 14 is about 1 cm thick (along the particle axis, left-to-right in the figure), and the integrated-circuit readout electronics is mounted immediately behind it. By using modules formed of many internal multichannel plates made of anodic alumina functionalized with atomic layer deposition, this structure can be replicated to large areas with minimal dead zones at boundaries. The anode segmentation is determined by a printed-circuit pattern that is very flexible; the actual segmentation for a given application can be easily tailored to trade off requirements of cost, channel count, occupancy, and resolution. These planar detectors will be physically robust, which is important for commercial use, and will be able to withstand high pressures such as would be present in large water neutrino detectors. The detectors also do not need to be shielded or compensated for magnetic fields, a major advantage for many HEP applications and scanners for transportation security.

As the readout electronics is integrated with the detector module, the time resolution is not affected by the overall size of the detector – for each pixel the total signal path from the initial Cherenkov radiator to the readout transmission line is about 1 cm; the transmission line carries signals to waveform-sampling electronics on each of its ends. Detailed simulations give a signal band-width for a 2” transmission line (typical of a collider detector application) of 3.5 GHz; for a 48” module, the bandwidth drops to 1.1 GHz (still more than adequate for neutrino detectors and security scanners). Remembering that 1 ps corresponds to a distance of 0.3 mm at the speed of light, it is clear that achieving ps resolution in a detector requires constraining the variance in the path lengths of light, electrons, and signals to be much less than a millimeter within the detector. That is not possible for traditional phototubes, but the few-micron pores of a micro-channel plate can do so.

4.2.2.2 Initial Test Results

Several aspects of this basic design have already been validated. For instance, the intrinsic time resolution of the Cherenkov radiator is quite good, as shown in Figure 15. Currently available commercial multi-channel plates (MCP) have almost adequate resolution, shown in Figure 16. The new anodic-alumina MCPs improve this, and new experiments are underway. Figure 17 shows that standard CMOS electronics using pulse sampling should be adequate. Further tests and experiments are underway.

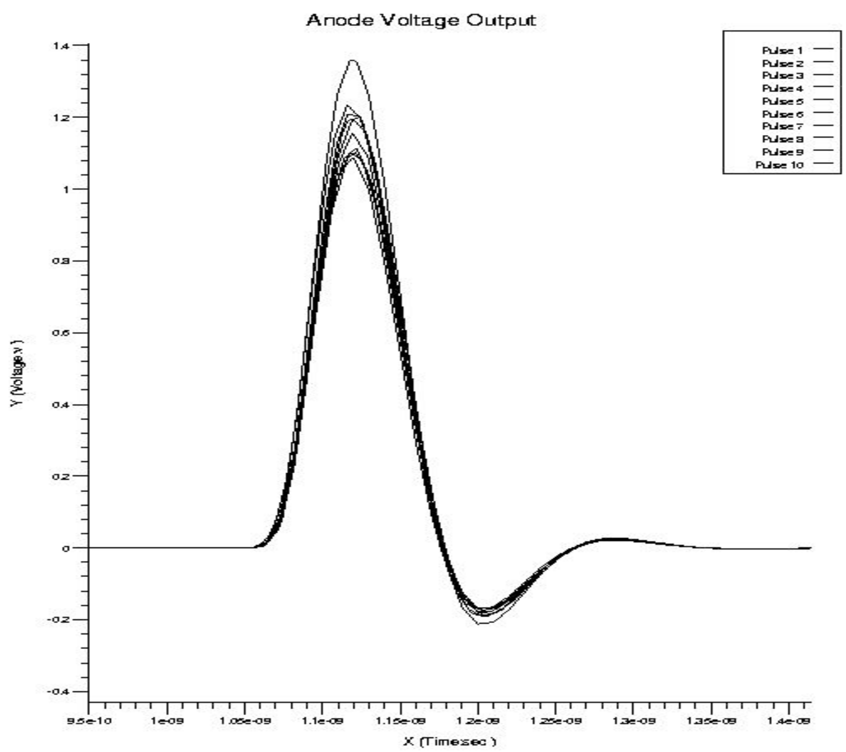

Figure 13 *Simulation of Cherenkov light from a quartz window. For these 10 particles the jitter on the leading edge is 0.86 ps [21].*

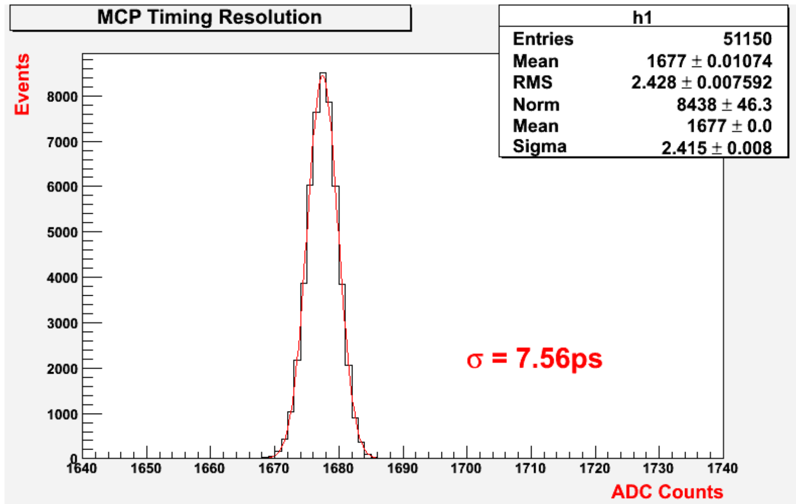

Figure 14 *Measurement of the time difference between two commercial MCPs with 25μm pores. Data are for a 408nm laser with ~50 photoelectrons, at the laser test stand at Argonne (Hamamatsu PLP-10 picosecond laser and a commercial CAMAC readout electronics system). The intrinsic jitter of the system is ~4ps and it has a resolution of 3.13ps [22]. The individual MCPs therefore have an intrinsic resolution about 4 ps.*

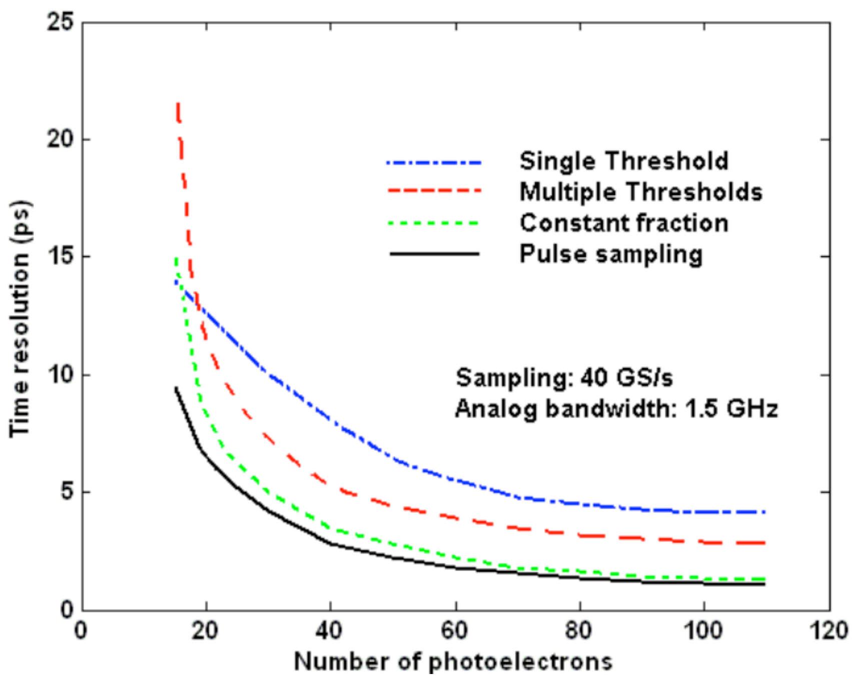

Figure 15 *Electronics simulation of a CMOS multi-channel readout using various techniques. The analog bandwidth is 1.5 GHz, and an 8-bit ADC sampling at 40 GHz is used for the pulse sampling [23].*

4.2.2.3 Diffuser and Time-of Flight Counter Placement and Precision

The current MICE experiment uses a Pb diffuser to increase the initial emittance sufficiently so that their anticipated 10% reduction in emittance by their cooling channels can be measured with sufficient precision. Their studies indicated that the optimal location for the diffuser is inside the bore of the upstream solenoidal spectrometer near the first tracking plane. In the MICE experiment the thickness of the Pb diffuser can be varied from 0 to 15mm to achieve the desired initial emittance, (from 2 to 10 mm-radians).

We have studied several possible arrangements of diffusers and time-of-flight counters to investigate the optimal placement of these elements. The time-of-flight (TOF) detectors introduce about 1 cm of quartz (SiO2) per detector plane, each about 8% of a radiation length. Pb diffusers of 5mm and 15mm introduce about 1 radiation length and 3 radiation lengths, respectively. For simplicity we have not considered placing the TOF counters inside the bore of the spectrometer solenoid. The following configurations have been simulated using G4beamline to study the effects of the stochastics of the energy loss and scattering processes on the precision of the time-of-flight measurement:

1. Two TOF counters, 1m apart, upstream of the spectrometer solenoid, Pb diffuser in the MICE position inside the upstream solenoid.
2. Two TOF counters, 1m apart, upstream of the spectrometer solenoid, Pb diffuser upstream of the first TOF counter
3. One TOF counter is placed upstream of the spectrometer solenoid, and one downstream of the solenoid. The Pb diffuser is placed just upstream of the first TOF counter.

In configuration #1 the scattering and straggling of the energy loss in the Pb diffuser alters the momentum in the spectrometer such that the rms variation of the expected momentum after the diffuser is much greater than the precision derived from the time of flight measurement (5 picoseconds). In effect the momentum measurement from the TOF counters is decoupled from the momentum after the diffuser.

In configuration #2 the energy loss in the diffuser takes place before the TOF counters and the spectrometer, so there is a good correlation between the TOF determination and the spectrometer determination of the momentum. The TOF measurement increases the precision of the longitudinal component of the momentum. However, moving the diffuser about 1.5 m upstream of the solenoidal spectrometer causes an unacceptable loss in acceptance. The scattered particles, particularly for the 15mm Pb diffuser, miss the aperture of the solenoid.

In configuration #3 the momentum loss takes place as in #2, and the Pb diffuser is closer to the solenoid, so that the losses are acceptable. Configuration #3 is the preferred configuration for the locations of the diffuser and the TOF counters.

4.2.3 Detector planes inside the HCC

Measuring space points along the particle trajectory inside the HCC is an important capability for the MANX demonstration experiment, even though an operational cooling channel would probably operate without detectors inside, to eliminate additional material in the liquid H or He.

4.2.3.1 Purpose of trackers inside the HCC

A record of space points along the trajectory enables study of the behavior of the particles as they lose momentum and scatter as they pass through the HCC. This helps test the underlying theory and the simulations. A further use of these measurements is to gain information about the trajectories of particles that do not make it all the way through the HCC to the external downstream spectrometer. Events can be taken with a trigger on particles that enter the HCC without requiring that the particle be within the acceptance of the downstream spectrometer. The HCC tracker gives information about the tracks that are lost in the HCC. Trajectories that are near the maximum radii are of particular interest for testing the theory. Having a record of the two transverse coordinates at several planes inside the HCC enables reconstruction of the “beam” profile along the HCC, which gives the ability to study the evolution of the shape of the muon distribution as the particles pass though the cooling channel. Additionally, trackers inside the HCC can be used as triggers, to enable selection of events that progress at least part way through the HCC. A variety of triggering modes can be implemented in the fast electronics. Furthermore, the interior tracking planes can be read out in an integrating mode to act as beam profile monitors inside of the HCC. In the early phases of the experiment it may be useful to operate the tracking planes in this mode, as diagnostics.

It is also possible to make a momentum determination of the particles inside the HCC. Although the particles lose momentum and scatter as they pass through the HCC, which makes momentum determination more complex, the upstream MICE solenoid spectrometer and time of flight yield the incoming momentum, and the downstream MICE spectrometer provides the outgoing momentum. With these constraints a fit can be made for the momentum at each of the intermediate measurement locations within the HCC. Inside the HCC there is a reference trajectory that remains a helix (ignoring scattering and straggling) about the HCC axis because the magnetic field decreases according to the energy loss. Particles with momenta higher and lower than the reference momentum have longer or shorter path lengths in the cooling medium, respectively, than the reference particles; however the tuning of the decreasing magnetic field is not as well matched to the energy loss. Thus, it is important to record space coordinates inside the HCC, to extract the best fit to the momenta inside, even with energy loss and a decreasing magnetic field in the HCC.

With the momentum vectors and space points at the measurement locations inside the HCC, the phase space distributions and the emittances can be computed at a number of planes inside the HCC. This information enables the study of the evolution of the emittance and the cooling function as the particles pass through the HCC.

The capability to measure the evolution of the emittance within the HCC is important in understanding the performance of the HCC.

4.2.3.2 Location of tracker stations inside the HCC

We propose to install 4 tracking stations inside the HCC, each consisting of 3 planes (u, v, and w), aligned at 120º angles, spaced at approximately equal intervals along the HCC axis.. We will undertake further simulation studies to determine if 3 coordinate planes are necessary in each station. In addition, we propose to install 2 tracker stations outside the HCC, one upstream and one downstream of the HCC. These would be useful to provide trajectory information in the regions in which the magnetic fringing fields are complex. From the standpoint of providing information along the trajectory, more tracking stations are better, but considering the amount of multiple scattering and energy loss straggling along the particles' trajectories, the gain may not be significant. For the MICE spectrometers the amount of material per station is 0.45% of a radiation length.

4.2.3.3 Type of trackers inside the HCC

Our baseline design is to use scintillating fiber trackers, similar to the ones used in MICE (and in the D0 Central Fiber Tracker). This will eliminate development time and reduce production costs. Each plane is designed to have a pair of scintillating fiber arrays, as shown in Figure18, to provide good efficiency with minimal amounts of material. The fibers are plastic, 0.35mm diameter, mounted 0.427 mm apart in double planes, and grouped in sets of seven fibers per clear fiber and one clear fiber per readout channel, as indicated in Figure 18. To completely cover a 50cm HCC inner diameter requires 306 channels, each 1.63mm wide each containing 7 fibers (2142 fibers total). Each 3-plane station requires 918 channels, or a total of 3672 channels inside the HCC.

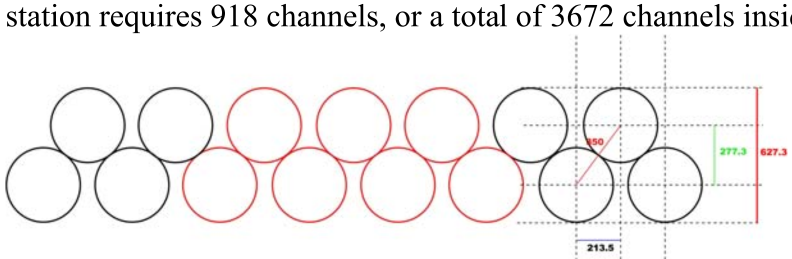

Figure 16 *Arrangement of scintillating fibers in a tracker station plane as used in the MICE trackers). The fiber diameter is 350 mm, 7 fibers/channel, 1.63 mm/chan, which gives a resolution of 0.47 mm per plane. The fibers amount to 0.45%* X_0 *per double plane.*

4.2.3.4 Methods to extract the tracker signals from the HCC

We are investigating a number of ways to bring out the signals from the fibers inside the HCC to be used in the data analysis, and possibly in the event trigger. The problem is more difficult than it is in MICE. In MICE the planes of fibers are in a straight-bore solenoid, so all planes are assembled as a single support structure, and the assembly is inserted into the bore of the solenoid. The HCC bore is helical, which makes insertion more difficult. Also the MICE solenoid bore is at room temperature, while the interior of the MANX HCC is filled with liquid helium. This means that the signals must be brought out through the cryostat wall. If the HCC cryostat is built as a closed and welded structure then the tracker planes and any associated elements will be required to be permanently built into the cryostat. The signals from the detector will need to be brought out by means of feed-throughs. These constraints lead us to consider two possible configurations for the installation of the planes.

