Phase II-STTR 2007-9

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PROJECT TITLE: **Development and Demonstration of 6-Dimensional Muon Beam Cooling**

TECHNICAL ABSTRACT (Limit to space provided)

Statement of the problem or situation that is being addressed - typically, one to three sentences.

Ionization cooling, a method for shrinking the size of a particle beam, is an essential technique for future particle accelerators that use muons. Muon colliders and neutrino factories, examples of these future accelerators, depend on the development of robust and affordable techniques for ionization cooling.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, one to two sentences.

This proposal is to develop an experiment to prove that effective six-dimensional (6D) muon beam cooling can be achieved using an ionization-cooling channel based on helical and solenoidal magnets in a novel configuration. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood, thereby overcoming a critical roadblock to intense neutrino factories and high-luminosity muon colliders.

What was done in Phase I – typically, two to three sentences.

In Phase I we synthesized developments in our other SBIR-STTR projects to generate simulations of a 6D experiment that included a novel design of a helical solenoid magnet and efficient emittance matching sections. A simulation/reconstruction program that was developed for a 4D muon cooling experiment has been adapted for our 6D purposes and it is ready to for exploitation in Phase II. We have made plans for the prototyping of a section of the helical solenoid magnet to test its magnetic, mechanical, and thermodynamic properties.

What is planned for the Phase II project - typically, two to three sentences.

The simulation/reconstruction program started in Phase I will be developed and exploited to optimize experimental parameters by improving beam cooling significance, understanding systematic errors, and exploring engineering simplifications and their ramifications. Phase II includes participating in the engineering of the HCC and emittance-matching magnet systems, helping to construct and test a three-coil prototype superconducting helical solenoid, and working with the Fermilab Muon Collider Task Force to develop a collaborative experimental proposal.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

The applications of the new techniques that will be developed and proved by this project involve very bright muon beams for fundamental research using muon colliders, neutrino factories, and muon beams with new characteristics. The most important application will be an energy frontier muon collider which achieves high luminosity by virtue of small emittance rather than large muon flux. The small emittance in all dimensions that is possible as shown by this project will allow high-frequency ILC RF structures to be used for such a collider and also for a high flux muon beam that could supply a storage ring used as a neutrino factory.

Key Words: Muon-beam, ionization-cooling, six-dimensional, demonstration experiment

SUMMARY FOR MEMBERS OF CONGRESS: (LAYMAN'S TERMS, TWO SENTENCES MAX.)

An energy frontier muon collider, potentially the most powerful subatomic micoscope, becomes a realistic machine if muon beams can be made small enough in their short lifetime. This project is to develop the required techniques to cool muon beams and design an experiment to prove that the techniques work.

NARRATIVE SECTION

Development and Demonstration of Six-Dimensional Muon Beam Cooling

Table of Contents

Overview

The theoretical description of the helical cooling channel (HCC) using a continuous homogeneous absorber [1] has guided several simulation efforts [2] which have confirmed the utility of the HCC approach to six-dimensional muon beam cooling. The ultimate HCC will involve new technologies now under development, namely high-pressure RF cavities and High-Temperature Superconductor used to get 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 is the next step.

The momentum-dependent HCC, where the energy lost in the absorber is not immediately replaced and the magnetic fields are reduced to match the beam momentum, has been developed as a precooler and more recently as a means to increasing the yield for stopping muon beams [3]. The momentum dependent HCC is the basis for the 6DMANX experiment that is the subject of this proposal.

Since the Phase I proposal for this project was submitted in December of 2005, there have been some very noteworthy developments:

1) In May of 2006, Muons, Inc. and collaborators from BNL, Fermilab, IIT, and Jefferson Lab submitted a Letter of Intent (LoI) to propose a 6D Muon Cooling Demonstration Experiment to Fermilab. This LoI is the first Appendix to this proposal. It was largely composed of material from the Phase I proposal of this STTR project.

2) One week after the LoI was submitted, Fermilab Director Pier Oddone, had us present our case in person to him and his management team. He then formed a Muon Collider Task Force (MCTF) headed by Vladimir Shiltsev and Stephen Geer. The charge letter to the MCTF is Appendix II of this proposal, where the enthusiasm for the ideas in the LoI and explicit references to working with Muons, Inc. are seen.

3) Working under the Phase I funding of this grant and the Phase II funding of our other grant with the Fermilab TD Division, we succeeded to come up with a very novel and amazingly simple design for a momentum-dependent HCC magnet. Appendix III is a reprint of a 2006 Applied Superconductivity Conference paper describing two approaches to the momentum-dependent HCC magnet. We note that the very novel design based on displaced coils (called the helical solenoid) 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.

4) We also developed a scheme to match the emittances of up and downstream spectrometers to the HCC. Appendix IV is a draft of a PAC2007 paper describing the present state of the 6DMANX design with the use of a shortened LHe absorber that is consistent with a lower momentum muon beam than was discussed in the Phase I proposal.

5) The MCTF has studied use of the MuCool Test Area (MTA) as a site for a muon beam suitable to do the 6DMANX experiment. (This is in addition to the 400 MeV proton beam to the MTA to measure the effects of passing a beam through an RF cavity.) An idea to improve the duty factor and the intensity for muon production for the MTA has been partially developed under Phase I of this STTR (see Appendix V). Muons, Inc. has also investigated other possible FNAL sites for the 6DMANX experiment, including several locations in the Meson area, and the former KTeV area. Studies also underway to evaluate spectrometer and detector requirements and types of detectors for measuring the cooling effectiveness of the cooling channel in the 6DMANX experiment, e.g. whether it is necessary to have detectors inside the cooling channel volume. Techniques such as tracking of individual particle trajectories and utilization of aggregate ensembles of particles ("beamlets") are being considered. We also continue to work with the MICE collaboration, and explore the possibility of testing our cooling channel in a later phase of the MICE experiment at RAL.

6) Since the 6DMANX experiment is a test of the HCC concept, we believe that it is important to know that the HCC will be actually be used. To that end, considerable progress has been made on the use of HCC schemes for muon cooling: a) The high-pressure RF cavity experiment had good results, showing no maximum gradient degradation even in a strong magnetic field [4]. b) 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 and operational by the end of 2007. c) The design of a series of HCC segments has been improved to operate with less stringent requirements on the magnetic and RF fields [5]. d) A new use of a HCC to enhance the stopping muon rate for rare event searches is described in Appendix VI, which is a draft of a PAC2007 paper describing a variation on the HCC which is very similar to the 6DMANX design itself to enhance the stopping beam for a muon to electron conversion experiment.

As described below, this STTR Phase II proposal, if granted, will allow us to continue the development of the 6DMANX concept. We will continue to improve the experimental simulations and participate in the prototyping of the helical solenoid magnet and particle detectors. We will continue to build the collaboration capable of carrying out a convincing experiment in good time with reasonable costs. The outcome of the project will be an approved and funded experiment that will generate the confidence to build wonderful machines based on cooled muon beams.

The Current Muons, Inc. Physics Program

The projects discussed below are concerned with the production, cooling, and uses of intense and bright muon beams to be used for various purposes. These SBIR and STTR projects represent a coherent, innovative program to reduce the cost of neutrino factories, facilitate designs of high-intensity muon colliders, and provide muon beams with new physics potential.

Muons, Inc. started with the idea that a gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve [6]. This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Additionally, use of a gaseous absorber presents other practical advantages that make it a simpler and more effective beam cooling method compared to liquid hydrogen flasks in the conventional designs.

Measurements by Muons, Inc. and IIT at Fermilab have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure. Consequently, much more gradient is possible in a hydrogen-filled RF cavity than is needed to overcome the energy loss, provided one can supply the required RF power. Hydrogen is also twice as good as helium in ionization cooling effectiveness, and has better viscosity and heat capacity. For these reasons hydrogen is our material of choice.

As discussed below, recent measurements show that hydrogen pressurized RF cavities do not suffer from a reduction in maximum gradient while operating in intense magnetic fields as do evacuated cavities. Thus it is possible to combine the energy absorber and RF reacceleration in pressurized cavities in regions where large magnetic fields create the required focusing for ionization cooling. This means that pressurized RF cavities have two very significant advantages over any scheme involving evacuated RF cavities: greater gradient in the required magnetic field and the simultaneous use of the hydrogen gas as energy absorber and breakdown suppressant. These two advantages each lead to shorter muon cooling channel designs, which minimize the loss of muons by decay and also lower construction costs.

The use of a continuous absorber as provided by a gas-filled RF system implies a new idea (first proposed as an SBIR topic) to provide a natural, very effective means of achieving emittance exchange and true six-dimensional (6D) cooling [7]. Namely, if the superimposed magnetic field provides dispersion down the beam channel such that higher momentum corresponds to longer path length and larger ionization energy loss, the momentum spread can be reduced. Simulations of a Helical Cooling Channel (HCC) of superimposed helical dipole, helical quadrupole, and solenoidal fields show a 6D emittance reduction by a factor of 50,000 in a channel only 160 meters long. This cooling factor is very much larger than in other cooling channels of comparable length.

Once the beam has been cooled in the HCC, other cooling techniques are possible. Recent developments have indicated that special cooling channels employing parametric resonances and/or very high field magnets can produce muon beams with small enough emittance that they can be accelerated using 1.3 GHz RF cavities. Thus we have started thinking about a muon collider using superconducting RF technology as a possible upgrade to the International Linear Collider (ILC).

One possibility that was explored at the Low Emittance Muon Collider (LEMC) Workshop held at Fermilab (http://www.muonsinc.com/mcwfeb06/) Feb 6-10, 2006 was to consider the proposed Fermilab 8 GeV superconducting proton driver Linac as a triple-duty machine on the path to an energy frontier muon collider. Such a Linac could accelerate protons to produce the muons, which would then be injected into the constant velocity section of the Linac to be accelerated by recirculation for use in a muon storage ring neutrino factory. (The third duty in this case would be to act as an ILC string test.) Such a neutrino factory could be very effective for two reasons. First, the neutrino production would scale with the repetition rate of the Linac and might easily outperform other designs. Second, the acceleration cost of the neutrino factory would be borne by the other uses of the superconducting Linac and the neutrino factory cost would be incremental. The present proposal is to explore ideas and techniques to capture and precool more muons so that this approach to a neutrino factory will be even more attractive.

The next step, first proposed under another SBIR grant (Reverse Emittance Exchange) with Thomas Jefferson National Accelerator Facility (JLab), described below, and explored at the first and second LEMC (http://www.muonsinc.com/mcwfeb07/) Feb 12-16, 2007 workshops, is to replace the muon storage ring of the neutrino factory with a coalescing ring to combine bunches for use in a muon collider. Such a muon coalescing ring could operate at the energy of the neutrino factory storage ring, above 20 GeV. The muon beam for the collider would then be similar to that of the neutrino factory up to the coalescing ring. This approach to a muon collider has several advantages that are very attractive. First, the development of the neutrino factory based on acceleration in the 1.3 GHz RF structures requires significant muon beam cooling so that the neutrino factory becomes an intermediate step to a collider. Second, the large single bunch intensities that a high luminosity muon collider requires are not needed at low energy where space-charge, wake fields, and beam loading are problematic.

Once the beam has been coalesced into a few high intensity bunches, recirculating Linacs using 1.3 GHz RF can accelerate them to a hundred GeV/c or more for a Higgs factory or to 2 to 3 TeV/c for an energy frontier muon collider. One of the studies of the present proposal will to be to investigate bunching techniques that are well suited for coalescing.