4.2.3.5 Tracker units within bore

One design for bringing the tracker signals out of the HCC is to adopt a method similar to the MICE trackers that are inside of solenoid magnets, that is, to splice groups of 7 scintillating fibers to a single clear 1-mm fiber and run the clear fibers toward the upstream (and downstream ends of the HCC). The clear fibers are attached to multi-fiber feed-throughs (MICE has 192 fibers per feed-through) that bring the signals out of the HCC. We would bring the fibers from the two upstream stations in the HCC out of the upstream end of the HCC and similarly the fibers from the downstream two stations are brought out of the downstream end of the HCC, as shown in Figure 19. Separating the upstream pair from the downstream pair simplifies the installation of the detector planes and reduces the space required for the clear fibers.

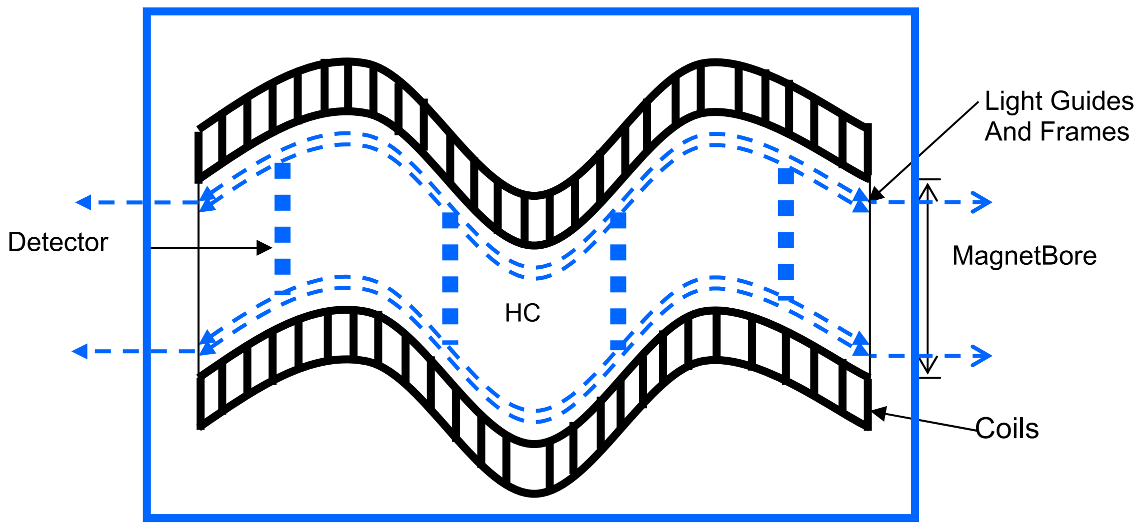

Figure 17 *Schematic of placement of four tracker stations inside of HCC.* There are also tracker stations upstream and downstream of the HCC, which are not shown. *Detector planes outside of the magnet are not shown.*

Clear fibers are attached to the external connectors of the feed-throughs, and are attached to photon detectors outside of the HCC and away from the region of strong fringe fields. Our baseline design for the photon detectors is to use the same types as used in the MICE experiment, based on the D0 central fiber tracker: VLPCs and readout electronics. It may also be possible to acquire VLPCs and electronics from D0 after the Tevatron shuts down, which will further reduce costs.

4.2.3.6 Tracker planes built into coil structure

The HCC solenoid consists of coil windings built into a supporting structure that serves several purposes: spacers for separation of the individual coils, displacing the positions of the centers of the coils so that the coil centers follow the desired helical path, and provision of mechanical strength to withstand the forces on the coils in the magnetic field. The tracker planes are mounted on custom spacers and built into the HCC assembly.

The advantages of this design are the following:

- The frames for the planes can be larger than the bore, so that the entire bore can be instrumented. In the baseline design the frames must fit within the bore.
- The clear fibers can be routed from the frames to the optical feed-throughs outside of the coils. In the baseline design the clear fibers are inside the bore, which introduces more material in the outer parts of the bore; the trajectories near the maximum radii are subject to scattering by the fibers in the bore.
- The fiber planes are built into the magnet structure and do not have to be inserted in the bore afterward.
- It may be possible to connect photon detectors such as SiPMs directly to the fibers inside the HCC. Perhaps the associated front-end electronics can be attached to the SiPMs, so that the digitized pulse-height information is brought out of the cryostat [24].

There are some disadvantages in this approach, e.g. when the planes are built into the coil structure they cannot be removed without disassembling the coils structure.

We present here a concept for the use of SiPMs and associated readout electronics. In Figure 20, we show a fiber plane that is attached to a supporting disk that can be mounted in the helical solenoid coil structure. Each group of fibers is connected directly to a SiPM and the readout elements are mounted on the support disk.

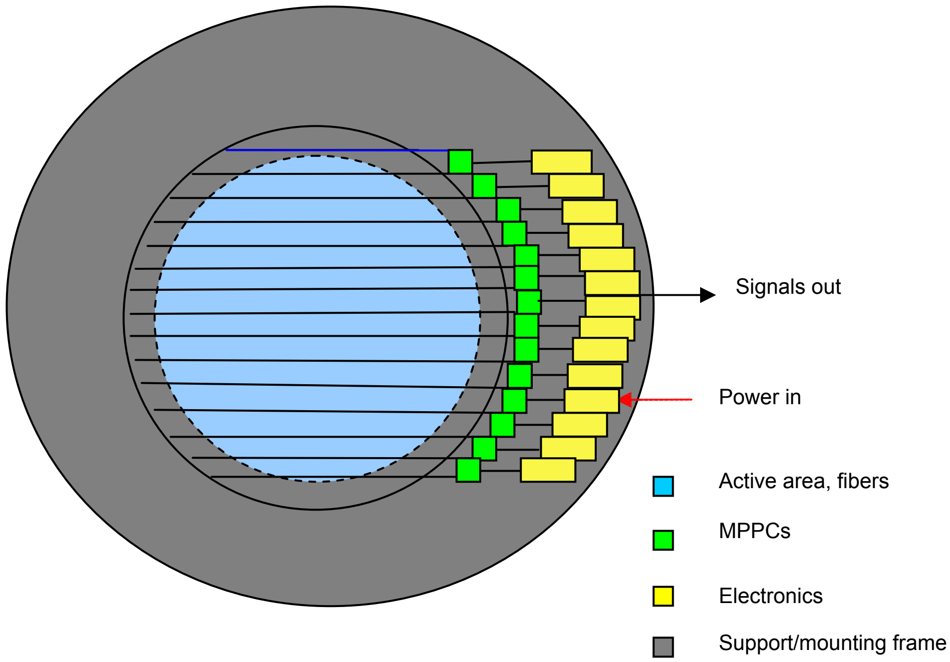

Figure 18 ***Scintillating fiber plane and associated SiPM detectors and readout electronics on a mounting frame that can be built into the HCC coil structure***

A representation of the HCC with scintillating fiber planes mounted in the coil structure is shown in Figure 21, using SIPM-based detectors. Only electrical feedthroughs are needed. Feedthroughs shown are meant to be schematic – in an engineered version they could be mounted in other locations, for example at the end wall of the cryostat vessel.

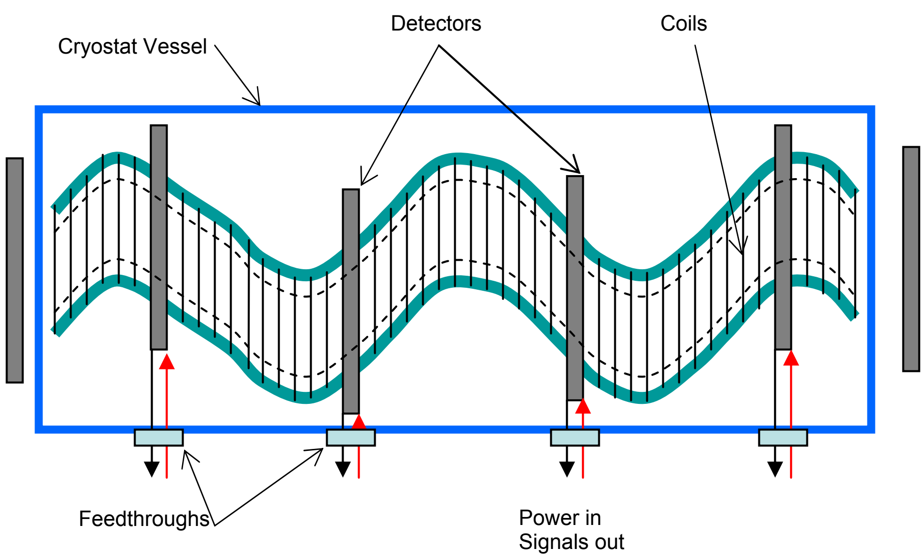

Figure 19 HCC with 4 tracker stations built into the coil structure. Detector stations upstream and downstream of the magnet are indicated.

4.2.3.7 HCC tracker development/testing issues

A number of issues need to be investigated and resolved concerning the use of scintillating fiber trackers in the HCC. The bore of the HCC is filled with liquid helium. It needs to be shown that the scintillating fibers produce sufficient light in that environment, and do not become stress-crazed due to the temperature range. Also the technique for constructing fiber planes must be such that the planes of fibers remain flat and intact in the He bath. They must also be able to withstand heating to room temperature and cooling to liquid helium temperature without damage to the fibers. Joints between scintillating fiber and clear fiber must be robust to withstand the temperature variations. Methods must be developed to be able to insert, align and position the tracking stations in the HCC.

We believe that fiber optic trackers will work in the LHe environment of the energy absorber. There already has been some prototype work to demonstrate this capability where we see that the scintillating fibers work well in LN2, having no loss of signal or any indications of trouble with the bond between the clear and scintillating fibers. Some specific areas of investigation regarding scintillating fiber trackers inside the HCC are: possible reduction of light output of the scintillators at LHe temperatures, maintaining integrity of the spacing and alignment of the fibers in the LHe environment, interfacing with the design of the HCC such that detectors can be accommodated inside the cryostat, design of efficient feedthroughs/couplers for bringing the optical fiber signals out of the cryostat, selection of photo-detectors to convert the optical signals to electronic signals, and evaluating electronic readouts for processing the signals from the detectors.

There has been impressive progress recently in the development of SiPM (silicon photo-multiplier) technology [25]. A number of companies have been producing commercial SiPMs, and the availability of new versions is growing. SiPMs consist of arrays of avalanche photodiodes (APD) and resistors on a single Si chip, where each APD corresponds to a pixel. Single photon quantum efficiency is near 100%, and because the APDs operate in the Geiger mode, each photon results in a standard signal from the corresponding pixel. Typical signals of multiple photons give rise to signals proportional to the number of photons received. The development of SiPMs is now focused on optimizing the designs to improve signal strength, reduce cross-talk, optimize the chip layouts to increase the active areas, reduce the noise levels, and improve quality and consistency of the units produced. Results from tests by particle physics groups have shown that SiPMs have good photon efficiency, are sensitive over a broad spectrum of light, are stable and have operated well in 4 Tesla magnetic fields, and are expected to work well in higher fields. SiPM costs are competitive with conventional PMTs, and their costs should decrease as production is commercialized.

4.2.4 Improved Particle Identification

4.2.4.1 Cherenkov Counters

The MICE experiment uses threshold aerogel-filled Cherenkov counters to reject pions and electrons. The radiators are designed for ~200-250 MeV/c, which is less than the desired momentum of MANX (~350 MeV/c). However, one of the aerogel radiators that is being used at MICE is also suitable for MANX, namely that with index of refraction equal to 1.07 aerogel. For index 1.07 aerogel the threshold for muons is 275 MeV/c, while the threshold for pions is 376 MeV/c, which is suitable for MANX (upstream). Thus, pions with momenta less than 375 MeV/c will not produce a signal in the counter.

4.2.4.2 Calorimeters

We are evaluating the performance of the rejection of electrons downstream of the HCC. The NIU group, which has experience in calorimetry, will provide calorimeters designed for the MANX experiment, if it is necessary to replace the current ones.

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5 Requirements for Measurements

5.1 Statistical Precision Needs

The amount of cooling anticipated for the HCC is considerably greater than that expected for the MICE cooling sections, about a factor of 2 reduction vs about 10% for MICE. A rough estimate is as follows. Based on the relative cooling factors the number of events required to determine the cooling at MANX to the same relative precision as MICE is about a factor of 100 less than at MICE. Measurement of the characteristics of the cooling of the HCC will require study of events near the limits of the acceptance of the HCC, which will require selection of sub-samples of the data. To get adequate statistics on selected regions will require additional data. More detailed studies of the statistical precision required to determine the emittance reduction performance of the HCC will be performed. The MICE experiment loses 90% of its beam due the need to select beam spill segments that are synchronized with the RF timing of their RF cavities. MANX has no RF so it can use the entire spill.

5.2 Systematics and Ancillary Measurements

The mapping of the magnetic field of the HCC magnet and the matching sections, if used, will be done at Fermilab.

Studies of systematics of the detectors and spectrometer will be done as part of the simulations, and in conjunction with systematics that are determined by the MICE experiments.

6 Beams

6.1 MICE Beam Line

The elements of the MICE beam line are shown in Figure 22. The target plunges into the ISIS beam, a quadrupole magnet triplet captures pions produced in the target, which are bent by a dipole magnet and pass into the MICE Hall, where they enter a decay solenoid. Muons of the desired momentum are selected by the second dipole magnet, and transported to the MICE upstream solenoid spectrometer. The MICE cooling sections and downstream spectrometer and detectors are not shown. A Pb diffuser is used to scatter the muons to increase the initial emittance of the beam to about 2π to 10 π m-mrad, depending on thickness of the Pb diffuser.

The MICE beam line was designed for a muon momentum of 220 MeV/c, but it can be run as high as 400 MeV/c, which is suitable for a MANX beam momentum of 350 MeV/c. The composition of the beam at 350 MeV/c has not been determined as yet.

The MICE beam has the following time structure [26]: MICE gets about 1 beam spill per second, depending on the allocation of spills from the 50 Hz ISIS rate. The expected rate is about 600 muons per 1 ms spill, in the MICE momentum range of 140MeV/c to 240 MeV/c, with an internal fine structure due to the ISIS 3 MHz RF frequency.