This path to an affordable neutrino factory and a compelling design of a muon collider has complementary projects that Muons, Inc. is pursuing with SBIR/STTR grants and proposals:

Phase II Projects

1) The development of Pressurized **High Gradient RF Cavities** was the subject of an STTR grant with IIT (Prof. Daniel Kaplan, Subcontract PI), which began in July 2002 and ended in September 2005. In this project, Muons, Inc. built two 805 MHz test cells (TC) and used them to measure the breakdown voltages of hydrogen and helium gases at FNAL with surface gradients up to 50 MV/m on copper electrodes. Phase II started in July 2003 to extend the measurements at Fermilab's Lab G and the MuCool Test Area (MTA) to include effects of strong magnetic fields and ionizing radiation at 805 MHz. A new test cell was built under this grant, passed

safety requirements associated with the high pressure hydrogen, and was used to extend Paschen curve measurements for hydrogen beyond 60 MV/m surface gradient (20μs pulse width) using electropolished molybdenum electrodes [8]. The new test cell is capable of 1600 PSI operation in the 5 Tesla LBL Solenoid, recently installed in the MTA, with ionizing radiation from the 400 MeV H^- Linac. IIT, Muons, Inc. and Fermilab staff members prepared a design [9] for a beam line from the Linac to the MTA using available magnets and other components, but the beam line is not expected to be completed until summer 2007. We had planned to have a demonstration of pressurized high-gradient RF cavities operating in intense magnetic and radiation fields by the end of the STTR Phase II grant period, however the Lab G work was terminated when Fermilab operations removed the klystron from Lab G in January 2004. A klystron became available to us in the MTA in the summer of 2005 without the Solenoid or the implementation of the beam line. The Solenoid began operation in the MTA in March, 2006 and work on high-pressure RF cavities has restarted.

2) **Six-Dimensional (6D) Cooling** using gaseous absorber and pressurized high-gradient RF is the subject of an SBIR grant with Thomas Jefferson National Accelerator Facility (Dr. Yaroslav Derbenev, Subcontract PI), which began in July 2003 and will end in July 2006. A magnetic field configured such that higher energy particles have a longer path length can be used to generate the momentum-dependent energy loss needed for emittance exchange and six-dimensional cooling. In the 6D channel, helical dipole and solenoidal magnets and the RF cavities in them are filled with dense hydrogen so that higher energy particles then have more ionization energy loss. A paper describing the concepts and dynamics of this Helical Cooling Channel (HCC) grew out of the proposal for this grant and has been published in PRSTAB [2]. Recent simulations of a series of four such HCC segments have shown cooling factors of more than 50,000 in a 160 m long linear channel [10]. The 6D grant itself is to support the simulation of the channel by modifying existing computer codes and to optimize the design of the channel.

3) **Hydrogen Cryostat for Muon Beam Cooling** is an SBIR project begun in July 2004 and funded to July 2007 with Fermilab (Dr. Victor Yarba, Subcontract PI) to extend the use of hydrogen in ionization cooling to that of refrigerant in addition to breakdown suppressant and energy absorber. The project is to develop cryostat designs that could be used for muon beam cooling channels where hydrogen would circulate through refrigerators and the beam-cooling channel to simultaneously refrigerate 1) high-temperature-superconductor (HTS) magnet coils, 2) cold copper RF cavities, and 3) the hydrogen that is heated by the muon beam. In an application where a large amount of hydrogen is naturally present because it is the optimum ionization cooling material, it seems reasonable to explore its use with HTS magnets and cold, but not superconducting, RF cavities. However, the Helical Cooling Channel (HCC) cryostat developed in Phase I, because of new inventions, now has more variants than originally envisioned and there are now several cryostat designs to be optimized. In Phase I we developed computer programs for simulations and analysis and started experimental programs to examine the parameters and technological limitations of the materials and designs of HCC components (magnet conductor, RF cavities, absorber containment windows, heat transport, energy absorber, and refrigerant).

4) **Parametric-resonance Ionization Cooling (PIC)** is a project begun in July 2004 and funded to July 2007 with JLab as a research partner (Dr. Yaroslav Derbenev, Subgrant PI). The excellent 6D cooling expected from the SBIR Project 2 above leaves the beam with a small

enough size and sufficient coherence to allow an entirely new way to implement ionization cooling by using a parametric resonance. The idea is to excite a half-integer parametric resonance in a beam line or ring to cause the usual elliptical motion on a phase-space diagram to become hyperbolic, much as is used in half-integer extraction from a synchrotron. This causes the beam to stream outward to large x' and/or y' while the spatial dimensions x and/or y shrink. Ionization cooling is then applied to reduce the x' and y' angular spread. The Phase II grant is to study the details of this new technique and to develop techniques for correction of chromatic and spherical aberrations and other higher-order effects using analytical calculations and numerical simulations.

5) Reverse Emittance Exchange (REMEX) for Muon Beam Cooling, with Jefferson Lab (Dr. Yaroslav Derbenev, Subgrant PI) is a Phase I STTR project begun in July 2005 to develop a technique to shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider. After the 6D cooling described in Project 2 above, the longitudinal emittance is small enough to allow high frequency RF for acceleration. However, the longitudinal emittance after the beam has been accelerated to collider energy is thousands of times smaller than necessary to match the beta function at the collider interaction point. We plan to repartition the emittances to lengthen the muon bunch and shrink the transverse bunch dimensions using linear cooling channel segments and wedge absorbers. A new concept of coalescing bunches to share longitudinal phase space with REMEX was developed in Phase I to enhance collider luminosity.

6) Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities, with Fermilab (Dr. David Neuffer, Subgrant PI) begun in July 2005 has computational and experimental parts. The use of gas filled RF cavities close to the pion production target for phase rotation and beam cooling will be simulated. In parallel, the project will also involve a continuation of the experimental development in the Fermilab MuCool Test Area (MTA) of high-gradient high-pressure RF cavities operating in a high radiation environment and in strong magnetic fields.

Phase I grants now being proposed for 2007 Phase II projects:

7) Development and Demonstration of Six-Dimensional Muon Beam Cooling with Fermilab (6DMANX). This project is to develop an experiment to prove that effective 6D muon beam cooling can be achieved using an ionization-cooling channel based on a novel configuration of helical and solenoidal magnets. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood sufficiently well to become an enabling technology for intense neutrino factories and high-luminosity muon colliders.

8) Interactive Design and Simulation of Beams in Matter with IIT. G4BeamLine (G4BL), a beam line design program based on GEANT4 for beams with significant interactions with matter, has been the workhorse for Muons, Inc. and the International Muon Ionization Cooling Experiment (MICE) [11] collaboration to simulate muon cooling channels to explore new techniques. This proposal is to improve the program for more general use, adding a Graphical User Interface and several new and enhanced capabilities.

Recent work on these and other projects by Muons, Inc. and collaborators can be seen as PAC07 abstracts (Appendix I), where we have submitted 13 papers.

Although each of these projects is independent, taken together they represent a coherent plan to generate a compelling design for an intense muon source. Muons, Inc. now has enthusiastic collaborators from IIT, Jefferson Lab, Fermilab, and Brookhaven who are part of this effort. The grants described above support over 12 FTE accelerator scientists. We hope that recent simulation results showing 6D cooling factors of over 5 orders of magnitude for a 4-section helical cooling channel and other cooling innovations will reenergize the muon collider community. The Linac community has likewise shown interest in the pressurized cavity development. This is a lively, creative collaboration dedicated to developing new options for the physics community.

Significance and Background Information, and Technical Approach

Identification of Problem

Bright Ionization cooling, a method for shrinking the size of a particle beam, is an essential technique for future particle accelerators that use muons. Muon colliders and neutrino factories, examples of these future accelerators, depend on the development of robust and affordable techniques for ionization cooling.

Technical Approach

This proposal is to develop an experiment to prove that effective six-dimensional (6D) muon beam cooling can be achieved using an ionization-cooling channel based on helical and solenoidal magnets in a novel configuration. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood, thereby overcoming a critical roadblock to intense neutrino factories and high-luminosity muon colliders.

Helical Cooling Channel

HCC Simulations

Anticipated Public Benefit

The applications of the new techniques that will be developed and proved by this project involve very bright muon beams for fundamental research using muon colliders, neutrino factories, and muon beams with new characteristics. The most important application will be an energy frontier muon collider which achieves high luminosity by virtue of small emittance rather than large muon flux. The small emittance in all dimensions that is possible as shown by this project will allow high-frequency ILC RF structures to be used for such a collider and also for a high flux muon beam that could supply a storage ring used as a neutrino factory.

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

A Neutrino Factory is an attractive first step toward a Muon Collider. Neutrino physics is extremely interesting at this time and there is considerable pressure to build such a machine.

Another attractive first step is a Higgs Factory built using existing Fermilab infrastructure, where the collider ring is only one or two hundred meters in diameter, depending on the mass of the Higgs particle. The enhancement factor of 40,000 in the s-channel Higgs production cross-section, proportional to the square of the lepton mass, is a strong argument for a muon collider over an electron collider.

Besides these wonderful opportunities to advance our understanding of the universe, high intensity, high brightness muon beams can be used for many other applications. Other fundamental studies that would be aided by such beams include elementary particle research, such as rare muon to electron decay searches and g-2 measurements, possible energy sources from muon catalyzed fusion, and sophisticated measurements of material properties using muon spin resonance.

The list of possible benefits to humanity from having intense and bright muon beams is very impressive, and there are certain to be more things to add to the list that are still beyond our imaginations. We are committed to seeing these beams happen and look forward to helping start the age of muon accelerators.

Degree to which Phase I has Demonstrated Technical Feasibility

In Phase I we synthesized developments in our other SBIR-STTR projects to generate simulations of a 6D experiment that included a novel design of a helical solenoid magnet and efficient emittance matching sections. G4MANX, a simulation/reconstruction program that was originally developed as G4MICE for the MICE muon cooling experiment has been adapted for our 6D purposes and it is ready to for exploitation in Phase II. We have made plans for the prototyping of a section of the helical solenoid magnet to test its magnetic, mechanical, and thermodynamic properties.

Phase I of this project has been quite successful. As described in the overview section above, many of the details of the research done in Phase I of this project are contained in the Appendices, which include drafts of PAC2007 papers on various aspects of the project.

The Phase II Project

Technical Objectives

G4MANX

Phase II continues the development of the analysis/simulation program G4MANX started in Phase I to optimize the experimental parameters by improving experimental significance, understanding systematic errors, and exploring engineering simplifications and their ramifications. G4MANX is based on G4MICE, the simulation code used in the MICE experiment. We have capitalized on the work done by the MICE collaboration in implementing Geant4 into a framework for advanced accelerator and detector simulation and particle track reconstruction. G4MANX is being developed as a suite of packages which include simulation, digitization, reconstruction and analysis of muon events for a demonstration of 6-dimensional ionization cooling. The Simulation package uses the CERN Geant4 toolkit and provides for the generation and tracking of muons through the 6DMANX spectrometer and detectors.

The Simulation package will be used to model the different scenarios for the implementation of 6DMANX. A first case implementation models the experiment that could be performed at the Rutherford-Appleton Laboratory using the MICE beam line where the MICE absorber and RF units are replaced by the MANX helical cooling channel and its associated matching sections. Figure 1 shows a sketch of the layout for MANX at RAL. In the figure, the orange rectangles illustrate the MICE modules that would be used by MANX. These include the MICE spectrometer, TOF detectors and beam line magnets. Shown in the red and salmon colored rectangles are the modules added for 6DMANX. A number of SciFi detector planes similar to those used in the MICE have been added to the Helical Cooling Channel (HCC) and the matching sections.

These additional detector planes help ensure that the muons used for the emittance analysis are not lost inside the HCC cryostat. ??

The Digitization package takes the muon tracks from the Geant4 simulation and produces a simulated detector response. The Reconstruction package constructs the muon track from the digitization and produces a summary file that describes muon track information which is to be used in the analysis. The initial track parameters can be obtained with reasonably good resolution in the MICE spectrometers since the field is uniform. The track parameters at and inside the cooling channel cryostat are obtained by propagating the track through the non-uniform fields in the matching section and in the HCC using a Kalman filter. The measurements from the planes inside the helium cryostat have good spatial resolution for muons, but must rely on extrapolation for momentum determination because of multiple scattering.

For Phase II we intend to model alternative 6DMANX cases with the G4MANX packages to describe single particle and beamlet experiments that could be performed at Fermilab. We will also develop the Digitization and Reconstruction packages for the 6DMANX experiment. These will be necessary to evaluate cooling channel and detector systematic errors, determine emittance measurement resolutions and optimize cooling performance for the formal 6DMANX ionization experiment proposal.

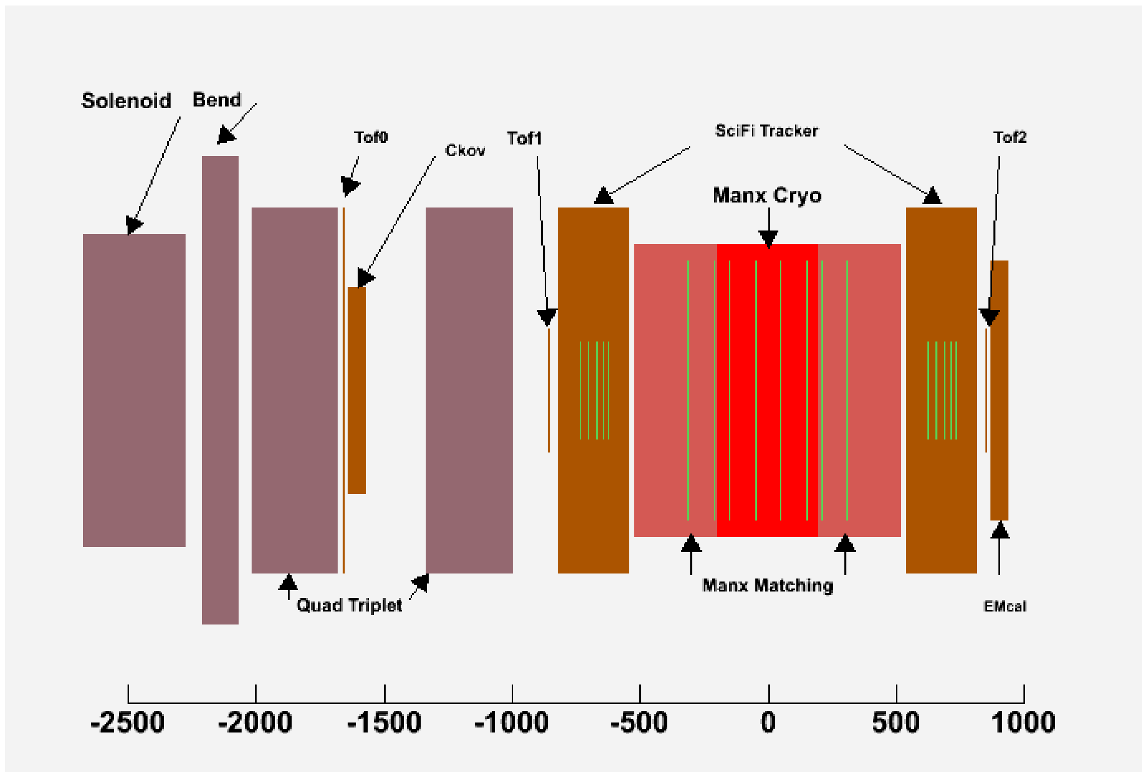

Figure 1: Sketch of RAL muon beam line with MANX helical cooling channel and matching sections positioned between MICE spectrometers.

Helical Solenoid Prototype

[Lamm]

Phase II includes working with the Fermilab Technical Division to accomplish the engineering of the HCC and emittance-matching magnet systems, including construction and testing of a three-coil prototype superconducting helical solenoid.

Beamline Possibilities

[Abrams]

Detector Development

Scifi in LHe

[Hu]

5 ps TOF

[Frisch]

Phase II Work Plan

6DMANX Experimental Design. Work to be performed by Rolland Johnson, Robert Abrams, Mary Anne Cummings, Stephen Kahn of Muons, Inc. and Katsuya Yonehara of Fermilab.

Having achieved the basic parameters for 6DMANX by using G4BL to verify the cooling performance of the helical dipole and the matching magnet systems in Phase I, the next step is to design a complete experiment. Traditionally, this involves a simulation of the experiment which uses realistic detectors and their behavior with actual reconstruction algorithms and serious studies of systematic effects including backgrounds from misidentified particles.

Our strategy to accomplish this higher level of simulation realism is to build upon the work that has been done by the MICE collaboration in their development of the G4MICE program [12]. Members of our MANX collaboration that are also in MICE have begun to turn this program into G4MANX. Besides taking advantage of the 5 or more man-years of G4MICE development effort, this approach has the added advantage of creating further opportunities for collaboration on the MICE and MANX cooling experiments.

One interesting idea that is being studied is to instrument the HCC absorber volume with trackers to add extra information. Thus the upstream and downstream spectrometers tie into the cooling section to become part of an integrated tracking system. We believe that fiber optic trackers will work in the LHe environment of the energy absorber, and we expect to have some prototype work to demonstrate this capability. 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 photodetectors to convert the optical signals to electronic signals, evaluating electronic readouts for processing the signals from the detectors.

We anticipated that Muons, Inc. personnel will work closely with the FNAL beamline physicists to design the muon beam for 6DMANX, and will play an important role in the design of the analysis spectrometers and detectors that are upstream and downstream of the HCC.

6DMANX Engineering Development Work to be performed by Drs. Rolland Johnson, Sergey Korenev and Moyses Kuchnir of Muons, Inc., Mike Lamm, Vladimir Kashikhin, Alexander Zlobin, of Fermilab

Responsibilities

Muons, Inc.: The direction of the project is the responsibility of the company and the PI.

Fermi National Accelerator Laboratory: Dr. Michael Lamm will be responsible for the Fermilab subgrant.

Performance Schedule (Tasks and Milestones)

6 months after start of funding:

1) G4MANX used for detector studies of resolution
2) Selection of baseline site for 6DMANX experiment proposal
3) Completion of baseline design of beam line
4) Completion of baseline design of experimental spectrometers and detectors
5) Establishment of a plan to form the collaboration groups participating in the 6DMANX experiment.
6) 3-coil magnet prototype designed

12 months after start of funding:

1) Initial collaboration formed, responsibilities identified
2) 6DMANX proposal drafted and submitted to FNAL
3) Designs for prototype detectors completed

18 months after start of funding:

1) Construction and evaluation of prototype detectors completed
2) Engineering design of spectrometers completed

24 months after start of funding:

1) Construction of detectors completed
2) Installation of equipment in experimental hall completed

Facilities/Equipment

Muons, Inc. currently occupies a building of approximately 4000 square feet of floor space in Batavia, Illinois, a short drive from Fermilab. This building is now used as office space, conference rooms, workshop area, and living quarters as needed. Muons, Inc. has several high-performance personal computers with high-speed net access and sufficient computing power to perform the simulations and the CAD work. Much of the high-pressure test cell itself was assembled and tested at Muons, Inc. and at the Device Technologies machine shop in Yorktown, IL. (Although we could use any machine shop, including the facilities at Fermilab, we have formed a fruitful relationship with Device Technologies where we get excellent and timely work done for more than fair prices).

The outstanding opportunity for this project is the availability of the MTA at Fermilab. This Test Area represents a contribution from Fermilab that represents the use of several millions of dollars worth of equipment.

Fermilab has made the construction of the MTA beam line a priority for 2007, in part because of the interest in seeing the next step in the development of pressurized RF for muon cooling (Steve

Holmes, private communication). We are happy to note that the beam line that is planned is based on one that Muons, Inc. played a significant role in designing[13].

Consultants and Subcontractors

We have no plans at this time for consultants or subcontractors other than Fermilab, our research partner.

Phase II Funding Commitment (Commercial Contribution)

Fermilab supports our work on this project in two ways. First, Pier Oddone has arranged to have Fermilab contribute the overhead charges for those Muons, Inc. SBIR-STTR projects that are directly relevant to the laboratory's future. This overhead charge is required by the DOE to be one of full cost recovery and has grown considerably in the last year. At present, the overhead rate is close to 100% for labor. Thus, Fermilab will contribute an amount that is roughly equal to the $225,000 subgrant that will go to Fermilab as the 30% share of the STTR grant. We note that projects 3) and 6) of the Muons, Inc. Program Overview section above are also beneficiaries of this overhead contribution, including the Phase I parts of the projects.

Second, the Fermilab Muon Collider Task Force has been explicitly charged with working with Muons, Inc. to develop the devices and techniques for muon beam cooling and to investigate the possibilities of a 6D muon cooling demonstration experiment. It is anticipated that this effort will also fall within the new Accelerator Physics Center that is being formed. Although the budget and manpower for this effort is not known by us at this time, it seems likely that the manpower to be devoted to the 6DMANX proposal will be of a size and nature comparable to the STTR project itself.

Phase III Follow-on Funding Commitment

Since Phase III of this project will involve the construction of equipment for muon beams, the primary user of our research results will be the US Government or some other international agency such as CERN. Our present strategy is to submit a complete experimental proposal to do the 6DMANX experiment so that it will be reviewed and approved by the Fermilab Accelerator Advisory Committee. Once it becomes an approved Fermilab experiment we would join our university colleagues to apply for supporting (non-SBIR-STTR) funds from the DOE and NSF in the more or less traditional way that approved experiments are pursued.

If the 6DMANX experimental proposal that is the goal of the first half of this STTR project is approved and funded by Fermilab as we anticipate, it will require funding from Fermilab, DOE, and NSF sources that are on the order of $10M. If the demonstration cooling experiment is in turn successful and leads to the use of cooled muon beams for the purposes described above, it could lead to rather large funding by non-SBIR-STTR sources. A Fermilab muon collider could well be in the $10B class.

Bibliography and References

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[2] R. P. Johnson et al., LINAC2004, http://bel.gsi.de/linac2004/PAPERS/TU203.pdf

[3] This concept is the basis for a 2007 Phase I SBIR-STTR proposal to generate a stopping beam for a direct muon to electron conversion experiment. A paper describing this use of a momentum-dependent HCC is attached below as Appendix VI.

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[9] http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0287/muc0287.pdf

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Letter of Intent to propose a

SIX-DIMENSIONAL MUON BEAM COOLING

EXPERIMENT FOR FERMILAB

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Synopsis

The experiment we will propose involves the construction of a 4 meter long, innovative superconducting magnet called a Helical Cooling Channel (HCC) and the measurement of its beam cooling properties. The measurement also requires a 300 MeV/c muon beam line equipped with up and downstream matching sections, particle spectrometers, and particle ID detectors. The expected cooling factor of nearly 500% will be a striking demonstration of a new technique to cool all dimensions of a muon beam in a time much shorter than the muon lifetime.

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

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

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

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

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

Several iterations of the 6DMANX design have already eased its engineering and construction difficulties with only a slight reduction in the cooling performance. The maximum field at any conductor is 5.2 T, so that NbTi can be used. The liquid hydrogen energy absorber has been replaced with liquid helium to alleviate safety concerns and to provide a straightforward way to refrigerate the magnet coils. A major simplification is the elimination of RF cavities. Measurements of the invariant emittances will achieve the goals of the experiment, which are to demonstrate:

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

We will request that Fermilab construct the HCC magnets to be tested and help determine the most expedient location for the experiment. We have started to examine two possible locations. First is the possibility of a merging of MICE and 6DMANX, such that the tests would be done at RAL using the MICE spectrometers. An alternative is to use an appropriate beam line at Fermilab, such as the MiniBooNE line or a muon test line in the Meson Lab, where the necessary modifications are just starting to be investigated.