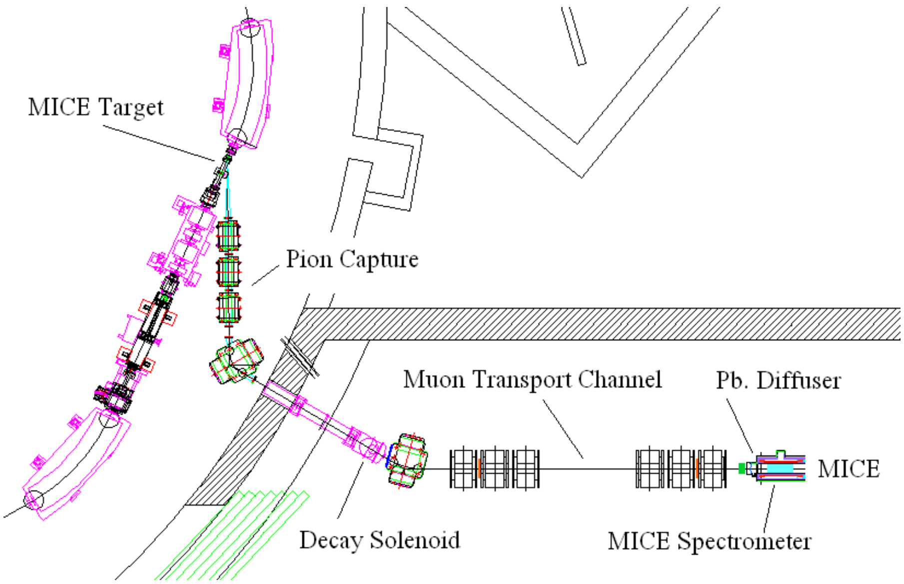

Figure 20 *MICE beam line at RAL (From the MICE TR).*

6.2 Test Beams at Fermilab

There are two test areas at Fermilab that will be available for MANX testing – the MuCool Test Area (MTA) and the Meson Test Beam facility (MTBF). The MTA has a beam from the Linac of 400 MeV protons, with short spills of ~25 nsec to ~100 μsec at a rate up to 15 per second. The MTBF beam is based on the Fermilab Main Injector beam of 120 GeV protons and a secondary target that can produce positive and negative beams from ~1 Gev/c to 120 GeV/c. There is now a secondary target that produces a low momentum tertiary beam of 200-400 MeV/c, initially for the testing of MINERVA calorimeters.

The beam has a long spill time of 1-4 seconds, with a rep rate of once per 1-2 minutes. Beam intensities vary depending on beam momentum and sign. Beams of ~10^6 protons per second at 120 GeV/c are available and rates are a few thousand per second at low energy.

The MTA beam is dedicated to muon cooling experiments such as the effects of beams passing through RF cavities, and operation of RF cavities in a magnetic field. It could be used for testing of MANX detectors.

The MTBF is a test facility that is available for any users, after approval of proposals. Groups have used the facility for a wide range of testing activities from very short runs of a few days to long term testing programs such as those of the CALICE calorimeters. The high energy primary and secondary beams can be used for testing of the TOF and scintillating fiber planes, and low energy tertiary beam is particularly well suited to test pion and muon identification in the low energy region corresponding to the MICE beam energies.

7 Simulations of Baseline Beam/Detector Configuration

We plan to use G4MICE to simulate the MICE beam operating at 350 MeV/c. The rates and beam composition are expected to be different than at 140 or 240MeV/c, the MICE design momentum. The higher momentum pions decay at a slower rate, so we expect a somewhat lower muon rate and a higher pion-to-muon ratio. Another difference is the relative production of higher momentum pions produced in the ISIS target. We are also very interested to learn how the measured MICE beam rates compare to the calculated and simulated rates.

We have begun to enhance the G4beamline program to incorporate the full MICE beam and detectors, and to include MANX channel types for a complete end-to-end simulation of MANX using the G4MICE program.

8 Components Currently Available and Needed

8.1 Helical Solenoid and Matching Sections

These components are to be provided for MANX. Details are contained in other sections.

8.2 Existing MICE Configuration and Adaptations Needed for MANX

The complete MICE layout in the MICE Hall at RAL is shown in Figure 23, including ISIS magnets and target, the MICE beam line elements, and the MICE components. Of particular interest to MANX is the amount of space between the MICE solenoid spectrometers as well as the amount of space between the electron calorimeter and the beam stop. The downstream end of the upstream spectrometer is at about 10 m on the metric scale in the figure, and the upstream end of the downstream spectrometer is at about 17 m on the scale, which indicates that there is about 7 m available for the MANX HCC if the MICE cooling channels were removed.

From Figure 13 the space required for the HCC and matching sections is about 10 m, with 6 m required for the matching section and about 4 m required for the HCC. Thus, in a version of MANX without matching sections the MANX apparatus could fit into the space made available by removing the MICE cooling sections, and the downstream spectrometer and calorimeter need not be moved downstream. (The optimal position of the downstream spectrometer would probably be immediately downstream of the HCC.) With matching sections it would be necessary to move the downstream apparatus about

3 m downstream. It can be seen that the space between the last element of the MICE layout and the shielding at the end wall of the MICE Hall is about 4.5 m, which accommodates a 3 m move of the apparatus.

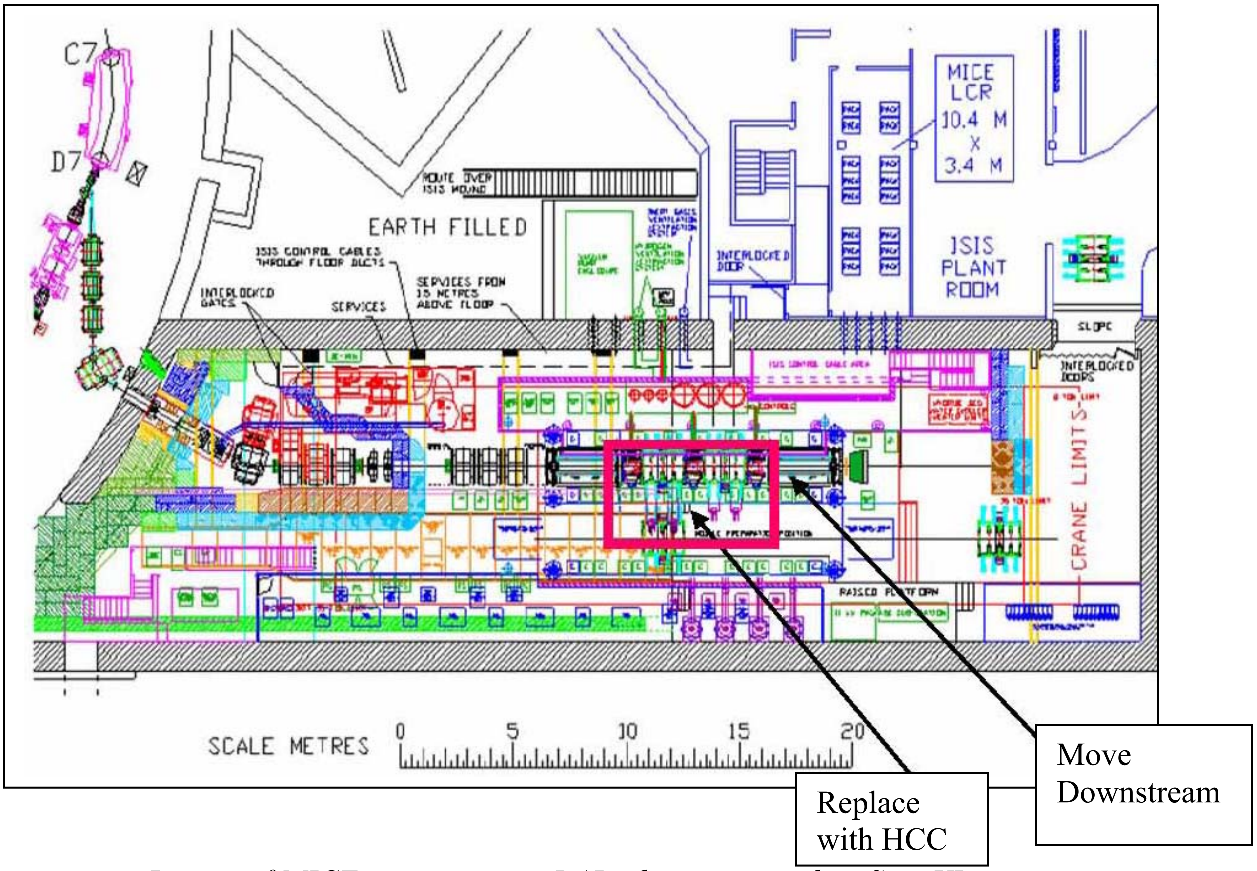

Figure 21 *Layout of MICE experiment at RAL, showing complete Step VI arrangement, as shown in Figure 24, with three cooling sections and the associated RF stations. A section of the ISIS accelerator magnets is at the left, with the MICE beam line quadrupoles and first bending magnet outside the MICE Hall. The equipment in the red outline (MICE cooling units and RF stations) would be removed to be replaced by the HCC. The equipment to the right of the red outline, indicated by the arrow, would be moved farther downstream.*

For the MANX channel as shown in Figure 11, in which there are no matching sections, but the HCC is placed at a 45º angle so that the beam enters aligned with the reference trajectory, space required along the beam line is about 3 m but the downstream emerging beam line is displaced by about 3 m to the upstream beam line. This requires that the downstream spectrometer must be moved transverse to the upstream beam line. It appears that there is about 3m of space to the right of the beam, which would accommodate the HCC and the relocation of the spectrometer. These are very rough feasibility assessments and all aspects have not been included. For example, additional space needed for the HCC cryostat (which has not been designed) is not considered.

8.3 Software

The existing and expected refinements and developments in software for MICE represent a rich resource that can be used by MANX. The simulation, data acquisition, track reconstruction and analysis functional packages will have been used throughout the MICE project, and will be of direct use to the MANX experiment. Several of the current MANX collaborators are already working on MICE software and will continue to do so through the MANX era. We anticipate that some collaborators from the MICE experiment will join the MANX experiment and continue to upgrade and support the evolving software.

The main additions that will be needed to upgrade the software for MANX are for the detectors inside the HCC, track fitting along the trajectory in the HCC, matching to the tracks in the existing spectrometers, and the determination of the longitudinal momentum component from the TOF information.

Additional DAQ software will be required for readout of the ps TOF counters and the detectors inside of the HCC and integration into the overall MICE DAQ.

The MICE analysis package will be augmented to incorporate the HCC and TOF information.

9 Schedule, Resources Needed, and Cost

9.1 Boundary conditions

MANX should not be installed until MICE has achieved its objectives. It also would be unfortunate to have a long break after MICE finishes and before MANX begins since the expertise of people and equipment tend to disperse and deteriorate. Ideally, the MANX apparatus should be ready to take data about a year after MICE is done. This is enough time to install the HS magnet, interface it and new detectors to MICE, and tune the beam to new requirements.

9.2 MICE Schedule

At the recent MICE collaboration meeting in October, 2008 [27], the MICE "aspirational" schedule shown in Figure 24 was presented. MICE is planned to proceed as a series of steps leading to a full complement of apparatus, with three hydrogen absorbers, two solenoid spectrometer trackers and particle identifiers. The following list enumerates the characteristics of the steps.

I. Step I includes setting up the beam, the beam monitoring counters, and the decay solenoid. Currently in progress, expected completion Spring 2009.

II. Step II adds the first solenoid spectrometer and TOF2 counter, scheduled for spring of 2009.

III. Step III adds the second solenoid spectrometer, a solid absorber, and downstream particle ID detectors, planned for summer and fall of 2009.

IV. Step IV replaces the solid absorber with the first liquid hydrogen absorber, planned for fall of 2009 until spring of 2010.

V. In Step V the first of the RF stations and the second hydrogen absorber are installed and expected to run in spring of 2010.

VI. In Step VI the complete setup, with two RF stations and three hydrogen absorber units, is planned for late 2010 and into 2011. This is the final step of the MICE program.

Following the completion of Step VI, the MICE collaboration has indicated that they desire to maintain the facility and make it available for additional studies and measurements. The earliest time for doing the MANX experiment in RAL as an extension of MICE is after Step VI, approximately 2011.

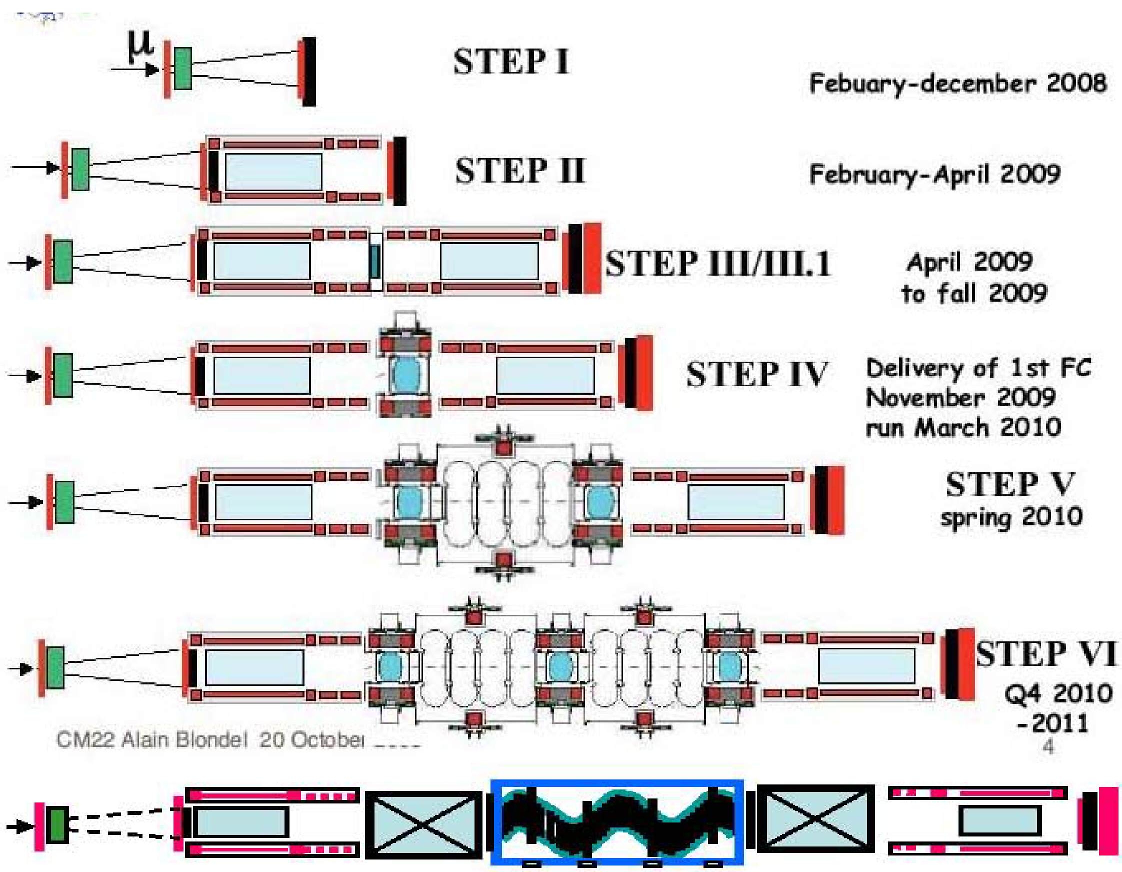

Figure 22 *Representation of the MICE schedule, showing a possible MANX layout (not to scale). The MANX layout at the bottom indicates reuse of MICE spectrometers and upstream and downstream detectors.*

9.3 Completion of HCC and Matching Sections

The four-coil model has been completed and the field mapping is underway at Fermilab. An estimate of the time required to build the full HCC magnet, without considering RF cavities or detectors in the design, was presented at the July, 2008 MANX meeting [28]. The time estimate, which included specification, engineering, cryogenics, procurement, fabrication, assembly and testing, was approximately four years for the HCC magnet, and did not include the matching coils. A decision on whether to build matching sections is required at the specification stage. Based on this estimate, if the HCC construction project were to begin in spring, 2009, the magnet would be completed in spring, 2013. The cost was estimated to be approximately $6M. Whether the magnet development group at Fermilab may be able to start working on the HCC as early as we desire depends on other magnet projects being undertaken and priorities to be determined by the Fermilab administration.

9.4 Responsibilities of Participating Groups and Needs from Fermilab Divisions

The mode of operation of Muons, Inc. is collaborative, by the nature of its funding. Muons, Inc. will provide enhancements to and support for G4beamline with its grant with IIT. The TOF project is a joint effort between Muons, Inc. and the University of Chicago. The development of detectors and electronics for the HCC detectors is a collaborative effort of Muons, Inc., Northern Illinois University and Fermilab. The HCC magnet development has been a joint effort of Muons, Inc. and Fermilab. The other participating groups will contribute to hardware, software, and electronics areas as the project proceeds. We are also seeking to participate more actively in MICE experiments, and are also seeking additional collaborators from the current MICE participants as well as additional groups. We anticipate that the collaboration will grow more rapidly after the proposal is approved.

We request support from the following Fermilab Divisions. The Technical Division has been the major player in the design, construction, and testing of the HCC magnet. The Research Division facilities and support will be important for scintillator plane development and construction, as will the electronics department design facilities for the design of front-end electronics for the detectors in the HCC. Individual members of the Accelerator Division will surely join the collaboration and contribute in their related technical areas.

The Northern Illinois University group has indicated an interest in providing an improved electron identification calorimeter for the downstream region and has graduate students who are working on beam-related and analysis issues.

The IIT group has one post-doc who is working on the muon beam simulations. Both NIU and IIT are likely to have students on the experiment.

The Jefferson Lab collaborators have worked on the fundamentals and systematics of muon cooling and will continue to support the planning, analysis, and interpretation of the data.

9.5 Support and Needs from RAL and the MICE Collaboration

We regard MANX as a follow-on phase to the existing MICE program, and that the transition to MANX will be smooth. We anticipate that groups that are part of the MANX collaboration will join MICE prior to the MANX phase at RAL. The following items are intended to clarify some possible concerns about the operation of MANX at RAL.

Support Anticipated from the Host Lab (RAL)

We do not require extraordinary support from RAL. Each of the systems that we provide will have been built and tested before moving them to RAL. We expect to work with the RAL staff to plan the installation of the equipment and the removal/reconfiguration of some of the existing MICE apparatus, e.g. removal of the MICE cooling sections and RF stations, and relocating the downstream MICE solenoids and detectors. One area to be worked out is the refrigeration plant needed for the HCC. The volume of liquid He (or possibly liquid H2) is probably greater than that for MICE. If the MANX project at Fermilab includes refrigeration components that can be sent to RAL then installation and integration will be required. If not then RAL may be asked to provide the refrigeration plant.

Lab space for a “staging and testing” area is probably needed to assemble and retest components that are sent to RAL for MANX. Although we intend to test all of the components before shipping them to RAL it is important to verify their operation before installing them in the experiment.

Support Anticipated from the 'Owners' of the MICE Instrumentation

Ideally the owners of the MICE instrumentation that will be used in MANX will be attracted to collaborate and continue to support the various subsystems. In some cases, if the groups do not join MANX we would expect that they would permit those elements to remain and that they would provide instruction to the MANX groups that take over those systems on operation and maintenance, and technical support during the initial MANX operating period.

In the case of the trackers that are inside the HCC, our current concept is that they are very similar to the trackers in the solenoidal spectrometers, being made of scintillating fibers. If the groups that built the MICE detectors continue in MANX it would be natural for them to build the new planes, to assist the MANX groups that will build the detectors, or to provide some of the tooling for us to use, if feasible. Anything that reduces cost and time is worthy of consideration.

Resources that MANX Could Provide for Integration/Engineering of MANX + MICE Instrumentation (Especially Spectrometers and the HCC)

Muons, Inc. and some of the other MANX proponents are already MICE collaborators, and others will also join MICE prior to MANX, and some MICE groups will join MANX. Thus we expect that the transition of MICE to MANX will be "evolutionary" rather than "revolutionary". We plan to use the MICE solenoidal spectrometers and use the same readout for the MICE detectors that remain for MANX. The DAQ system will require modifications to include the new MANX detectors and the deactivation of some of the MICE components that are not used by MANX. The MANX collaboration will develop expertise in managing the data acquisition system and triggering, etc. for the MANX experiment.

Resources that MANX Could Provide for Mounting MANX (and possibly demounting MICE)

During the transitioning from MICE to MANX we expect that the MANX-MICE collaboration will have a core team in place for the duration of the transition, and technical specialists for the new components will be available to be on-site as needed.

Resources that MANX Could Provide for Operating and running MANX

The MANX-MICE collaboration will provide personnel 24/7 to operate and run MANX. We anticipate that a number of graduate students and post-docs will be assigned to work on MANX at RAL full-time and that senior staff and faculty members from the participating institutions will spend a part of their time at RAL during the MANX phase, and take part in meetings and technical discussions when they are at their home institutions.

Software for Simulation, Reconstruction, and Analysis

We are extending the G4MICE simulation program to include MANX-specific functionality. The enhanced version of G4MICE will include the HCC, the internal HCC detectors and the TOF counters. It is not fully functional yet, so the detailed simulations and studies of resolutions, sensitivities and precisions have not been done yet.

Software for the simulation of the TOF counters is part of a pending grant proposal by Muons, Inc. and the University of Chicago, about which we should receive a decision on in April. Muons, Inc. and collaborators will develop the software for the readout and reconstruction of the TOF information in conjunction with the testing program at Fermilab before MANX begins operating at RAL.

Similarly we have a pending proposal for development of the HCC internal trackers. We plan to test the trackers in a test beam at Fermilab with a dedicated readout system and an analysis package before installing it at RAL.

We plan to utilize and enhance the MICE reconstruction and analysis software to apply to the MANX configuration and requirements, e.g. to incorporate the new tracking elements inside the HCC and the time-of-flight detectors.

9.6 Completion of Additional Components Needed for MANX

The two major Detector developments/additions for MANX are the pico-second time-of-flight detectors and the tracking detectors inside the HCC. These could be developed and built with support from the SBIR Phase 1 (9-month) and STTR Phase 2 (2-year) grants. Additional support from other collaborators is likely to be provided.

9.7 Timeline for Building, Testing, Installing and Running the Experiment

Assuming that the schedule for the construction of the HCC magnet requires the longest preparation time, the transport of the equipment to RAL could take place in early 2013. This fits in well with the conclusion of the present MICE program in 2012. In broad terms the magnet could take 4 years and the detectors 3 years. There is approximately one year after the completion of MICE for the MICE apparatus to be reconfigured to permit installation of the MANX equipment. Following this we anticipate about 2 years to install, test, and run the MANX experiment.

We envision that the HCC magnet and associated cryogenic system will be designed at Fermilab. The superconducting magnet wire will be obtained from the available supply of wire from the former SSC project, and we anticipate that the coils will be wound at Fermilab. Some of the mechanical parts may be machined by outside vendors. The power supplies and miscellaneous electrical and cryogenic control elements can be purchased if available commercially.

Testing of the HCC and cryogenic system will be done at Fermilab. Mapping of the HCC field will be done at Fermilab. We foresee that field mapping may present some new techniques and apparatus, since there is no straight line path through the twisted helical field region. The conventional zip-track system, in which the Hall probes move along a long, straight track would have to be redesigned to negotiate helical paths, or a different procedure, such as measuring points on a grid, would be necessary.

The new detectors, such as time-of-flight and HCC internal detectors, would be developed and built by the MANX collaborating groups, as is done in particle physics experiments. The new detectors are to be tested, in part at the local institutions using cosmic rays and sources, and in a test beam at Fermilab.

9.8 Cost Estimate

At this time we have only a preliminary estimate of the cost of the HCC magnet, which is the major cost item. The HCC magnet and cryogenics was estimated by the Fermilab Technical Division to cost about $6M. We are currently discussing requirements and possible design alternatives with the Fermilab TD.

The cost items for RAL include reconfiguring the MICE apparatus to accommodate the MANX equipment, installation costs, and costs of operating the MICE beam and facility for approximately two years for the duration of the MANX startup and data taking.
The cryogenics needed for the MANX magnet will be discussed in view of expected RAL capability and the design optimized accordingly.

9.8.1 Scope of Estimate

At this time the overall cost estimate has not been done. We will provide information to Fermilab and to RAL as the information becomes available.

9.8.2 Estimate Methodology and Basis

We will use the standard DOE estimation methodology for Fermilab-supported items, and according to the RAL methodology for cost items that relate to support required from RAL.

9.8.3 Contingencies

Contingencies will be assigned according to standard procedures, based on the degree of maturity of the designs, and risks perceived.

10 MANX and Other Muon Collider and Neutrino Factory R&D

10.1 Relationship to the Muon Accelerator R&D 5-Year Plan

The Fermilab Muon Collider Task Force (MCTF) was established in 2006 to develop a plan for a program to advance the technologies necessary for a possible energy-frontier muon collider (> 1 TeV) at Fermilab. Many of the concepts and technical elements of this proposal were included in the Muon Collider Task Force Report [29], co-authored by most of the MANX collaboration as well as groups from Brookhaven, LBNL, UCLA, and U. of Mississippi. The high pressure RF studies, the helical solenoid magnet work, high temperature superconductors, and the cooling studies that relate to MANX are described in the report. The proponents of this proposal are in close contact with the MCTF, and our plans are well known to the MCTF.

Recently the MCTF and the Neutrino Factory/Muon Collider Collaboration (NFMCC) have started work on a 5-year plan [30] which has been presented to the Department of Energy for funding. The 5-year plan is directed toward delivery of a Muon Collider Design Feasibility Study Report (MC-DFSR) and participation in the preparation of a Neutrino Factory Reference Design Report (NF-RDR) in 5 years. It does not address other uses of muon beams, such as intense stopping muon beams for studies of rare processes, e.g. the muon-to-electron conversion (mu2e) experiment, which recently was granted Stage I approval at Fermilab. In the section relating to 6D cooling, the draft plan discusses the HCC as one of three schemes under consideration, and it does not advocate a particular choice. There is also a discussion of the MICE experiment and its relationship to a neutrino factory.

The 5-year plan supports the development of the MANX proposal but does not request funding for the experiment itself within the 5-year time frame. The plan proposes to ramp up the effort and funding for a muon collider technical program. As such, the plan outlines a program of building several short helical solenoid sections that can be used to study the operation and integration of RF with the sections of coils, and designing a hydrogen gas-filled HCC that has integrated RF cavities. A 6D test with beam would come later, after the time period covered by the plan.

We believe that doing the proposed MANX 6D cooling experiment with helium absorber and without RF will further the goals of the MCTF and NFMCC and will provide a meaningful test of cooling principles. It will also lay the technical groundwork for designing useful cooling channels for stopping muon beams.

In short, we believe that MANX is an essential complement to the Muon Accelerator 5-year Plan. To the extent that it can be supported by people and funds that would not otherwise be used on the 5-year Plan, MANX is much more than just aligned with the Plan in that it is a valuable addition.

Muon accelerator science and technology will be advanced by adding resources from other countries and other US institutions that will join an interesting 6D cooling experiment, but not necessarily a Fermilab study. For example, several universities have joined in this proposal and we anticipate more of them will join in the coming year. These university people from the high energy physics world not only have the right background for MANX, they also are the ones to energize their community and make it aware of the excitement of a muon collider.

MANX as part of the MICE program will attract a larger group of collaborators, with valuable equipment and well-matched expertise, to both MICE and MANX. This is an extraordinary opportunity.

10.2 Relationship to MICE

Several of the MANX collaboration members and institutions are already participating in MICE. It would be natural for them to continue this work by doing MANX at RAL, instead of mounting a separate experiment at a different facility. It is a mutually beneficial association – the MICE experiment would benefit by having additional participation by the MANX collaborators, and the MANX collaborators would be able to save a great deal of effort and cost by using the MICE beam, experimental hardware and software. It also benefits the MICE program and RAL by extending the return on the investment to do additional physics and make further technical advances.

Appendix A: Development program for high pressure RF cavities

High Pressure RF and the Continuous Absorber Concept

Filling RF cavities with gas is a new idea 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 MANX experiment 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, where HCC sections much like MANX would alternate with sections of conventional evacuated RF cavities.

Experiments are underway at the Fermilab Mucool Test Area (MTA) to test the concept of RF cavities pressurized with hydrogen gas. A test cell has been constructed, as shown in Figure 25. The test cell has two hemispherical electrodes, which can be made of various materials. Tests have been made of Cu, Be, W, and Mo thus far. The cell can be pressurized up to 1600 psia at STP, and can be operated at 800 MHz.

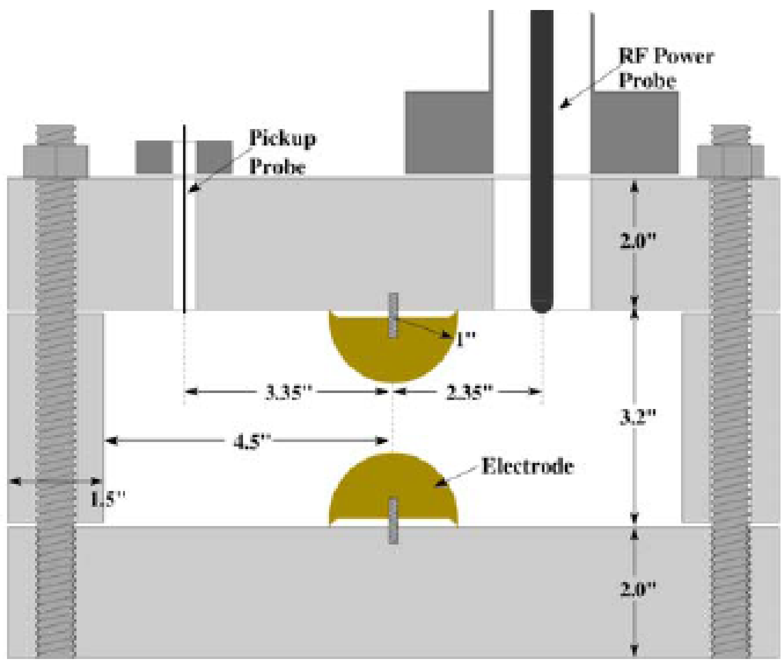

Figure 23 ***High Pressure Gas-filled RF Test Cell***

The results of tests of the test cavity filled with hydrogen gas are shown in Figure 26. 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 solenoid 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.