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

6DMANX

SIX-DIMENSIONAL MUON BEAM COOLING EXPERIMENT

Table of Contents

Background and Motivation

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

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

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

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

Potential Applications

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

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

Smaller emittance also:

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

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

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

Timeliness

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

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

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

Technical Approach

Helical Cooling Channel (HCC) in Context

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

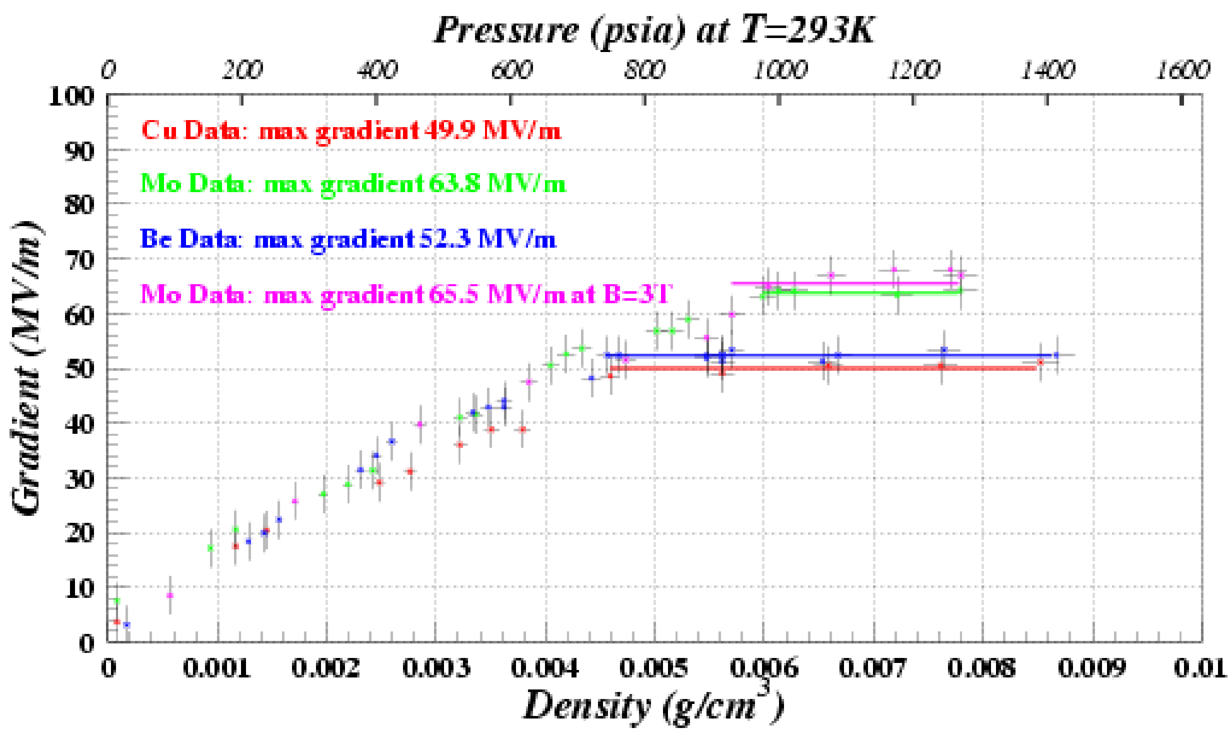

FIG 1 Measurements of the maximum stable TC gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue). As the pressure increases, the mean free path for ion collisions shortens so that the maximum gradient increases linearly with pressure. At sufficiently high pressure, the maximum gradient is determined by electrode breakdown and has little if any dependence on pressure. Unlike predictions for evacuated cavities, the Cu and Be electrodes behave almost identically while the Mo electrodes allow a maximum stable gradient that is 28% higher. The cavity was also operated in a 3 T solenoidal magnetic field with Mo electrodes (magenta); these data show no dependence on the external magnetic field, achieving the same maximum stable gradient as with no magnetic field. This can be compared with measurements of 805 MHz evacuated cavities that show the maximum surface gradient is reduced from 50 MV/m to about 15 MV/m at an external magnetic field of 3 T.

This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Although the experiment we are proposing supports the use of a HCC filled with hydrogen-filled RF cavities, the experiment itself does not require RF cavities and, in addition, also supports an alternative to the gas filled RF cavity approach to 6D cooling.

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

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

HCC Concept

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

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

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

HCC with z-dependent Field Amplitudes

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

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

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

The new idea that is the basis for this proposal is that equation (2) is not just a description of the requirements for a simple HCC, but is also a recipe to manipulate field parameters to maintain stability for cases where one would like the momentum and/or radius of the equilibrium orbit to change for various purposes. Examples of these purposes that we have examined include:

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

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

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

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

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

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

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

HCC Precooling Examples

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

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

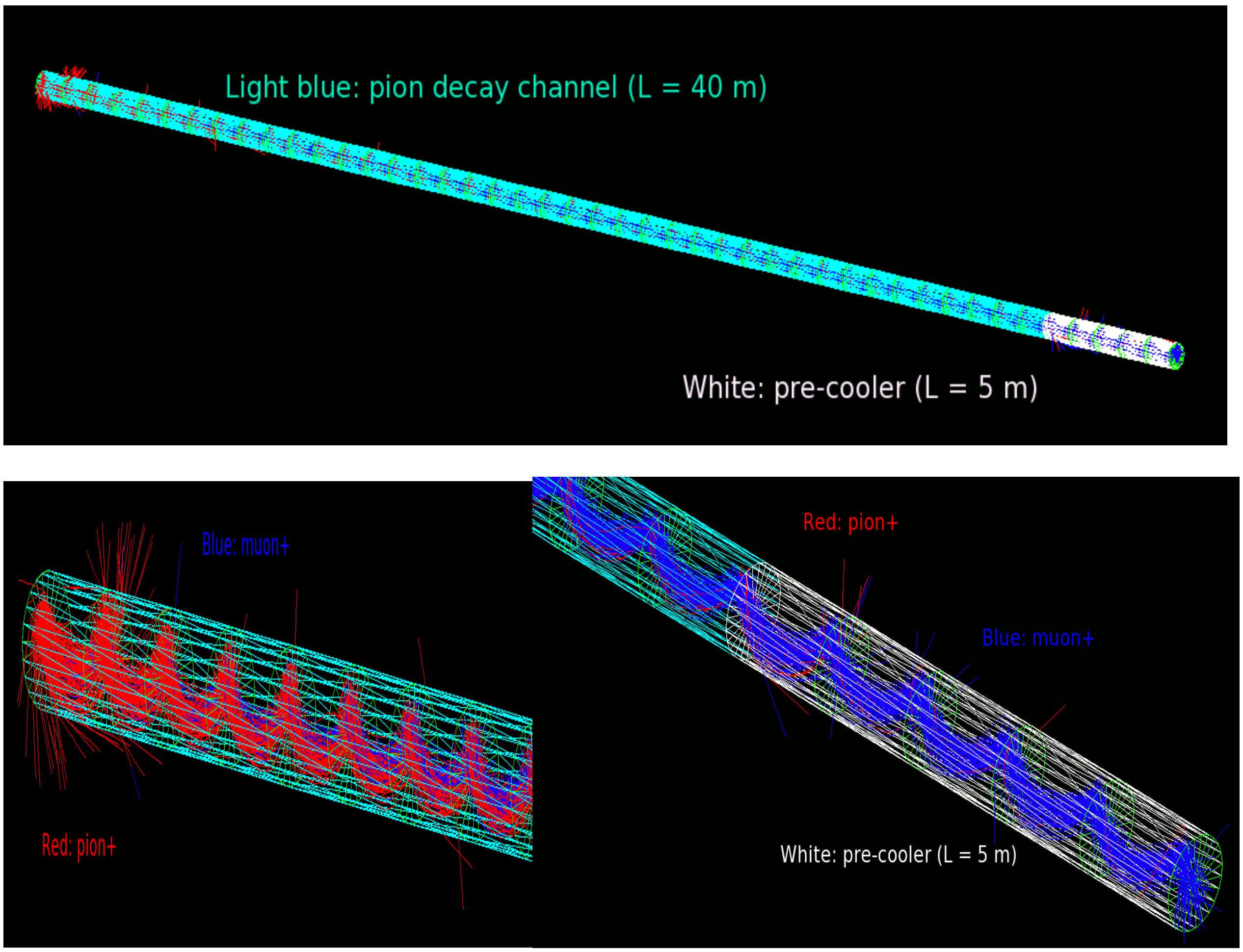

FIG 2: G4BL display of a pion decay HCC (light blue) followed by a 5 m precooling (white) HCC. The top display shows the whole layout, the lower left display is the beginning of the decay channel, and the lower right display shows the precooler end. The red and blue lines show the pion and muon tracks,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

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

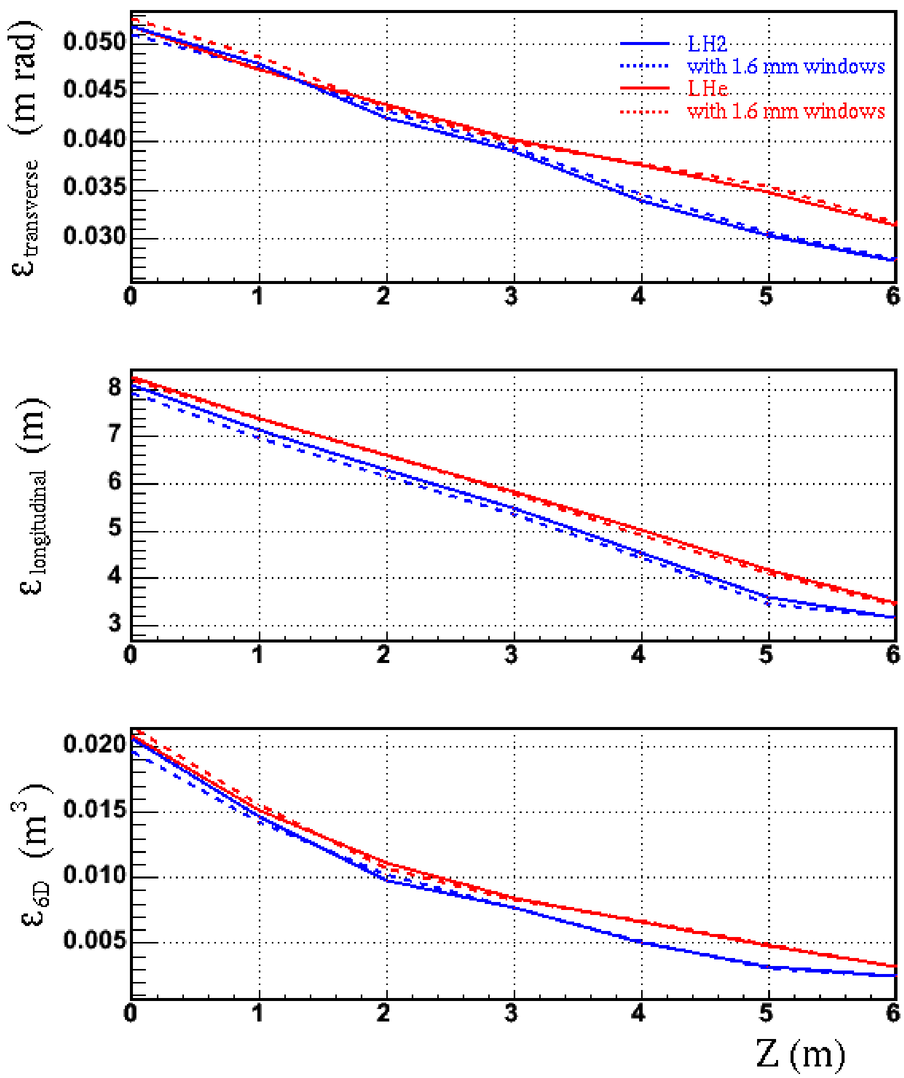

FIG 3: Simulations showing normalized emittance evolution for particles that survive to 6 m for a HCC precooler filled with liquid hydrogen (blue) or liquid helium (red), with (dashed) and without (solid) 1.6 mm thick aluminum windows on each end.