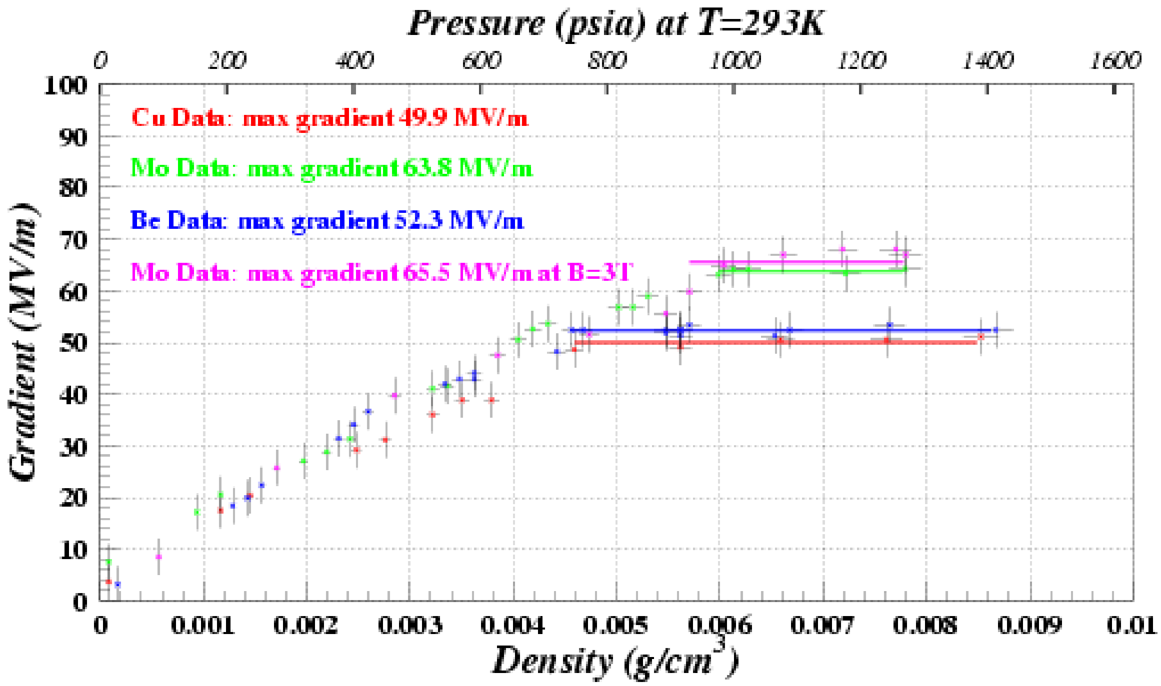

Figure 24 *Measurements of the maximum stable Test Cell gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue*

Figure 26 displays results from tests at the MTA that show that pressurized cavities have an advantage over usual cavities that operate in vacuum in the strong magnetic fields that provide the strong focusing required for effective beam cooling. In a 3 Tesla field, the maximum stable gradient of the Muons, Inc. 800 MHz test cell showed no maximum gradient degradation, while an evacuated cavity had reduced performance under similar conditions. Additionally, the dual use of the real estate for energy absorption by the hydrogen and for energy regeneration by the RF cavities can be an important feature for cooling channels requiring the highest muon flux where the muon lifetime is relevant.

The next important step will be tests of the pressurized RF test cell in an intense radiation environment. A 400 MeV proton beam line is being installed in the MTA and an experimental program to develop pressurized RF suitable for operation in a muon cooling channel should start soon. In addition to the test cell used for the measurements in Figure 26, a new pressurized RF cavity is being designed, which will be more like a conventional cavity with new features to mitigate breakdown and tune changes that may be caused by the bright beam in a muon cooling channel.

Appendix B: Four-Coil Model of Helical Solenoid Magnet

The MANX collaboration is working with the Fermilab Technical Division to design and engineer the HCC and emittance-matching magnet systems, including construction and testing of a four-coil demonstration magnet for the superconducting helical solenoid.

The four-coil demonstration magnet has been designed and constructed, and is currently set up for magnetic measurements at Fermilab in the Dewar of the Technical Division Vertical Magnet Test Facility (VMTF).

The status of the project has been presented at a recent conference [31]. Figures in this section are from the conference report.

This program will have many benefits to the MANX program to build a full scale helical cooling channel.

First, the tooling to make the coils and the coil manufacturing procedures of the engineering design will be directly applicable for the full scale MANX solenoid. The coil manufacturing process is a major time and cost driver for the full scale magnet and the 4-coil test will thus reduce the uncertainty and required contingency in the final project.

Second, the mechanical support structures and the measuring system for the 4-coil test are directly applicable to full scale MANX. The mechanical structure is designed to withstand the forces from adjacent coils, with the end coils likely having the largest asymmetric forces. In the central part of the HCC magnet channel the coil forces are largely radial, whereas there are significant longitudinal forces near the ends of the magnet channel that must be supported.

Finally, these coils can be used to do magnet studies that would be too costly or involve too much program risk for the full scale magnet. Studies include quench protection, complicated by strong field coupling of adjacent coils, and powering schemes for individual coils to compensate for the required momentum or z dependent field variation due to dE/dx loss. It is also possible to safely study the magnet response due to certain error conditions such as quench detection failure. We will design the support structure so that the center coils of the 4 coils will be easily replaceable, allowing QA tests of production coils for the full scale MANX Helical Solenoid.

Plan Details: Figures 27 and 28 show a schematic of the 4-coil test geometry. The coils are modular and will operate in liquid helium.

Coil design manufacturing: Existing NbTi cable from the Fermilab cable inventory was used. Tooling was designed to wind the cable on a stainless steel mandrel. Detailed mechanical/field calculations guided the design of the coil mechanical structure.

Support structure: The support structure will be designed to accommodate the expected 300 kN longitudinal forces and ~200 kN transverse restoring forces. The Dewar dimensions are approximately 600 mm in diameter and 4000 mm in length. Coil offset is accomplished by mounting the rings perpendicular to the gravity/Dewar axis.

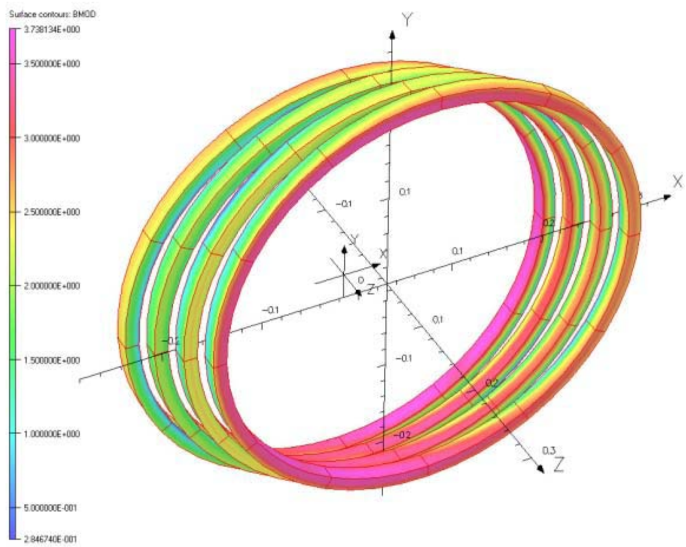

Figure 25 *Geometry of the 4-coil test model magnet, configured for VMTF dewar. The color scale shows the flux density.*

Magnets tested in a vertical dewar cryostat are typically tested using a “top hat”, which provides electrical connections and serves as the room temperature interface of the helium volume. The magnet is hung from support rods from this top hat plate. Power leads and instrumentation feedthroughs come through top hat penetrations.

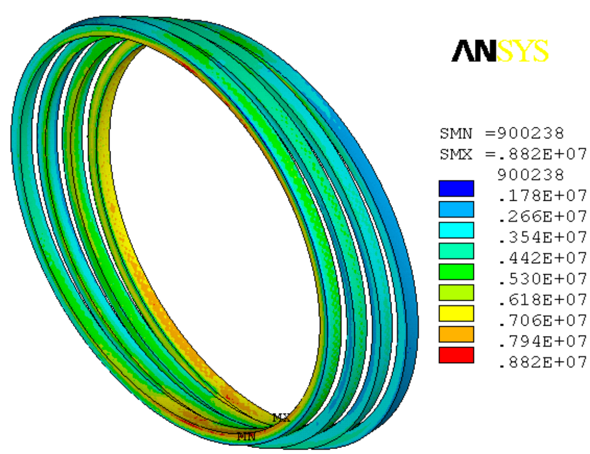

Figure 26 *Coil stress at peak current of 14 kiloAmp*

The stress analysis of the coils is shown in Figure 28. An illustration of the 4-coil assembly is shown in Figure 29. The maximum stress in the support structure is ~23 MPa, as shown in Fig. 29, which is acceptable.

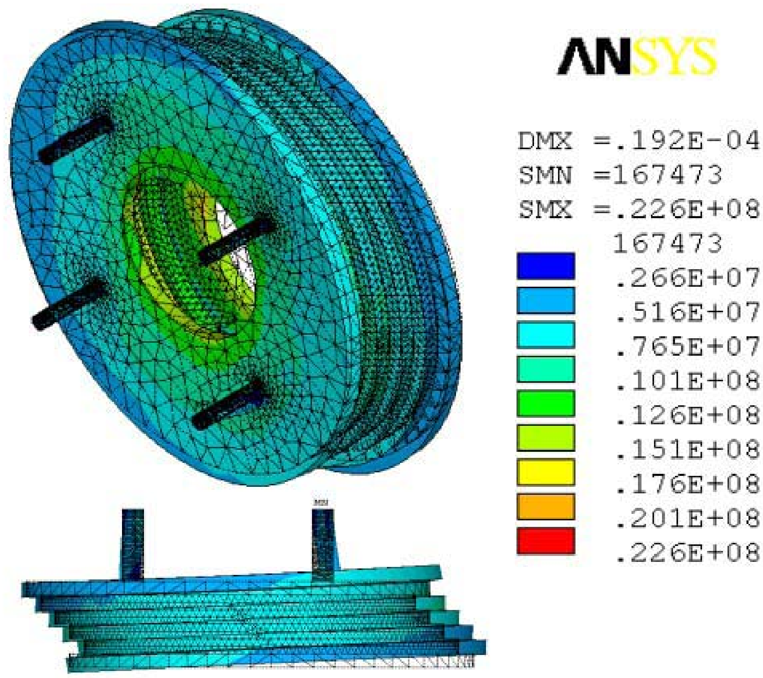

Figure 27 *Model of the coils, support structure and mounting rods, with the stress and deformation analysis results indicated.*

Tests will be performed in the Fermilab VMTF, The test will consist of the operation of the coils at full operational field. Magnetic measurements will be performed to determine field quality. Strain gauges will be used to determine the mechanical stress of the coils and coil support structure.

The 4-coil model is shown in Figure 30, during construction.

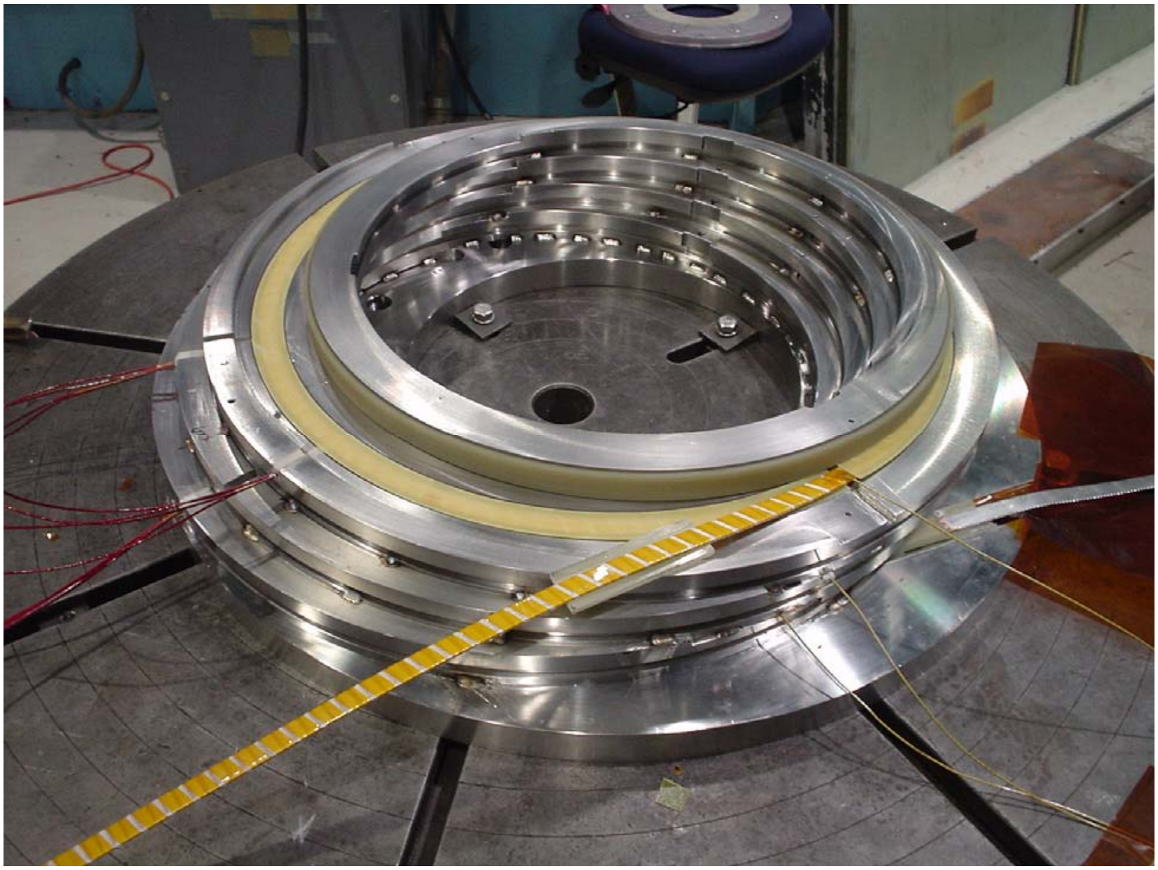

Figure 28 *Assembly of 4-coil model before 4th coil has been wound*

Status as of Dec. 5, 2008. After several quenches the magnet reached a quench limit of about 13500 amperes at 4.2K. This is quite a bit higher than the required ~9.5 kA during operation on a long string HCC, but the field is lower in this 4 coil configuration. We have not done all the analysis, the forces are different on this magnet configuration but the magnitude is comparable to the likely MANX operation. So we are quite pleased with the results. The test is very successful: good news for the Muons Inc/Fermilab collaboration!

Appendix C: Application of an HCC to Produce Intense Stopping Muon Beams for the Mu2e Experiment

Muons, Inc. and Fermilab have received Phase I and Phase II SBIR grants to study the use of cooling techniques to develop effective stopping muon beams. In the first proposal a preliminary study indicated that a MANX-like HCC channel could increase the flux of stopping muons in the Mu2e experiment, essentially by shifting the higher flux region of the muon production spectrum downward to lower momentum. Simultaneous momentum cooling is required when the energy is degraded to compensate for the natural momentum heating that is a consequence of the unfavorable slope of the dE/dx as a function of momentum curve. This study was reported at EPAC08 [6].

Phase II of this project was approved to develop the concept described above and to study mitigation approaches to suppress backgrounds for rare event searches. In Phase II of this proposal we expect to be able to push the idea of beam cooling for better stopping beams further, where more beam cooling using RF regeneration in the cooling channel can produce even brighter stopping beams. Such a cooling channel would be a natural step to the cooling channels needed for a muon collider or high-energy neutrino factory.

A scheme described in the Phase II proposal consists of a "dipole and wedge" following a production target, in which the combination of momentum dispersion and varying energy loss in a wedge produces an approximately monoenergetic beam of pions and muons, as indicated in Figure 31. This beam enters a HCC, in which more of the pions decay and the muons are cooled to produce a high intensity muon beam. As the end result is to be a stopped muon beam, no RF is needed to restore the lost energy.

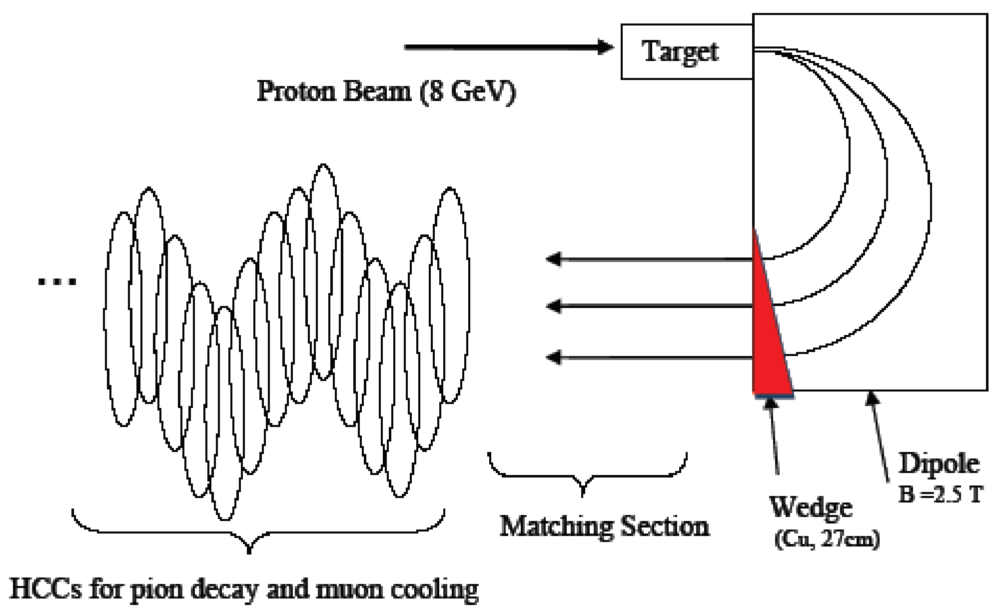

Figure 29 *Scheme using a dipole and wedge to produce a monoenergetic pion beam, followed by HCC decay and cooling channels, for an intense stopping muon beam.*

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Fermilab Accelerator Advisory Committee Meeting
February 3-4, 2009

Final Report
May 18, 2009

AAC Committee:

Members present: Katherine Harkay (ANL) (acting chair), Ilan Ben-Zvi (BNL), Gunther Geschonke (CERN), Roland Garoby (CERN), Stuart Henderson (ORNL), Kwang-Je Kim (ANL), Katsunobu Oide (KEK), Tor Raubenheimer (SLAC), Jamie Rosenzweig (UCLA), Hans Weise (DESY)
Excused: Swapan Chattopadhyay (Cockcroft Institute) (chair), Hasan Padamsee (Cornell)

Tasks/Assignments:

Overview**:** K. Harkay (lead), K. Oide
PX Linac/SRF**:** H. Weise (lead), G. Geschonke
PX Rings/other**:** S. Henderson (lead), T. Raubenheimer, R. Garoby
6-D cooling theory/simul.**:** K.-J. Kim (lead), K. Oide
MANX vs. mu2e**:** I. B-Z. (lead), R. Garoby, G. Geschonke, J. Rosenzweig

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1. Executive Summary

The AAC was convened from February 3-4, 2009 and asked to comment on several topics supporting Fermilab's strategic plan in the post-Tevatron era. About two thirds of the material concerned Project X and about one third concerned muon cooling. The hard work by FNAL staff and collaborators in preparing the scientific and technical talks is much appreciated, as is responding to committee requests for additional material in real time. Supplemental talks requested include: design criteria for alternative PX configurations, NML beam structure, HINS milestones through 2011, beam dynamics calculations plan, stabilization of low-beta linac, Muon 5-year plan schedule details, and MANX demo total cost estimate.

First and foremost, the FNAL staff is to be commended for their dedication and tenacity in carrying the national accelerator-based HEP program. In particular, the AAC commends Steve Holmes and FNAL staff for much progress since the last AAC meeting (May 2008) in developing the Initial Configuration Document (ICD) (31 October 2008) and updated Research, Design and Development (RD&D) plan for Project X (PX) presented at this meeting. It is acknowledged that many of the AAC's prior recommendations have been addressed for PX.

Fermilab is preparing for PX CD-0, anticipated in 2009. Project planning appears to be progressing well, and the focus on the physics mission need and specification of high-level goals is highly commendable and at the appropriate level. Beyond the ICD, investigations of promising alternative configurations (ACD) are in the early stages, too preliminary for comment by the committee. But further studies are strongly encouraged, to include cost and performance analysis. This is particularly stressed in anticipation of the natural trend of rising scope and cost of the PX. This committee is not qualified to comment on the "physics value-matching to cost", but feels obliged to raise concerns and request vigilance in its monitoring.

Project X is a Fermilab-led national collaboration. As such the AAC believes that Fermilab needs to prioritize the R&D program and should require clear reporting and management of critical R&D. The collaboration organization and responsibilities were not entirely clear from the presentations.

Many technical issues are addressed adequately in the RD&D plan. However, the committee recommends increased emphasis on beam dynamics, especially in the ring systems, and system design optimization studies in several areas. Project X will be a large undertaking and will need focused resources. While much progress has been made in the ILC/SRF and HINS programs, a plan for hardware and infrastructure integration with both the ILC/SRF and HINS effort is needed so as to ensure optimum alignment with Project X goals. Although not part of the official charge, defining a plan for integration with Fermilab's electron program at NML is recommended.

The committee was also asked to comment on the MANX proposal, an experimental demonstration of enhanced muon 6-D ionization cooling in a Helical Cooling Channel (HCC). Fermilab has been asked to participate. The committee was asked to address MANX in terms of technical feasibility, schedule, and relationship to mu2e upgrade and the muon 5-year plan. As background, the Muon 5-year plan and Mu2e experiment and plans were described in excellent presentations, and the physics cases are both compelling and scientifically exciting. The MANX proposal was described with enthusiasm and the potential enhancement in cooling, if it can be realized, is significant.

Recent muon cooling developments are far from mature, and the compressed agenda did not allow sufficient time to consider all the details. Firm recommendations would necessitate much more information about the status and proposals concerning alternative schemes. For these reasons, the committee offers only general comments and conclusions on this topic, while advising the laboratory management to encourage the MANX team to further pursue their R&D, particularly emphasizing detailed simulations with realistic system configurations and associated errors and undertaking a comparative analysis of alternatives.

The committee respects the consensus reached by the NFMCC and MCTF in the 5-yr plan, but encourages taking advantage of the momentum generated by the MANX effort. The 6-D cooling scheme that was presented is novel and encouraging. The committee believes more homework is needed to better understand the HCC technology, particularly in specifying the tolerances and optimizing the parameters. More homework is also needed to evaluate its role with respect to mu2e applications and the muon program in general.

The committee expresses sincere appreciation to the FNAL directorate for its hospitality during this review.

2. Project X

2.1 Summary response to charge

Does the ICD describe a configuration that is likely to meet the proposed mission objectives?

Observations

- Focus on mission needs is commendable.
- Mission needs are, in priority order:
  - Long-baseline neutrino oscillation (2 MW proton source at 60-120 GeV)
  - Muon-to-electron (mu2e) conversion (150 kW at 8 GeV)
  - Compatibility with future upgrade to 2-4 MW at 8 GeV
- Project X linac beam parameters has been redefined in ICD to address mission, i.e., decoupled from ILC, as appropriate.
- Revised baseline configurations addresses greater compatibility with mu2e (60 GeV MI and 160 kW mu2e or 120 GeV MI and 225 kW mu2e).
- Alternative config. (ACD) studies have been initiated for future PX power upgrades that are compatible with muon collider beam requirements.

Recommendations

1. The ACD schemes, especially the one with a synchrotron, need further evaluation of the performance and the cost. FNAL recognizes that beam power is limited in this case. Further ACD studies are encouraged.
2. Compare costs of Recycler rf upgrade with adding H- injection region to MI.

What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?

Observations

- Project X relies on a new linac system and reuse of the existing Fermilab ring infrastructure.
- Design of the new linac systems has lots of flexibility while PX team will need to design around limitations of the ring systems.
- Important to establish performance limits of the rings using experiments and simulations as soon as possible.
- 325 MHz low-energy linac essential ingredient for PX. Focus on more limited HINS program is well aligned with PX program. Concerns:
  - Slow progress of HINS and dropping of SSR2 leaves gaps in the injector R&D program.

- Low energy (30 MeV) removes opportunity for important study of beam halo generation.
- R&D program for triple spoke (TSR) cavities was not discussed.

- Electron cloud expected to be an important effect according to simulations; RD&D experimental program is appropriate.
- Primary elements for SRF/Linac RD&D appear reasonable.
  - 1.3 GHz β=1 cavity systems are relatively well established and national collaboration exists.
  - 1.3 GHz β=0.81 cavities need design effort. Recently started collaboration with Indian institutes needs strong FNAL leadership since cavity modification much more than technology transfer.
  - Need design study to optimize transition from β =0.81 to β =1.
  - Long pulse (up to 2.5 ms) might be an issue for klystrons/modulators.

Recommendations

3. Increased effort on beam dynamics and design studies for the rings is highly recommended in order to evaluate and optimize performance in several key areas; e.g., space charge tune shift, collective effects, and beam loss in rings.
4. The 1.3 GHz β=0.81 cavities require significant design effort, and strong FNAL leadership is recommended.
5. Establish beam instrumentation design requirements based on beam dynamics analyses and accelerator tune-up requirements.
6. Develop a plan to test beam instrumentation *in situ;* explore opportunities elsewhere as needed if this cannot be done locally.
7. For Linac HOM couplers, strongly suggest solving technical issues rather than consider eliminating them.
8. High average power dissipation the challenging issue for the RF input couplers; need a strong team for coupler R&D.
9. Choice of cryogenic segmentation should be carefully evaluated for expense vs. risk and should be based on assessment of world-wide experience in this area.
10. Once PX linac replaces Booster, rf frequency for rings could be reconsidered with respect to cost and electron cloud mitigation (EC accumulation is sensitive to bunch spacing).

Is the RD&D plan appropriately integrated with the ILC, SRF, HINS, and Muon programs?

Comments

- Cavity/cryomodule test requirements and test rates differ between ILC and PX programs. PX cavity gradient (25 MV/m) more modest than ILC; PX can benefit from ILC R&D. Scale of testing plans for PX (at ~400 cavities) should be compared with XFEL project (twice the cavities).

- The role of electron beam R&D within the lab should be clarified with respect to PX, e.g. A0 and New Muon Lab (NML). What are the motivating applications? How does the PX RD&D plan address them?
- Beam tests in NML may be relevant if electron gun can produce PX bunch structure.
- Integration with the Muon program was not evaluated at this time.

Recommendations

11. Present progress of SRF and HINS programs are aggressive and much progress has been made, although progress appears slower than desired. Further delays should be avoided.
12. Hardware and infrastructure development plans for both SRF and HINS should be better aligned with Project X goals. The 325-MHz linac is an essential ingredient to PX. Resources should be allocated by PX management as far as specifications are driven by PX. Extent that HINS program goals differ from PX requirements should be clarified.
13. The cryomodule test should be given the highest priority. CM test rate is an issue: evaluate whether assumed capacity of one module per month is sufficient for PX.
14. Fermilab now has several high-gradient (> 35 MV/m) cavities tested at Jlab and delivered to FNAL. The work to dress these cavities with a He vessel and couplers needs to be accelerated to assemble a second module as soon as possible with these good cavities. This will strengthen FNAL's module assembly capability and improve FNAL's prospects of delivering a 31.5 MV/m module for ILC. It will also be essential to the long-term effort of determining how to achieve the target one-module-per-month rate.
15. Adoption of type-IV ILC cryomodule a good choice for PX β=1 linac to leverage the ILC/SRF program for PX. Major difference is location of quadrupoles. The linac lattice and cryomodule design should be modeled and optimized as soon as possible.

2.2 Linac

2.2.1 ILC/SRF and Project X

The ILC/SRF program's mission is to contribute to the ILC machine design and to further develop the field of superconducting accelerator technology with main emphasis on ß=1 cavities. The detailed plan for Fermilab's SRF infrastructure development was reviewed in the past. The new infrastructure offers a vertical test as well as a horizontal test system and includes the now-completed and commissioned string and cryomodule assembly facilities. This infrastructure and the expertise gained in SRF technology at Fermilab will be available not only for the ILC/SRF program but also for Project X. All future SRF work at Fermilab will strongly profit from the experience with cavity installation and processing but also from the recent assembly of the 3.9 GHz accelerator section consisting of four nine-cell structures, rf input couplers, frequency tuners, etc.

Fermilab's work with the GDE Americas Regional Team to develop the ILC machine design includes participation in the Technical Design Phase and work towards the GDE SRF goals (S0: a cavity gradient of 35 MV/m with good yield; S1: complete cryomodules with an average gradient above 31.5 MV/m; S2: one or more ILC RF units with ILC beam parameters; design improvements for cost reduction). In addition, Fermilab is pursuing a study to host ILC. The work towards the GDE SRF goals is important and is not expected to be compromised by Project X prototyping.

Project X, construction being planned for 2013 to 2017, is going to use the same accelerator technology, although some differences between ILC and Project X modules exist. Project X is aiming for a higher beam current over longer macro pulses (20 mA × 1.25 ms × 5 Hz) at moderate accelerating gradient (25 MV/m). The upgrade path assumes a macro pulse length of 2.5 ms at 10 Hz repetition rate. The strategy with respect to the cold linac is to base the cryomodule development on the ILC program, and to take full profit from the Fermilab's SRF infrastructure. The final goal is a cryomodule assembly and testing rate of one module per month. In total there is need for 38 ILC-like ß=1 cryomodules and possibly another 8 low ß=0.81 modules; the latter depends on the success of the Fermilab – Indian collaboration.

2.2.2 Cavities

For Fermilab it is important to transfer the SRF technology to U.S. industry. The first U.S. cavities were delivered and tested, but improvement in gradient is clearly needed. Even if some first cavities have reached quite acceptable performance for Project X, more cavities need to be produced in order to establish cavity production. This, unfortunately, needs time. A successful cavity program requires on the order of a dozen well-performing cavities. As frequently discussed in the SRF community, e-beam welding during cavity production is one of the main issues. In case the U.S. program proceeds at a slower pace, i.e., new U.S. vendors are not qualified within approximately the next two years, this is an acceptable risk for Project X since European vendors could be seen as a backup. Project X might profit from the forthcoming ordering of 800 XFEL cavities in European industry.

The Project X cavity design differs from the ILC and XFEL cavities with regards to the end groups and the HOM couplers. All changes especially in the end groups require a series of tests. A decoupling from the standard cavity tests might be required, thus additional cavities are needed. The time needed from the final test of a prototype cavity to the ordering of 300 cavities should not be underestimated. The first-series cavities have to be available in 2014, i.e. the call for bids is in less than 3 years. As a first step, reproducibility in surface treatment is a must, i.e. the closed-loop testing started in collaboration with JLAB should be continued.

2.2.3 Cavity and module testing

Fermilab has established the successful operation of vertical and horizontal testing. The test rate and duration is acceptable for the ILC/SRF R&D program; it can be compared with similar activities at KEK and DESY. The qualification of cavities from new vendors should be possible.

Nevertheless, Project X is a different order of magnitude. Plans to further develop SRF infrastructure were mentioned. A horizontal test stand and two more vertical test stands with larger radius to accommodate the Project X spoke resonators are under design. Processing facilities are to be expanded (with industry and JLAB involvement as well as ANL/FNAL). These plans should clearly be compared with the actually planned and ordered XFEL infrastructure at Saclay, Orsay, and DESY. Project X requires 38 + 8 CMs of 8 cavities each, i.e. almost 400 cavities, or 50% of the XFEL project's cavities. Maybe Fermilab can profit from mechanical design work actually done in Europe, e.g. transport frames being part of the test cryostat inserts. Plug-in compatibility might be desirable.

For Project X a yield of 80% at 25 MV/m in the years 2014+ was mentioned; this yield seems to be conservative if not pessimistic. The acceptable gradient spread should be discussed and a minimum gradient be specified. The choice of 25 MV/m seems to be reasonable. If higher gradients are available in 5 years then Project X can profit in terms of higher availability, i.e. 'spares' can be included in the original design / number of components.

The test of completely assembled accelerator modules requires attention. So far no cryomodule test was carried out at Fermilab due to last year's budget cuts. The cryogenic test and the test of the accelerator cavities in the first module are now scheduled for summer 2009. Highest priority should be given to this test. Project X requires changes in the cryomodule design. These necessary changes need a larger number of tests of prototype modules.

The final test rate for the modules is clearly an issue. A comparison with the work done and planned for the XFEL might be useful to align the activities.