The 6DMANX Experiment

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

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

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

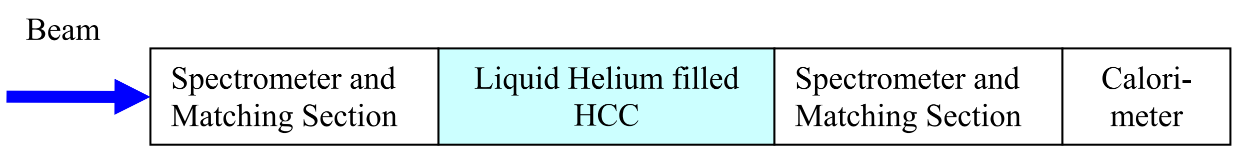

FIG 4: Generic diagram of the 6DMANX experiment.

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

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

Solenoidal Spectrometer and Matching Section

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

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

Dipole Spectrometer and Matching Section

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

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

First Experimental Configuration

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

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

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

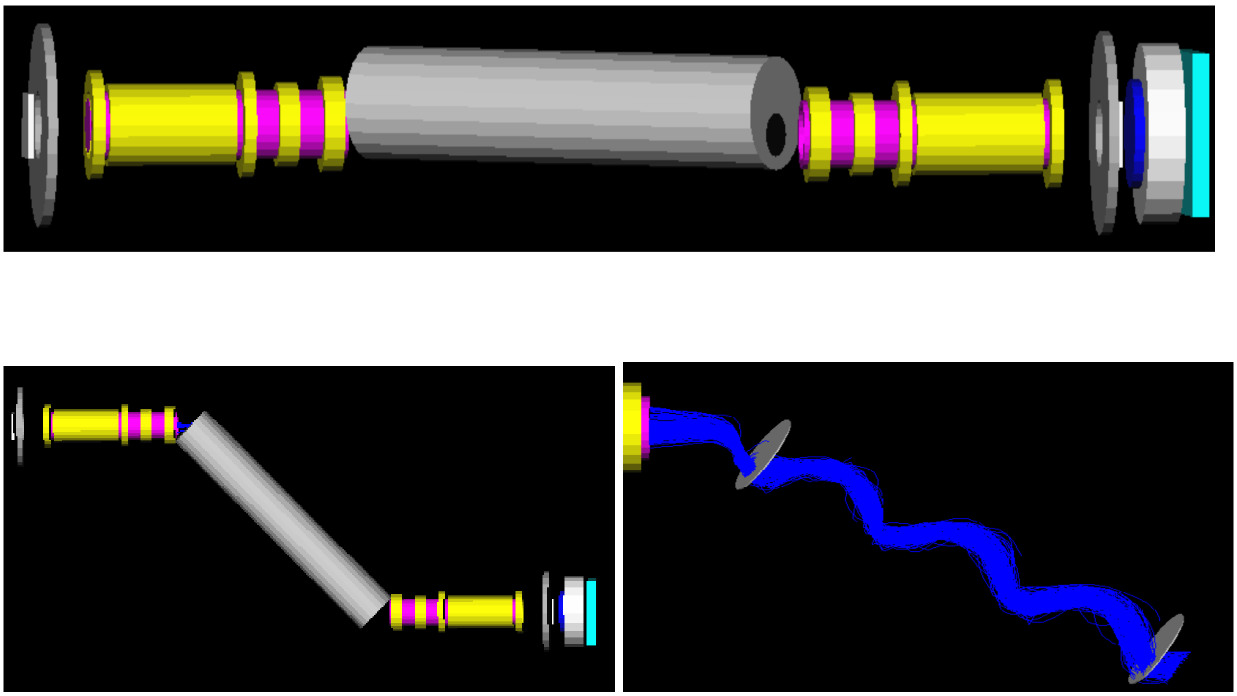

FIG 5: G4BL simulation program displays of the elevation (upper), plan (lower left) and beam trace (lower right) views of the 6DMANX HCC using the MICE spectrometers. The yellow devices correspond to the matching coils and spectrometer magnets of the particle measurement sections of the MICE experiment.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

6DMANX Design

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

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

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

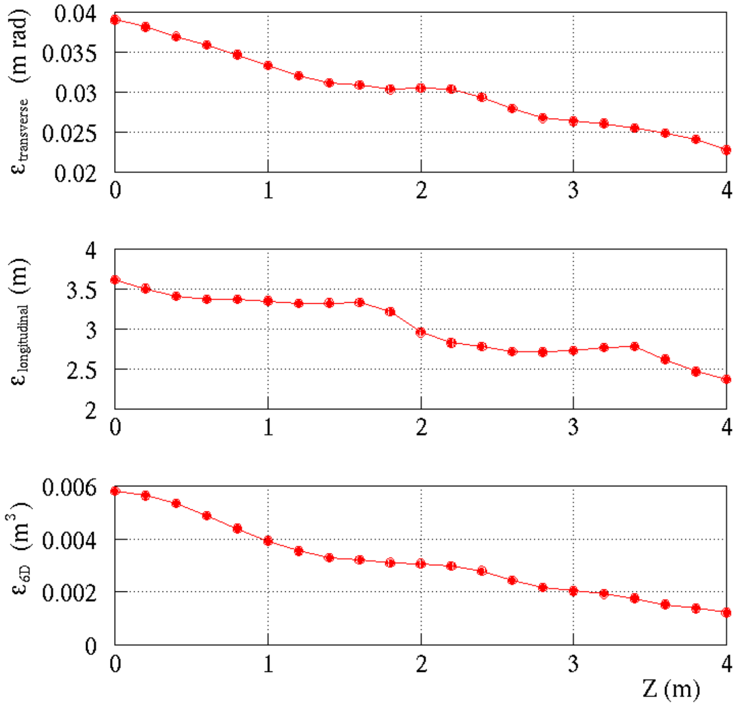

FIG 6: G4Beamline simulation of a liquid helium filled 6DMANX section with reduced field requirements. The initial momentum has been decreased from 400 to 300 MeV/c (as required for the RAL beam), λ has been increased from 1 to 2 m, and κ decreased from 1 to 0.8. The maximum field at a conductor has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

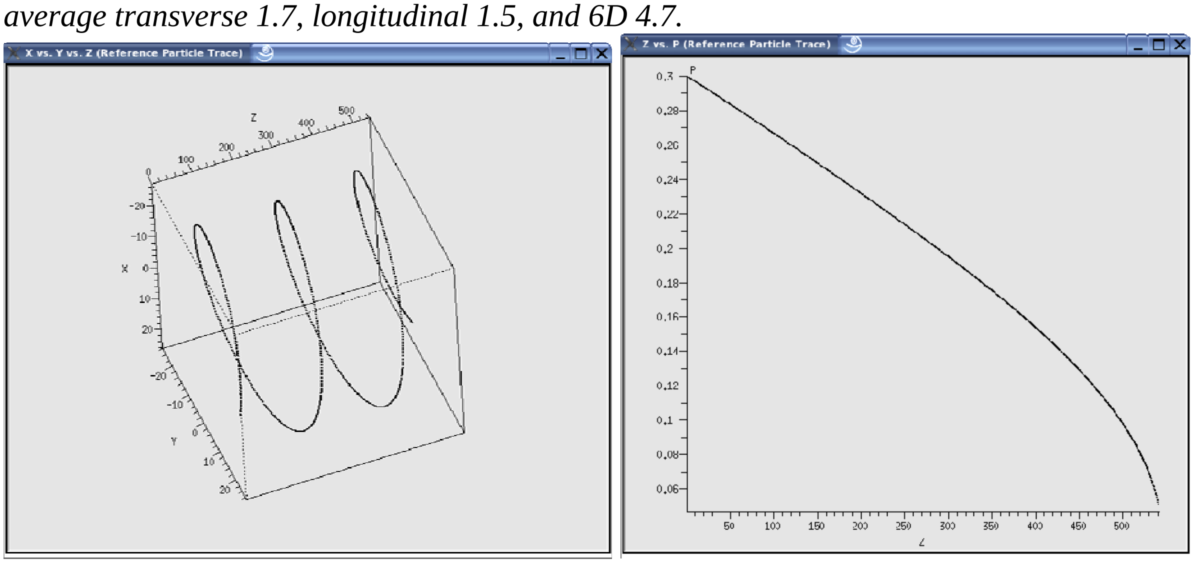

FIG 7: Path (LEFT) and momentum (RIGHT) of the equilibrium orbit as a function of z.

Magnets

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

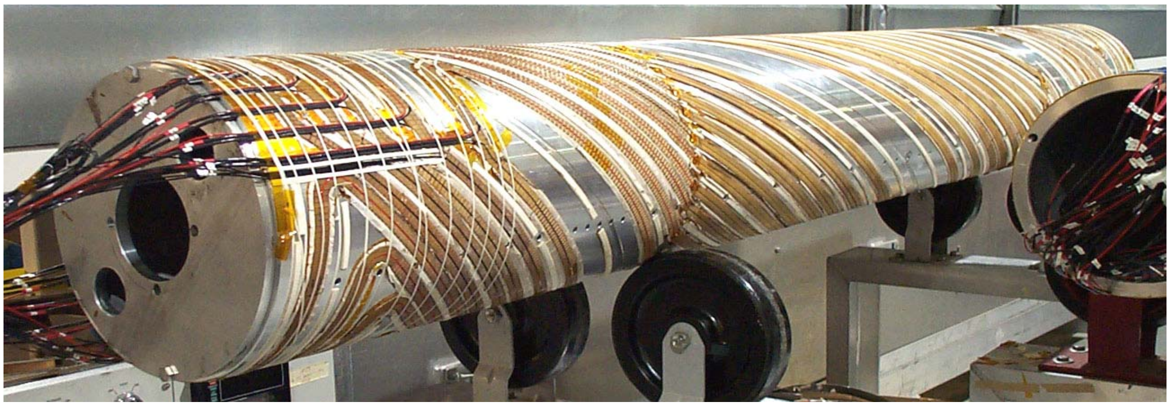

FIG 8: BNL Helical Dipole magnet used for spin control in the AGS. The inner diameter is 0.20 m and the length is 1.9 m. The field is 3 T and must have exceptionally good field quality as expected for a magnet in a synchrotron. In comparison, the HCC magnet is larger with diameter of 0.80 m, length 4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