Horizontal cavity testing is under discussion. Here the rational for testing should be understood. Are there other reasons than field emission, i.e. a check of the assembly procedure? Is the rf power coupler assembly seen as more risky than the final string assembly?

2.2.4 Cryostats

The work on the type-IV cryomodule is a good basis for the future Project X modules, as it leverages the ILC/SRF program for Project X. One of the major differences is the location of the quadrupole package. Here it should be understood that varying the position along the string may become a challenge with respect to clean assembly (pump and purge during the string assembly is usually done in one well-defined direction) and with respect to mechanical issues. If cryomodule production is to be established at U.S. companies, it would be timely to integrate the prototype production in the project plan. The qualification of a new company, the production of at least one prototype, the assembly and test of such a Project X cryomodule requires approx. two years after the final specification. The first type-IV cryomodule is scheduled for 2011, and the second for 2012; therefore, the first Project X cryomodule could be available in 2014 if no parallel development is foreseen.

A critical question is to what extend U.S. regulations require similar if not additional 'destructive' tests such as the one carried out with the TESLA-like module at DESY last year. Which module type has to be used – the final Project X type cryomodule? If so, one should take this into account in the project plan.

2.2.5 Cavity string and module assembly

There was and still is quite convincing 3.9 GHz assembly work. The final acid test will be the module test after arrival at DESY. The experience gained should be used for further work at Fermilab, and expertise should be integrated wherever it has not yet occurred.

Very important steps in the FNAL SRF program are the cold test of the 'assembly kit' and the complete string and module assembly of the second cryomodule using the existing cavities at

FNAL; both are scheduled for FY09. Again, the assembly and test should be given high priority. The critical issue will be field emission at the design gradient.

Is the assumed capacity of one accelerator module per month sufficient for Project X? To what extent can assembly problems be covered? Do the components arrive just-in-time? Does the plan assume the integration of industrial partners for the assembly?

2.2.6 ß=0.81 cavities

One design option for these cavities is a compressed 'standard' TESLA-style cavity, but the number of cells, HOM couplers, RF input couplers, and possible other design options are under discussion. This requires a full RD&D program, and the design issues should addressed over the next several months. The final solution will have significant impact on the cryostat design so it might become time critical. The recently started collaboration with Indian institutes needs strong leadership and a well-though-out project organization since the cavity modification adds a lot to the 'simple' task of technology transfer.

2.2.7 SRF materials

Impressive work was reported and Fermilab is contributing to generic cavity R&D. Unfortunately, a prediction of cavity performance based on optical inspection is not yet possible and might need quite some more R&D within the SRF community.

R&D on the gradient and yield is important not only for the ILC R&D but also for all other SRF projects. Further studies of the e-beam welds and the heat-affected zone are extremely important; the goal should be to understand the differences between different vendors. According to most of the SRF experts, we are dealing with a welding 'problem' and not with a material problem.

Laser melting and healing could become a repair method for some clearly identified defects in select cavities, i.e. it could be used to rescue some individual cavities. But the yield in gradient is the essential question, and the project needs the result of the first vertical test. Temperature mapping and other more sophisticated diagnostics (second sound) can only be used during the R&D phase.

2.2.8 Project X Linac RD&D plan

The breakdown of primary elements in the Project X Linac RD&D plan looks reasonable, as is the technical strategy as reported. Nevertheless, some comments:

- **Need for HOM couplers:** Go through the exercise, check if the HOM couplers are needed, but as a suggestion: it is better to solve the technical problems than lose flexibility in beam time structure. HOM couplers cannot be added later on.

- **RF couplers:** The average power dissipation is the issue; another might be to identify the RF coupler team developing the necessary Project X coupler. There are some good starting points as referenced in the AAC contribution. .

- ♦ **Klystrons/modulators:** The long pulse of up to 2.5 ms (upgrade scenario) might become an issue. The TESLA Multi Beam Klystron was characterized as somewhere between a pulsed and a cw klystron; is 2.5 ms / 10 Hz now quasi cw?

- ♦ **325 MHz Linac:** The scope is clear; the 325 MHz part of the linac with its source is an essential ingredient to the Project X. Resources should be allocated by the Project X management team as far as the specifications are driven by Project X. A number of important technical milestones were identified in the past and are still valid; further delays should be avoided. It might be useful to clarify to which extent the goals of the HINS program differ from the requirements of Project X.

2.3 MI/Recycler, Transfer Line and Injection, Civil, Controls, Cryogenics, Instrumentation

The AAC acknowledges that significant progress has been made since the last AAC meeting in May 2008, both in the content of the Project X proposal (ICD) and in the analysis of alternative configurations to better address the future needs (ACD). The operating modes envisaged in the ICD better take into account the capabilities of the recycler and debuncher rings. Preliminary attempts are being made in the context of the ACD to design solutions meeting the characteristics required by a future Muon Collider from the 8GeV - 4 MW proton beam. Although important, the work started for the ACD is not advanced enough and has not been sufficiently explained to be commented by the AAC at this stage.

As a way to reduce the risk associated with accumulating in the recycler, we suggest exploring the benefits of accumulating in the Main Injector for the neutrino program and perhaps accumulating for mu2e in another machine.

2.3.1 Beam Dynamics

The Main Injector and Recycler are existing rings at Fermilab that would be modified to operate with roughly 3 times the present beam current for Project X. It is critical for Project X that the performance of these rings be understood. There are many open questions in regards to beam dynamics in the Recycler and Main Injector, even in the ICD. These include maximum allowable space-charge tune-shift, allowable phase-space painting amplitudes, KV-painting schemes, estimates of conventional instability thresholds, estimates of electron-cloud effects and mitigation, performance of collimation systems, etc.

We urge a dedicated, vigorous effort of beam dynamics evaluation for the Recycler and Main Injectors as an urgent task. This effort should include both an experimental effort to benchmark existing simulation codes and a strong beam dynamics effort to make predictions for the new operating regimes.

We recommend the development of a beam-studies program aimed at exploring, to the extent possible, parameters more typical of those to be encountered in Project X.

In the Project X era, once Linac/Booster operations cease, the choice of RF frequency in the Main Injector is no longer constrained. This opportunity should be used to optimize the overall performance of the future facility, for example, with respect to electron-cloud effects which strongly depend upon the time structure of the beam and especially upon the distance between bunches.

We recommend reconsidering the choice of RF frequency in the MI and RR based on beam dynamics.

With every-other pulse in the linac having a different intensity, there may be other dynamics effects that could influence the beam quality. With the same linac peak current, space-charge in the linac dynamics is identical pulse-to-pulse. The low-level RF system response will be different every other pulse, which can readily be incorporated into the design. There may be other effects worth considering.

Exceedingly small beam loss can be tolerated in the transfer lines. The AAC takes note and finds adequate the work planned to meet that goal and allow for hands-on maintenance.

2.3.2 Cryogenic Systems

The choice of cryogenic segmentation in the superconducting linac is a critical one with far-reaching operational implications. The risk associated with limited segmentation is that the thermal cycling of a large segment may result in cold-leaks. On the other hand, full segmentation is expensive. At one extreme, SNS requires warming up individual cryomodules (which is possible due to the parallel feed system), at a rate of a few per year to gain access to components in the insulating vacuum space. At another extreme, the FLASH accelerating sections are treated as a single continuous cryomodule, which is rarely cycled.

An assessment of world-wide experience in this area is essential in order to make an informed decision.

Cryogenics infrastructure and Civil Engineering will represent a significant part of the cost of Project X. The AAC agrees with the content and schedule of the corresponding activities.

2.3.3 Control Systems

Controls have to smoothly evolve from their present status to first fulfill the needs of Nova and later support the upgraded accelerator complex. The control system for Project X is being developed to be back-ward compatible with the existing CAMAC-based Fermilab control system. Project X will be a large accelerator and care should be taken in the choice of the control system architecture and technology to ensure the desired performance and the ability of external users to collaborate. The plans to test new control system ideas at NML and HINS should be supported. The Committee is satisfied with the foreseen plans for the control system.

2.3.4 Beam Instrumentation

The existence and placement of beam instrumentation must be derived from the beam dynamics simulations and requirements for machine tune-up. One cannot overstate the importance of establishing a high-quality beam for injection into a high-power linac. Beam instrumentation must be incorporated into the front-end design to ensure that the capabilities for transverse and longitudinal matching are there, and that emittances and emittance growth and halo can not only be measured, but used to refine set-points in order to minimize halo and beam loss.

We recommend an approach to beam instrumentation deployment that is based on beam dynamics evaluation and accelerator tune-up requirements. Perform a beam dynamics evaluation to establish the optimum spacing for BPMS, BLMs, profile monitors, emittance measurement etc, keeping in mind the routine tune-up activities that are required at any high intensity linac (trajectory correction, RF setpoint determination, transverse and longitudinal matching).

Instrumentation developed for Project X will require in-beam tests to validate performance. The project should pursue possibilities for beam tests at other institutions, SNS for example, if they cannot be obtained locally.

2.3.5 Summary technical risks

Regarding the charge question, "What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?", we see the following primary technical risks:

- Main Injector and Recycler: The three-fold increase in intensity in the Main Injector, and use of the Recycler as a high-throughput, high-intensity accelerator demands very careful consideration of collective effects. There are plans to evaluate collective effects in the RD&D plan.

- Transfer Lines and Injection: The Injection region is arguably the most complicated region in the Project-X complex. Risks include the proper transport and handling of waste beams, achieving sufficient phase-space painting amplitudes to minimize space-charge effects and therefore minimize halo growth.

- Civil Facilities: The risk in Civil construction is primarily related to cost and schedule; we do not see substantial technical risks.

- Cryogenic Facilities: The choice of segmentation is critical. There are risks to the operational efficiency and flexibility of the facility associated with the choice of segmentation. This decision requires very careful consideration.

- Controls: The primary risk relates to the smooth deployment and integration of new control system components with existing legacy systems. The risk is identified and plans are in place to address this.

- Instrumentation: There is technical risk associated with insufficient beam instrumentation deployment, particularly in the longer term era, when multi-MW beams are needed for the linac.

3. Muon Cooling

3.1 Summary response to charge

Observations

- 6-D ionization cooling in a helical solenoid version of a helical cooling channel (HCC) is a novel idea in a very compact configuration.
  - Scheme appears promising, but as other cooling schemes were not discussed, the committee was unable to make a comparative judgement. The magnet part of the HCC concept is relatively advanced, including construction of demo magnets, thanks to SBIR funding (Muons, Inc).
  - Analytical work and system optimization via simulations appears correct without obvious flaws.
- MANX experiment aims to test the 6-D HCC cooling model without resorting to the use of RF (RF acceleration problems are common in all ionization schemes).
- An achievement of a factor of two cooling would be a convincing demonstration of the concept and significantly stimulate the NF/MC R&D program.
- We were told that MANX has the potential to increase the physics reach of the Mu2e experiment.
- In view of the Mu2e timeline, it would be useful for the potential MANX upgrade to be considered.
- The question of the timeline and resources is the most difficult.
  - The cost of MANX was estimated as ~$10M, assuming it is a follow-up to MICE and reuses a significant portion of the equipment. The committee had no basis for evaluating this estimate. A detailed cost and schedule should be prepared, providing the basis for the estimate and including expected funding sources.
  - Both the magnetic channel and RF system need major R&D effort.
  - MANX should consider applying for SBIR/STTR funding for the TOF detectors and magnets.
  - FNAL may consider providing resources for MANX in equipment that may become available from the HEP experiments, as well as limited personnel based on their availability. One possible item, if and when the design is well developed, is to provide the magnets. Another possibility is help with cryogenics.

Recommendations

16. Firm recommendations by the AAC are not possible without a comparison of MANX with alternative schemes. But the laboratory leadership is strongly encouraged to help the MANX team accelerate its R&D effort to establish its critical cost and performance advantages with respect to alternatives as fast as possible, given its significant promise.
17. More homework is needed for MANX and the HCC. We encourage a more detailed simulation effort, on the scale of one year, to better understand the technology, to determine the acceptance and matching tolerances, and to optimize the parameters.
18. We encourage a study, on the scale of one year, of the impact of HCC on the Mu2e upgrade (est. in ~2020.) This is not inconsistent with the decision by the NFMCC/MCTF 5-yr plan to adopt a particular 6-D cooling scheme by ~2013, followed by 5 yrs construction and 2 yrs testing at RAL.

3.2 HCC 6-D Cooling Theory/Simulation

A novel, 6D ionization cooling scheme employing the "Helical Cooling Channel" (HCC) was presented during the AAC meeting. The HCC is a very valuable new idea that can be applied in numerous parts of a Muon Collider, as well as in physics experiments (e.g. Mu2e). As other cooling schemes were not discussed, this Committee is not able to make a comparative judgment of the proposed scheme against other schemes. However, the scheme appears to be promising since cooling and emittance exchange occur continuously in HCC.

The magnetic field of HCC is a clever superposition of several different types of magnetic fields – solenoidal field, and helical dipole and helical quadrupole fields. The combined field provides a helical reference orbit, and longitudinal-transverse coupling (thus emittance exchange) and focusing of trajectories around the reference orbit. The direction of the solenoidal field remains constant. By filling the channel with a homogeneous absorbing medium and providing rf acceleration, cooling can occur continuously in 6D phase space. The HCC can therefore be more compact with a larger acceptance compared to other schemes in which the direction of the solenoidal field needs to be reversed periodically and the absorbers are placed in discrete locations. It is claimed that a 6D cooling of 10^{-6} can be achieved in a sequence of three HCC sections of decreasing cross sections (increasing RF frequencies).

The optimization of the system was performed analytically and also with particle-tracking simulation. These analyses look correct without any obvious flaw. However, it may help to understand the system by describing the beam optics with usual linear optical functions such as beta, phase advance, dispersion, and x-y coupling parameters. For instance, the acceptance and the matching tolerance may be more easily discussed with such linear optical functions. Also it will help the optimization of the parameters.

For tracking simulation, it is always important to define the independent variable(s) and the associated canonical variables, otherwise one cannot discuss the emittance. Some notations on the presented slides may have not been clear concerning this point.

The HCC scheme provokes excellent hardware development: Design of the "helical solenoid" (HS) producing an appropriate magnetic field for HCC was presented consisting of a sequence of solenoidal coils whose centers follow a helical path. A concept for an RF cavity fitting within the helical solenoid was also discussed, consisting of wedge-shaped cells. The cavity cross section can be further reduced by using a suitable dielectric lining.

The HCC is not the only 6-D cooling idea. Others include what are called a RFOFO ring or "Guggenheim" cooler. However, thanks for significant SBIR funding (given to Muons, Inc.), the HCC cooling scheme is in a relatively most advanced stage, down to the construction of demo magnets. The HCC theory and simulation effort, as well as the hardware development, may be regarded as one of the particularly successful SBIR programs.

A test experiment, MANX, was proposed aiming for a factor of two reduction in 6-D phase space volume in a 10-m HCC. More details on MANX are described in the next section. The channel would not be equipped with RF since RF acceleration problems inside an absorbing material have not been solved yet—a problem common to all ionization cooling schemes. The Committee supports the proposal in principle; an achievement of a factor of two cooling would be a convincing demonstration of the ionization cooling concept providing a significant stimulation for the neutrino factory/muon collider R&D program.

However, MANX can cost up to $10M. An experimental effort of this magnitude should be fully integrated with the mainstream ionization cooling R&D program coordinated by NFMCC and MCTF. The Committee notes that MANX is currently not in the Muon 5-year plan of NFMCC and MCTF**.** We therefore endorse the Muon 5-year plan to decide on proceeding with experiments after MICE, to take advantage of HCC and other schemes.

3.3 MANX and Mu2e

The Mu2e experiment and the MANX helical cooling experiment have to be seen in the broader context of the FNAL plan for future facilities and the international collaboration pursuing the particle physics and accelerator physics of muon generation, acceleration and cooling.

The Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) are strong, international and productive activities. These collaborations are pursuing a broad and well-managed R&D plan, including design, theory, simulations and component testing.

The Mu2e experiment and the MANX helical cooling experiment were described in a few excellent presentations. Clearly the subjects are scientifically exciting and the material was delivered with passion. The Mu2e physics potential is very impressive. A design is in place based on the proposed (and cancelled) MECO experiment on the AGS at BNL. This design, which is being used for the Mu2e experiment, represents a large investment, and a good use is being made at FNAL of that effort.

Clearly, the benefits to the reach of Mu2e from the beams that may be delivered by Project X are significant. MANX potentially adds even more reach, as we were informed, of about 2 orders of magnitude. That adds to the potential uses of MANX, which thus go beyond its significance as a demonstration of 6-D muon cooling scheme.

The committee was presented with the NFMCC and MCTF's five-year plan, which describes in detail the R&D program for muon accelerators. This plan calls for a NF Reference Design Report (RDR), to be done through participation in the International Neutrino Factory Design Study by 2012. The emphasis of the proposed U.S. participation in this RDR is on: a) design, simulation and cost estimates for those parts of the NF front-end that are (or could be) in common with a MC; b) develop overall system design and staging scenarios; and c) address siting issues.

The five-year plan also calls for a MC Design Feasibility Study Report (DFSR) to be completed in 2013. The DFSR is aimed at a multi-TeV MC including a physics and detector study, an end-to-end simulation of the MC accelerator complex using demonstrated or expected technologies, a cost estimate, and an identification of further needed R&D.

In particular we note that the five-year plan calls for hardware development, needed for cooling down-selection and the completion of MICE. Other work is associated with RF (considered the most critical item, attaining high RF gradient in strong magnetic fields), magnets, absorbers and target.

3.3.1 The MANX Experiment

The Helical-Cooling Channel, of which MANX is a proposed demonstration experiment, is one possibility to achieve the required muon cooling. The theoretical studies need to be complemented by experiments. If this were successful, it would be a great step forward towards the feasibility demonstration of a muon collider.

In the context of this Accelerator Advisory Committee it is impossible to review the concept of HCC or appreciate all its implications and limitations. We note that the scheme that was presented has some issues, such as the magnetic channel and the RF system. For the MC, this is a 1.5 GV system, which has to work under adverse conditions. Both magnetic channel and RF system need a major R&D effort.

The MANX experiment's purpose is to design, engineer and build a 10-m section of HCC cooling channel for physics and technology demonstration aimed at a muon collider and/or a neutrino factory. In particular it will test a six-dimensional helical cooling model, aiming for a factor of two reduction in 6-D phase space volume, and investigate the capability and limitations of a helical cooling channel without resorting to the use of RF.

The most cost-effective location of MANX is at RAL, following and on the site of the Muon Ionization Cooling Experiment, MICE. Studies that were presented to the AAC indicate that MANX can fit in the MICE hall, actually in two configurations, an in-line (matched) version and an off-axis version. The off-axis version reduces the cost of the magnets and improves the performance of the experiment.

The questions of the timeline and resources are the most difficult.

Considering first the timeline, there are two issues. One is the completion of MICE, the other is the 5-year plan of the NFMCC and MCTF. First, the MICE experiment is currently expected to be done 2013. Based on observation of past progress and the tasks that remain to be done at this time, this schedule is expected to slip. The second issue is the 5-year plan. The MC collaboration plan is that a 6D cooling experiment should start only at year 5, after a bench test, end-to-end simulations and planning of 6D demo experiment, that is after year 5. Furthermore, due to the various cooling options that exist, the 5-year plan calls for the selection of a baseline 6D channel in year 3. After selection, build and bench test cooling channel section. This is limited by developing confidence, making decisions and limited manpower.

A statement by the 5-year plan developers underscores the last item, limited manpower. The 5-year plan is pushing the envelope of financial and manpower resources, even as it expects a significant growth in funding. This plan does not allow for funding a 6-D cooling experiment at this time.

The cost of MANX, as provided to the AAC, is estimated at $8M + 23 FTE for the matched MANX, or $5.5M + 18 FTE for the off-axis version of MANX. This cost assumes MANX to go into the MICE location and use a significant portion of the MICE equipment. The committee did not receive a detailed schedule for the MANX experiment, showing at what time these resources are needed.

One motivation that the AAC was asked to evaluate was the benefit of MANX to the Mu2e experiment schedule and when does Mu2e need MANX working. The benefit is clear, being the addition of two orders of magnitude to the reach of Mu2e, beyond the large increase provided by Project-X.

We were told that the fastest time possible for Mu2e to start is by 2016. With that, the next stage of using a HCC channel upgrade is at about 2020. Therefore we conclude that a decision resulting by the 5-year plan at about 2013 which adopts a particular 6-D cooling scheme (possibly HCC), followed by five years of construction and perhaps two years or testing at RAL is not inconsistent with the demand for the HCC channel to go into Mu2e by 2020, but is seems tight. One concludes that it is desirable to make progress on MANX during the next five years (taken by the 5-year plan), subject to the availability of resources.

Given that the whole muon program is resource limited, one could take advantage of the SBIR program to move ahead and in parallel to the main program. It is somewhat unfortunate that SBIRs do not lend nicely for cryogenics, which is a large expense item for MANX.

We recommend that the impact of HCC on the Mu2e plan be evaluated within one year**.**

3.3.2 Conclusions

If successfully executed, the MANX experiment can provide a partial validation of the HCC 6-D ionization cooling scheme, based on requirements for a Muon Collider. There is a much more significant cooling needed in parametric ionization cooling (PIC) and reverse emittance exchange (REMEX), of which the committee heard little more than a mention of the name.

An optimum mix of simulations and experimental demonstration to provide validation should include execution of MICE followed by a 6-D cooling scheme with full simulations. Much more homework needs to be done, results and lessons learned from Mice should be taken into account before one can decide if MANX is the right thing to do.

The primary technical risk within the MANX proposal is the high magnetic field with unusual configuration. In particular, the return field of the magnet has to be accommodated. It is appropriately mitigated through the development program, which includes the construction of high field magnets.

New high-resolution TOF counters (<5 psec resolution) are needed, and are being developed, but this represents another risk.

Given the anticipated timelines within the Muon five-year plan and the Mu2e development plan, the appropriate place and schedule for implementation of MANX (assuming MANX is not displaced by a new scheme) are RAL for the location, installation as soon as possible after MICE ends (2013). Equipment should be prepared ahead of time subject to previous remarks about resources.

The AAC was asked also to consider if the MANX resource requirements appear reasonably estimated. The committee has no basis for making this evaluation.

The application aspect of MANX to Mu2e is very appealing. Physics-wise, we heard that "Mu2e might be the only stepping stone between Neutrino physics and muon collider, if NF disappears". Still, in applying MANX to Mu2e, we are talking about an upgrade of an experiment that has not even started. However, the benefit for the Mu2e experiment is expected be large. There were many decision points on the road and MANX should be carefully considered in the mix.

Simulation of the cooling process is very important. It seems that the programs still need to be significantly improved to include many more physical effects.

The time is right to start thinking what will be a follow-up experiment to MICE. MANX is a fairly well developed 6-D cooling scheme. Given the limited resources as outlined by the 5-year plan, and respecting the consensus reached by NFMCC and MCTF, one solution would be that FNAL considers providing resources for MANX from FNAL in equipment that may become available from the experiments, as well as limited personnel based on their availability. One possible item, when the design is well developed, is to provide the magnets. Another possibility is help with cryogenics. However it goes however beyond the capability of the FNAL AAC to firmly recommend such a solution, which would necessitate much more information about the status and proposals concerning alternative schemes.

MANX should pay attention to the return field path of the magnet and its effect on the field and environment. Another recommendation is, if possible, use wedges, not liquid helium since LHe is not appropriate for the NF/MC application due to the large expected heat load. The MANX collaboration should carry out a detailed comparative study of the on-axis (matched) MANX and the off-axis version. We were led to believe that there are clear advantages to the off-axis approach.

MANX should consider applying for SBIR/STTR funding for the TOF detectors and magnets.

A detailed cost and schedule of MANX should be prepared, providing the basis for the estimate and outlined expected funding sources. The MANX collaboration should identify results from MICE are needed to proceed with a follow-on like MANX, and estimate the likely impact the MANX schedule.

Fermilab Accelerator Advisory Committee
February 3-5, 2009

Charge (Draft Rev. 2)

The Fermilab Accelerator Advisory Committee is asked to look at several activities supporting the Fermilab strategic plan for the post-Tevatron era. The primary topics for review and discussion are:

1. Project X ICD and R&D Plan

An Initial Configuration Document (ICD) has been developed and released for Project X (see http://projectx.fnal.gov). The ICD is based on specific mission objectives that are expected to form the basis for the establishment of a mission need for Project X (CD-0 in the Department of Energy system). The purpose of the ICD is to provide the basis for a preliminary cost range estimate for Project X (required for CD-0), for the refinement of the Research, Design, and Development (RD&D) plan developed early in 2008, and to establish a starting point for consideration of design alternatives.

The Project X RD&D effort is aimed at supporting all activities required to complete a technical, cost, and schedule baseline (CD-2 in the language of DOE) by the end of 2012. The RD&D plan is integrated with R&D programs running in parallel on ILC, SRF Infrastructure, High Intensity Neutrino Source (HINS), and Muon-based Facilities.

The Committee is asked to review and offer comments/recommendations relative to the ICD and the accompanying Project X RD&D plan. In particular we request specific comments and recommendations in the following areas:

- Does the ICD describe a configuration that is likely to meet the proposed mission objectives?
- What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?
- Is the RD&D plan appropriately integrated with the ILC, SRF, HINS, and Muon programs?

More generally, we would be happy to receive comments and suggestions from the AAC on how the initial configuration and associated RD&D program could be strengthened.

2. Muon 6-D Cooling Development

A proposal for experimental demonstration of six-dimensional ionization cooling in a Helical Solenoid (HS) version of a Helical Cooling Channel (known as MANX) has been received by Fermilab. This proposal goes beyond the scope of the Muon Ionization Cooling Experiment (MICE) being mounted at RAL, in particular by aiming to demonstrate cooling techniques that would be applicable to muon colliders, neutrino factories, and stopping muon beams. The MANX HS design also serves as a prototype for a stopping muon beam system for an upgrade to the mu2e experiment that could benefit from 1 MW of Project-X beam power.

In parallel, two related developments are in place: First, the Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) have jointly prepared and submitted to the DOE a five year proposal for the U.S. muon program with primary goals of: 1)contributing to the International Design Study for a Neutrino Factory currently being pursued by an international collaboration; and 2)completing a first feasibility study for a Muon Collider operating at an energy above 1 TeV with a luminosity of order 10^{34} $cm^{-2}sec^{-1}$. It is anticipated that the DOE will conduct a formal review of this proposal sometime over the next six months. Second, the laboratory has received a proposal to mount an experiment to search for muon to electron (mu2e) conversions at unprecedented sensitivity utilizing the existing Booster and Antiproton Source.

The Committee is asked to review and offer comments/recommendations relative to the MANX proposal both within the context of the Muon five year proposal and possible upgrades to the mu2e experiment. More specifically we would like the Committee to comment on:

- If successfully executed does the MANX proposal provide a validation of 6-D ionization cooling, based on requirements for a Muon Collider. What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
- If successfully executed does the MANX proposal provide a validation of an upgrade of the mu2e experiment based on a collection scheme that reduces "flash" deadtime and the use of the ionization-cooling energy-absorber to range out hadronic backgrounds? What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
- What are the primary technical risks within the MANX proposal and are they appropriately mitigated through the development period?

- Given the anticipated timelines within the Muon five year proposal and the mu2e development plan, what is the appropriate schedule for implementation of MANX, either at Fermilab or at RAL?
- Do the MANX resource requirements appear reasonably estimated?
- Can the MANX approach to a mu2e upgrade impact the outlook for Project X?

As usual the committee is invited to issue comments or suggestions on any aspect of the programs discussed beyond those specifically included in this charge. It is requested that a concise report responsive to this charge be forwarded to the Fermilab Director by April 1, 2009. Thank you.

Fermilab Accelerator Advisory Committee
Agenda

Feb 3-5, 2008
Comitium, Wilson Hall 2SE
Revision 12-Jan-2009

Tuesday, February 3

8:30-9:00	Committee Executive Session	K. Harkay
9:00-9:20	Welcome, Meeting Context, and Presentation of Charge	S. Holmes

Project X (Session organized by Sergei Nagaitsev and Steve Holmes)
Overview of the ICD and RD&D Plan

9:20-9:50	Overview of the ICD	P. Derwent
9:50-10:20	Overview of the RD&D Plan Including evolving thought on operating scenarios and design alternatives	S. Nagaitsev
10:20-10:45	Break	
10:45-11:10	Overview of the ILC and SRF programs With emphasis on PX components	S. Mishra

RD&D Plan
This set of talks should cover the elements of the RD&D plan:
- *Description of the scope of the system*
- *Performance specification of the system*
- *Primary technical issues and the strategy to address them*
- *Goals of the plan by year*
- *Role of outside collaborators.*

11:10-11:30	325 MHz Linac Includes HINS program	R. Webber
11:30-12:00	1300 MHz Linac	M. Champion
12:10-12:30	Discussion	
12:30-1:30	Lunch	
1:30-1:50	MI and Recycler Rings	I. Kourbanis
1:50-2:10	Beam Transfer Line	D. Johnson
2:10-2:30	Civil Facilities	R. Alber
2:30-2:50	Cryo facilities	A. Klebaner
2:50-3:05	Controls	J. Patrick
3:05-3:20	Instrumentation	M. Wendt
3:20-3:45	Discussion	
3:45-4:00	Break	
4:00-5:00	Committee Executive Session. Requests for supplementary or breakout presentations on Wednesday	

6-D Cooling Experiment (MANX – Session organized by Rol Johnson and Vladimir Shiltsev)

The opening two talks are meant to set the context for evaluation of the proposal. Each presentation should define the role of ionization cooling, the required cooling performance, and the time at which such performance needs to be demonstrated.

<u>*Context*</u>

5:00-5:35	Muon Collider 5 year plan Plan, timeline, resources	A. Jansson
5:35-5:50	Mu2e Plans and needs	R. Bernstein
5:50-6:35	Overview of MANX Helical Cooling Channel basics, MANX as part of larger muon program	R. Johnson
6:35-8:00	Dinner	

Wednesday, February 4

6-D Cooling Experiment (MANX - continued)

8:30-8:50	Theory of the HCC History, derivation, epicyclic channel	S. Derbenev
8:50-9:10	Uses of the HCC Muon collection, 6D cooling, extreme cooling for MC, NF, and stopping muons	M. Cummings
9:10-9:35	Mu2e applications Overview, upgrade to HCC, relationship to Project X	C. Ankenbrandt
9:35-9:55	Helical Solenoid Magnet concept, 4-coil model, cost estimates	V. Kashikhin
9:55-10:20	Break	
10:10-10:40	MANX Concepts, simulations	K. Yonehara
10:40-11:00	RAL Siting Detectors, logistics, resources	R. Abrams
11:00-11:20	MANX at RAL Integration, timeline, MICE viewpoint	D. Kaplan
11:20-12:30	Discussion Break Supplementary presentations/discussion as requested by the committee	
12:30-4:00	Working Lunch Committee Executive Session	
4:00-5:00	Closeout	
5:00	Adjourn	