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

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

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

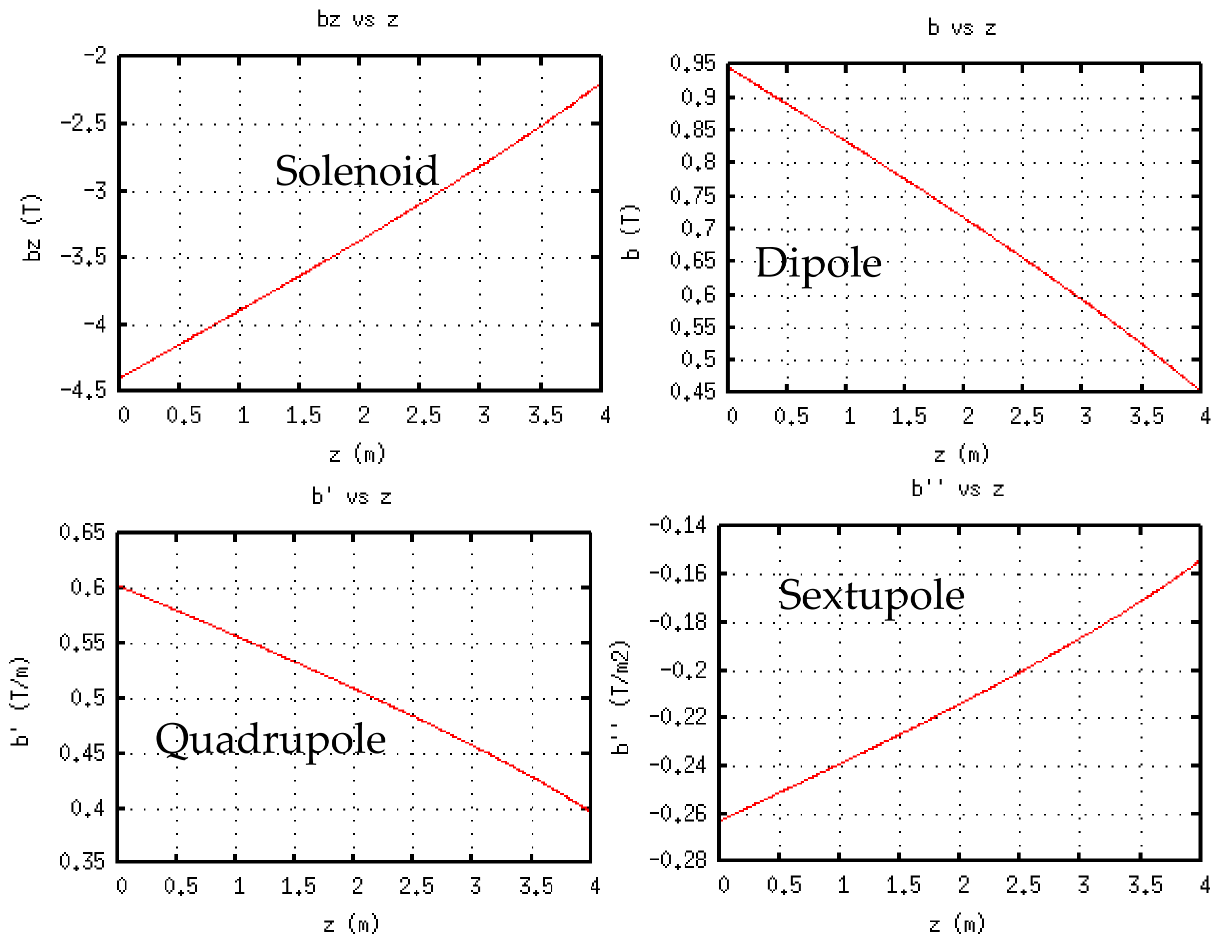

Fig. 9: Magnet strengths as a function of z for the four circuits of the HCC. Each must have decreasing strength to match the momentum of the muons as they lose energy.

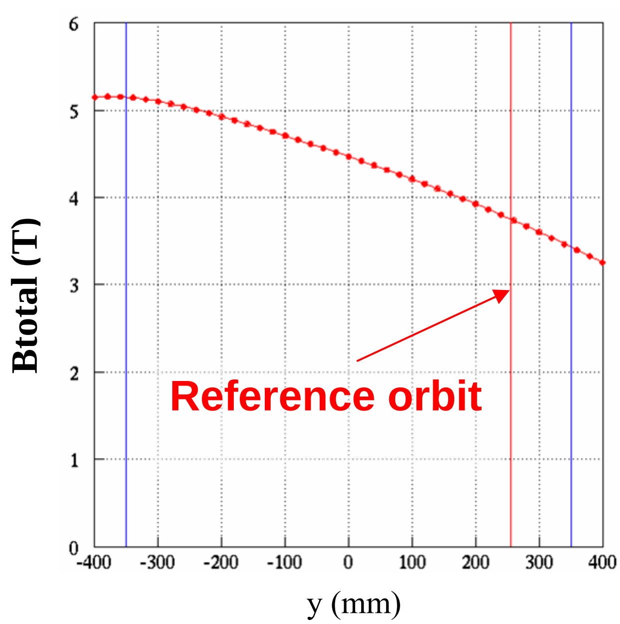

FIG 10: B_{total} on the y axis at x=0

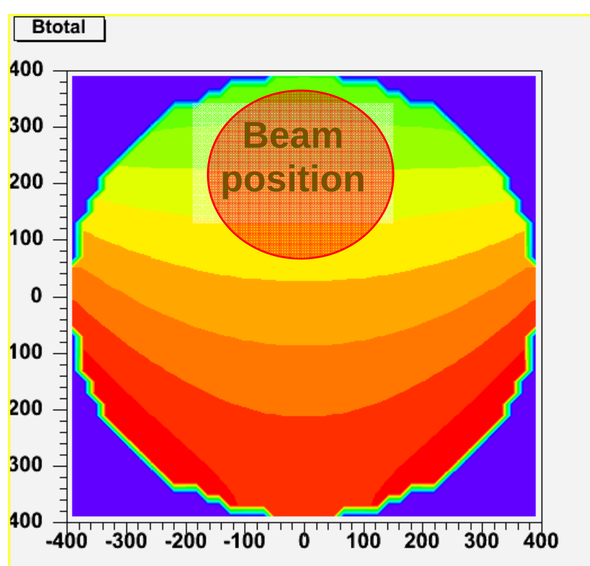

FIG 11: x-y contour plot of B_{total} in the LHe HCC (red: > 5 T, green 3.5 T, blue = 0)

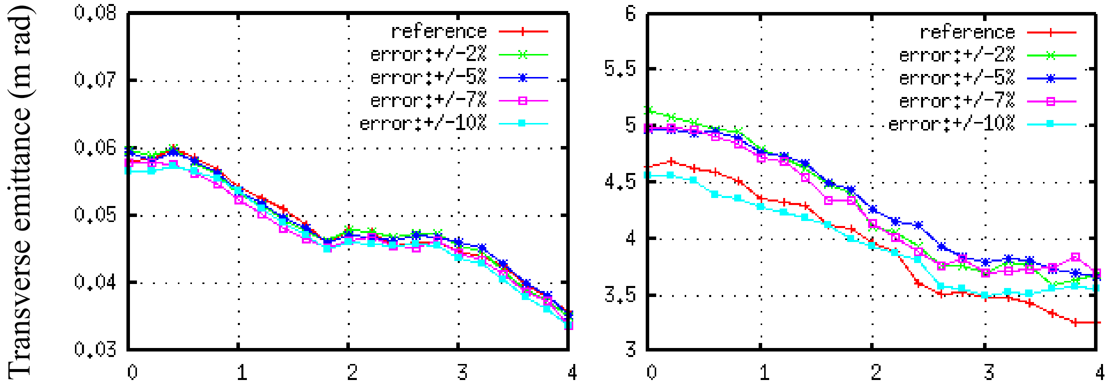

FIG 12: Simulation study of effects of random field errors on the cooling of the transverse (LEFT) and longitudinal (RIGHT) beam emittances in the 6DMANX HCC.

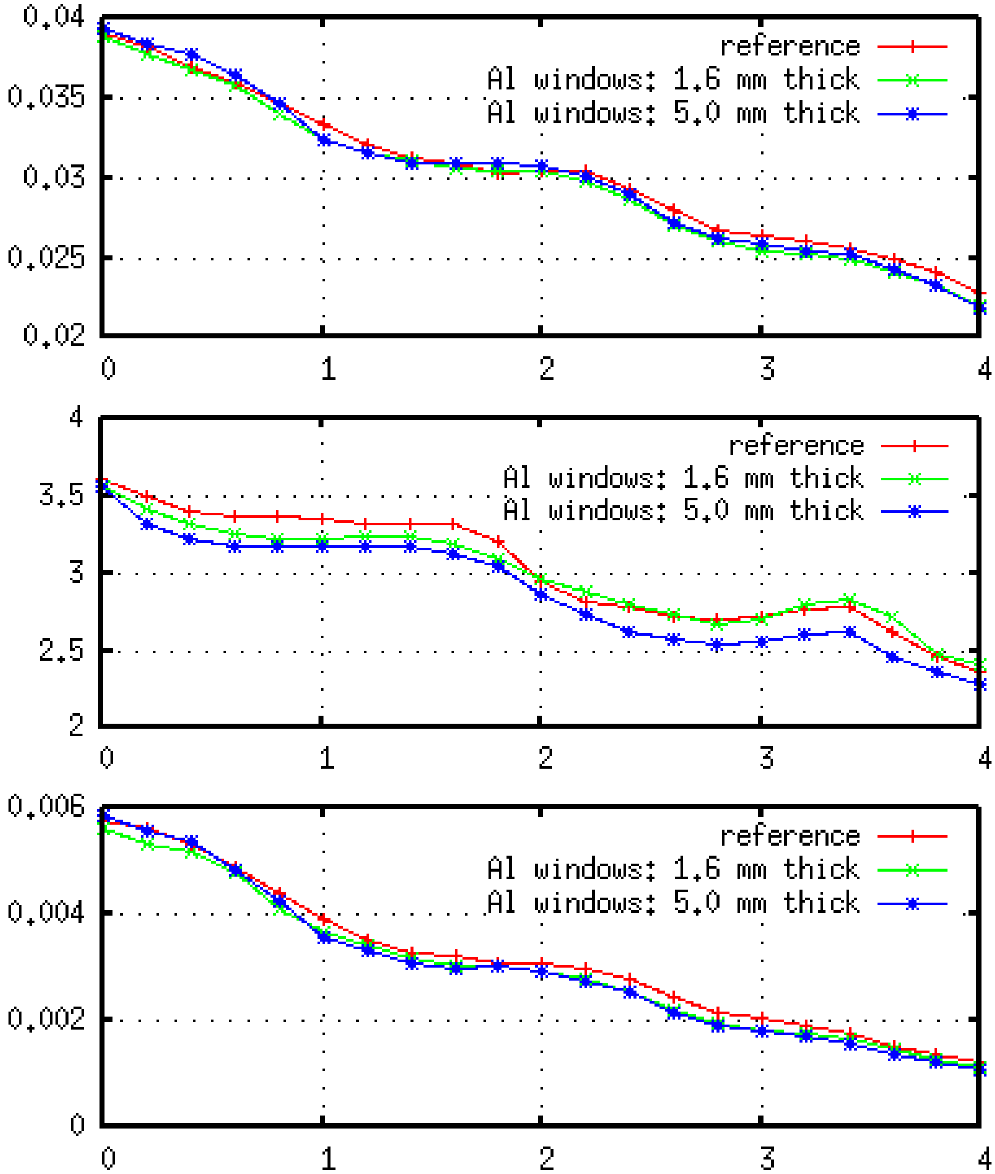

FIG 13: Simulation study of the effect of window thickness on the cooling of the transverse (TOP) longitudinal (CENTER) and 6D (BOTTOM) emittances in the 6DMANX HCC.

LHe Absorber and Containment Windows

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

Cryostat

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

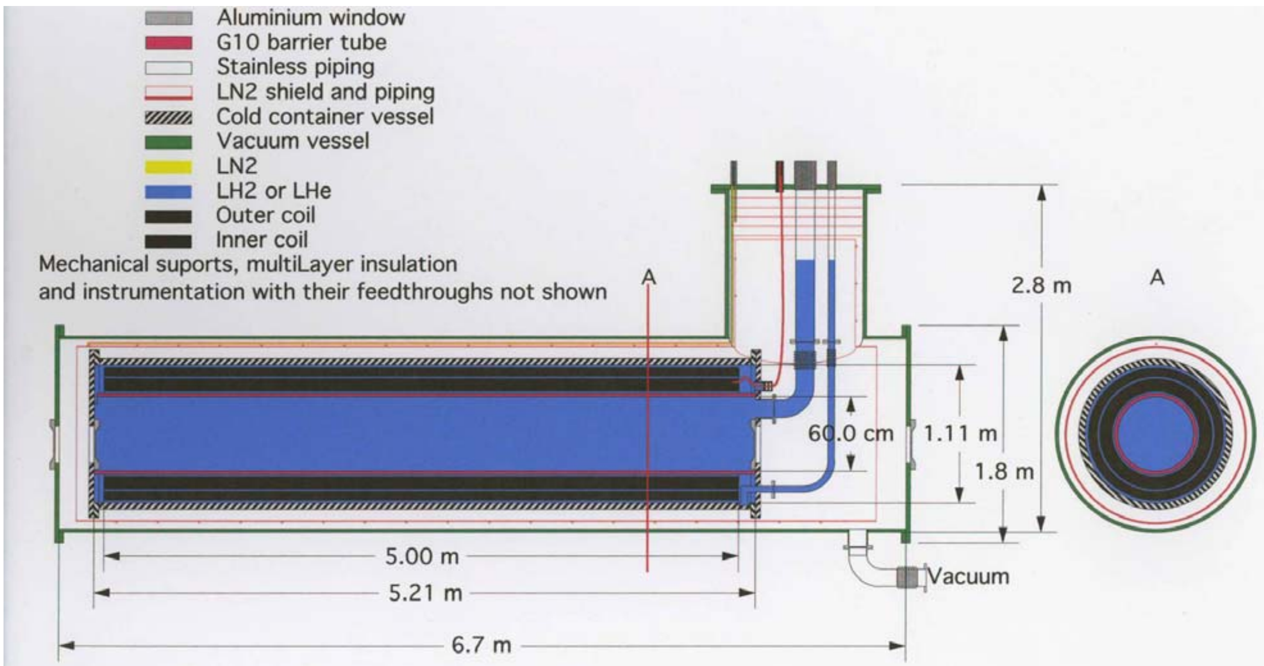

FIG 14: Five meter long MANX cryostat schematic. For RAL, the length becomes 4 m. At FNAL perhaps 5 m is possible. The use of liquid He at 4 K is possible, with NbTi magnets. Thin Al windows designed for MICE can be used.

Spectrometers

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

Costs

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

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

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

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

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

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

Summary and Conclusions

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

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

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

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

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June 22, 2006

To: Vladimir Shiltsev and Steve Geer

From : Pier Oddone

Subject: Muon Collider Task Force

I would like to ask the two of you to form and lead a Task Force to develop a plan for an advanced R&D program aimed at the technologies required to support the long term prospects of a Muon Collider. In doing so I would ask that you operate in consideration of the attached charge, taking special note of the deliverables requested for September 2006: A report outlining a plan for developing the Muon Collider concept based on recent ideas in the realm of ionization cooling, and an associated cooling R&D plan that can be implemented starting in FY2007. Following receipt of this report I will expect to initiate the Muon Collider study, including the associated cooling channel study and development program, in 2007.

The Muon Collider represents a possible long term path for extending the energy frontier in lepton collisions beyond 1 TeV. It is important to establish the possibilities and to outline the R&D program that will be necessary to develop the underlying technology base. I look forward to working with you to formulate and execute a plan to explore these possibilities and to provide options for Fermilab and the world HEP program in the future.

Cc

R. Dixon
S. Holmes
R. Kephart
H. Montgomery
J. Strait
V. Yarba
V. White

Muon Collider Task Force Charge

1. Introduction

The Muon Collider represents a potential long term path to lepton-lepton collisions at center-of-mass energies beyond 1 TeV. Recent progress in 6-dimensional (6D) muon cooling concepts hold promise for preparing an intense muon beam with an emittance small enough for acceleration and injection into a Muon Collider. Several new, innovative, cooling ideas deserve evaluation to (i) identify which ideas are the most promising, (ii) identify the main technical questions that must be addressed before a 6D cooling channel could be built, and (iii) formulate the R&D path that is needed for their development. In addition, a fresh look at a Muon Collider design by accelerator experts would establish the ionization cooling requirements, and identify the remaining muon source and collider design and performance issues.

2. Charge

i) **Cooling Channel and Collider Design Concept**.
Taking into account recent developments in muon cooling ideas, develop a coherent design concept for a Muon Collider with a center-of-mass energy of 1.5 TeV, based upon a low emittance parameter set. Outline the general scheme, the parameter choices, and the 6D ionization cooling channel requirements to support a usable luminosity. Additionally identify the primary design challenges beyond the 6D cooling systems. Results should be documented in a report in September 2007. A plan for the one year study, including an estimate of the required Fermilab effort and the expected contributions from outside of Fermilab, should be documented in a brief report in September 2006.

ii) **Cooling Channel R&D**.
Prepare a one year study plan to (a) evaluate the technical feasibility of the components (rf cavities, magnets, absorbers, etc) needed for a muon collider class 6D cooling channel as identified in i), (b) identify the technical issues that must be addressed before a 6D cooling channel could be built, and (c) formulate a plan for the associated component R&D and 6D cooling tests that must be performed to establish basic viability of the cooling channel. The study plan should be documented in a short report in September 2006. The results of the one year study should be documented in a more detailed report in September 2007.

iii) **Component Development and Testing.**
(a) Prepare a plan to implement, in FY07, the beam and experimental setup required to test the high-gradient operation of a high-pressure gas-filled rf cavity operated in a multi-Tesla magnetic field and exposed to an ionizing beam. The implementation

plan should be documented in a short report made available in September 2006. This plan should include a description of the measurements to be made, should be formulated in collaboration with Muons Inc, and should document the connection between these activities and charge elements i) and ii)

(b) Design, and prepare a plan to build, a helical solenoid suitable for a 6D cooling channel section test. The implementation plan should be described in a short report made available in September 2006, developed in collaboration with Muons Inc. and documenting the connection between this activity and charge elements i) and ii). A complete prototype design and fabrication plan should be described in a concise report in September 2007.

(c) Prepare an R&D plan to explore the feasibility of building a very high field (~50Tesla) high-Tc superconducting solenoid suitable for the final stages of a muon cooling channel for a Muon Collider. The implementation plan should be documented in a short report made available in September 2006, including documenting the connection between this activity and charge elements 1) and ii).

Superconducting Magnet System for Muon Beam Cooling

V. S. Kashikhin, V. V. Kashikhin, K. Yonehara, R. P. Johnson, N. Andreev, I. Novitski, , A.V. Zlobin

***Abstract*—A helical cooling channel has been proposed to quickly reduce the six-dimensional phase space of muon beams for muon colliders, neutrino factories, and intense muon sources. A novel superconducting magnet system for a muon beam cooling experiment is being designed at Fermilab. The inner volume of the cooling channel is filled with liquid helium where passing muon beam can be decelerated and cooled in a process of ionization energy loss. The magnet parameters are optimized to match the momentum of the beam as it slows down. The results of 3D magnetic analysis for two designs of magnet system, mechanical and quench protection considerations are discussed.**

***Index Terms*— Helical magnet, muon cooling, solenoid, superconducting magnet**

I. Introduction

THE helical muon cooling channel is being designed at Fermilab. Investigations of the cooling channel physics demonstrated the high efficiency of a such system [1-2]. Proposed by Muons, Inc. the MANX experiment [3] is to experimentally verify this approach. To achieve the maximum 6D emittance reduction, the MANX magnet system should produce longitudinal and transverse field components on the beam orbit. In addition, all field components should have appropriate gradients in the longitudinal direction.

During the physics investigation phase, the beam optics analysis was based on magnetic field analytically described by Bessel functions that automatically satisfies the Laplace equation in the current-free region, but gives no guarantee that a particular field distribution is feasible from a practical viewpoint. The main goal of the work being described is to determine if it is possible to generate the necessary fields by a realistic magnet system via a reasonable number of coils.

The design principles employed for the helical magnets have been known for decades [4]-[5]. Normal-conducting helical dipoles with the operating field of 1.7 T were constructed at IHEP [6]. A superconducting helical dipole magnet with the operating field of 3 T was built at BNL [7]. Those magnets, however, had a constant helical field component in the longitudinal direction. The requirement of having longitudinal field gradients brings an additional design challenge that has not been addressed before.

Two approaches to the magnetic system of muon cooling channel have been studied. The first one has a large cylindrical bore encompassing the beam helix. The second one has twice smaller helical bore that follows the beam orbit.

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R. P. Johnson, is with Muons Inc., 552 N. Batavia Ave., Batavia, IL 60510, USA (e-mail: roljohn@aol.com).

II. Muon Cooling Channel Parameters

The muon cooling channel parameters were carefully optimized to obtain the maximum beam cooling effect in the MANX experiment [3]. Table 1 summarizes the latest generation of geometrical constraints and magnetic field requirements on the beam orbit in cylindrical coordinates, where B_τ is the tangential field component and B_z is the longitudinal field component. The second transverse field derivative was not considered in this study due to its small effect on the beam cooling factor.

TABLE I
Reference Parameters of Muon Cooling Channel

Parameter	Unit	Large bore	Small bore
Length of the good field region	m	4.0	3.2
Helix twist pitch	m	2.0	1.6
Radius of the reference orbit	m	0.25	0.25
Initial B_τ	T	1.045	1.249
$\partial B_\tau/\partial z$	T/m	-0.133	-0.170
Initial $\partial B_\tau/\partial r$	T/m	0.603	-0.882
$\partial^2 B_\tau/\partial r/\partial z$	T/m^2	-0.052	0.069
Initial B_z	T	-3.753	-3.859
$\partial B_z/\partial z$	T/m	0.467	0.544

III. Large Bore Cooling Channel

The relatively small field level in the cooling channel encourages use of well-known NbTi technology. NbTi superconducting wire with J_c(5 T, 4.2 K) = 3000 A/mm^2 was used in the design of the cooling channel. In order to provide good field quality over the necessary length, the accelerator magnet design typically requires adding at least one bore radius to each end of the good field region: that results in a straight section length of 5 m for the given channel.

A. Helical Dipole

After weighing different design approaches in terms of simplicity and efficiency, a layered design concept was developed. In that concept, the coil consists of a number of layers; each layer has a uniform cross-section and a constant current throughout the entire length. The upstream end of each layer is located at the same longitudinal coordinate, while the downstream end coordinate varies along the channel, providing the longitudinal gradient.

In the current iteration of the cooling channel design the helical dipole consists of six layers. The first layer has a 5 m long straight section that results in a total coil length of ~7 m. Each next layer straight section is shorter than the previous one by a half-period of the helix (1 m), with the last layer having zero straight section length. Fig. 1 shows the layered helical dipole coil designed with the help of OPERA 3D code to match the B_τ and $\partial B_\tau/\partial z$ components in Table I and the field it produces on the beam orbit. It is possible to see that the required helical dipole component and its longitudinal gradient are reproduced relatively well. Also, the initial $\partial B_\tau/\partial r$ component is pretty close to the required value. Thus, only the average longitudinal gradient $\partial^2 B_\tau/\partial r/\partial z$ needs correction that can be achieved with the help of a dedicated quadrupole coil.

B. *Helical Quadrupole*

The helical quadrupole coil design is based on the same layered concept as the helical dipole coil. Since at upstream the transverse field quadrupole component produced by the dipole is close to the required value, the current in the quadrupole coil should start from zero at the upstream end that allows trimming the coil length. Fig. 2 shows the eight-layer helical quadrupole coil around the dipole coil and their combined fields. The first layer of the quadrupole coil has a 3.5 m long straight section and is shifted by 1 m towards the downstream end. Each next layer is shorter than the previous one by a quarter-period of the helix (0.5 m), while the downstream end of each layer is located at the same longitudinal coordinate as the downstream end of the first layer. One can see that the average $\partial^2 B_\tau/\partial r/\partial z$ component is close to the required. Also, it is clear that the helical coils produce B_z and $\partial B_z/\partial z$ components with the opposite signs than required. This has to be corrected by the main solenoid.

C. *Main solenoid*

According to Table I, the solenoid should produce the largest field component of all. Thus, it makes sense to place it between the dipole winding and the bore tube: first – to maximize its efficiency, and second – to avoid unnecessary exposure of other coils to the strong longitudinal field. The sectioned design was used to generate the field gradient in the longitudinal direction. Since the solenoid has no geometrically distinguished ends (like a dipole), an extra two bore radii were added to the criterion mentioned earlier to compensate the field decay. The solenoid has a total length of 6 m and consists of 12 sections with a varying number of ampere-turns. It can be achieved by changing the number of turns in each section or powering each section from a separate power supply. Each section has a uniform current density. Fig. 3 shows the helical dipole, quadrupole and solenoid coils and their combined field. One can see that, on average, all field components and their longitudinal gradients are close to the required values.

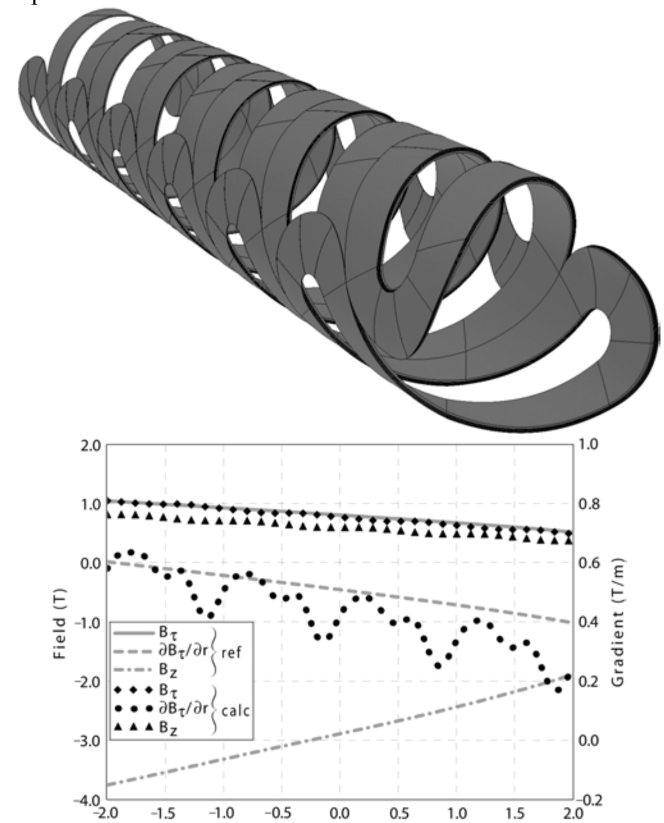


Fig. 1. Upstream end view of the layered helical dipole coil (top) and the field it produces (bottom).

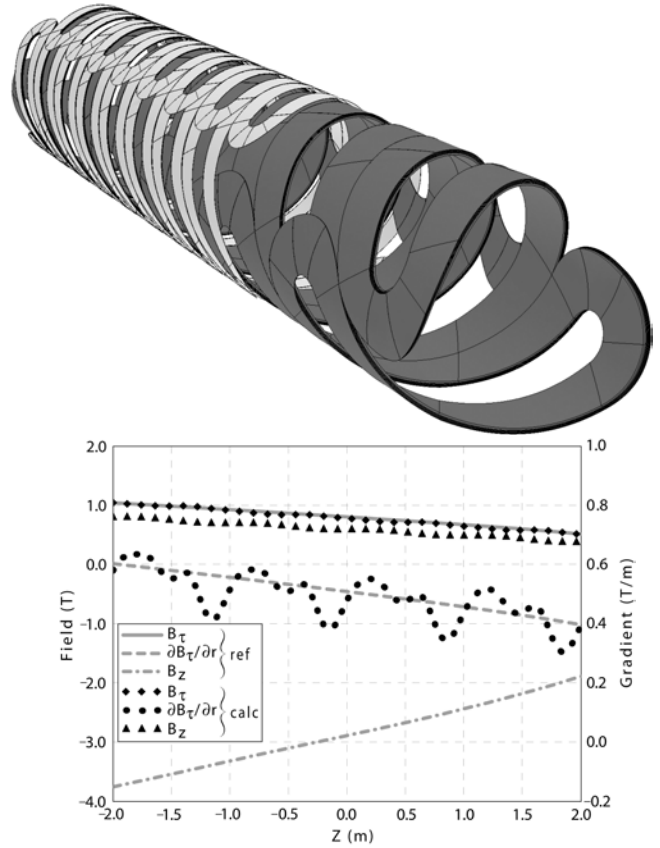
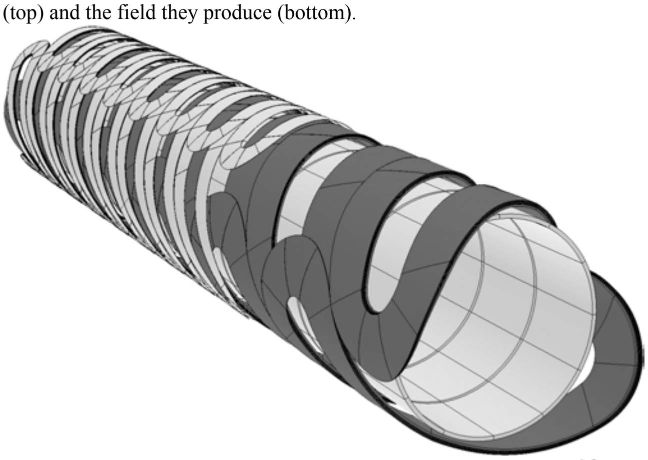


Fig. 2. Upstream end view of the layered helical dipole and quadrupole coils (top) and the field they produce (bottom).



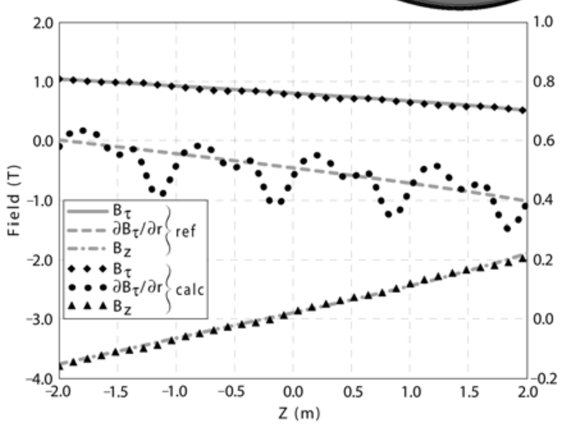


Fig. 3. Upstream end view of the layered helical dipole, quadrupole and solenoid coils (top) and the field they produce (bottom).

Table II lists the parameters of the large bore system. One can see that the dipole and quadrupole coils have large (30-50%) field margins to quench, which offsets the unknown factors related to complicated helical coil geometries. The solenoid, on the other hand, has a simple axi-symmetric geometry with a large bending radius that may reliably operate with a 10% margin. Otherwise, the radial thickness of several upstream sections can be increased to gain the necessary margin.

TABLE II
PARAMETERS OF LARGE BORE COOLING CHANNEL

Parameter	Unit	Dipole	Quad	Solen
Inner radius	m	0.55	0.58	0.50
Radial thickness: innermost layer	mm	10.00	1.00	20.00
Radial thickness: all other layers	mm	2.72	1.00	-
Radial space between layers	mm	1.00	1.00	-
Operating current density†	A/mm^2	174.3	61.3	253.6
Operating peak field	T	6.41	2.49	7.60
Quench peak field‡ at 4.2 K	T	8.56	3.66	8.37
Operating stored energy	MJ		31.84	

†Calculated as the total current over the total conductor cross-section.

‡Calculated assuming that the non-Cu fraction of superconductor spans 30% of the total conductor area and the current density in other coils remains at the operating value.

IV. SMALL BORE COOLING CHANNEL

Another novel approach is to use a helical solenoid to generate the needed fields. The solenoid consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit. The current in the rings changes along the channel to obtain the longitudinal field gradients. Apart from the large bore system, where the longitudinal and transverse field components are controlled by independent windings, the small bore system has a fixed relation between all components for a given set of geometrical constraints. Thus, to obtain the necessary cooling effect, the coil should be optimized together with the beam parameters.

Fig. 4 shows the optimum initial transverse field gradient $\partial B_\tau/\partial r$ from the beam simulations and the one calculated in the helical solenoid as a function of helix period.

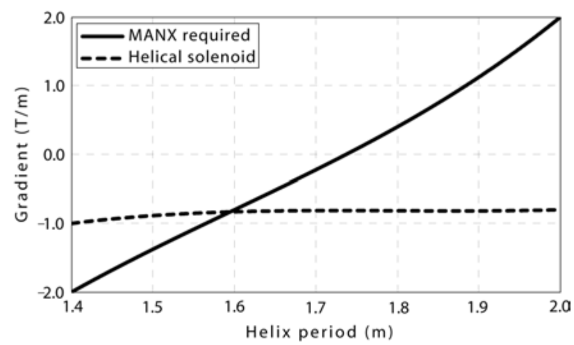
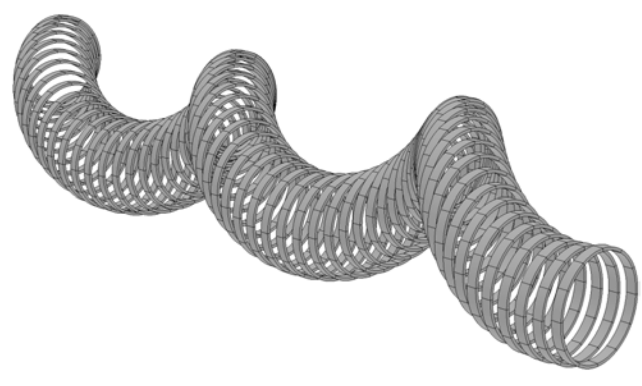


Fig. 4. Initial transverse field gradient as a function of helix period.



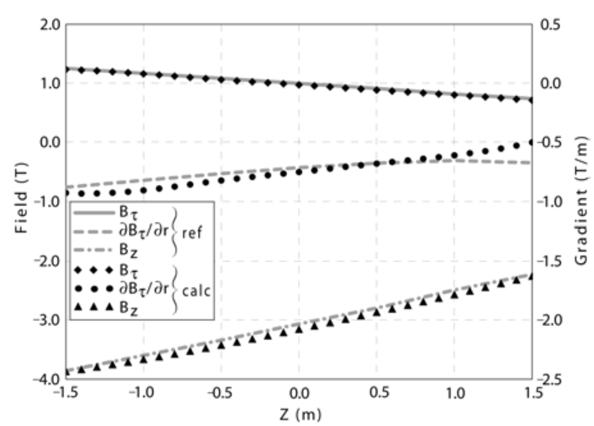


Fig. 5. Helical solenoid coil (top) and the field it produces (bottom).

One can see that the optimum gradient for the helical solenoid is -0.8 T/m, corresponding to a period of 1.6 m. Besides that, the system has other variables, one of which is the inner coil radius. For example, 0.2 m radius increase corresponds to -1 T/m change in the transverse field gradient. At the same time, it has a small influence on the dipole and longitudinal field components which provides another effective way to optimize a transverse gradient. Fig. 5 presents the optimized helical solenoid with 1.6 m period, consisting of 73 coils, and its field. Table III lists the parameters of the small bore system.

TABLE III
PARAMETERS OF SMALL BORE COOLING CHANNEL

Parameter	Unit	Value
Inner radius	m	0.28
Radial thickness	mm	15.00
Operating current density†	A/mm^2	346.4
Operating peak field	T	5.72
Quench peak field‡ at 4.2 K	T	7.38
Operating stored energy	MJ	4.42

†Calculated as the total current over the total conductor cross-section.
‡Calculated assuming that the non-Cu fraction of superconductor spans 30% of the total conductor area.

V. MECHANICS AND QUENCH PROTECTION

The magnet systems generate 6-7 T fields in the coils. Large Lorentz forces should be intercepted by a strong support structure to provide the conductor mechanical stability. Forces applied to the dipole and quadrupole coils are relatively small because they are mounted outside of the solenoid in a lower field area.

The helical solenoid has more complicated forces and torques between the coils. The maximum forces are at the beginning of the cooling channel. The forces are both compressing the magnet in the longitudinal direction and acting to straighten the helical coil.

The magnet systems store 3-30 MJ of energy in magnetic field and should have active quench protection. In spite of the large stored energy, the sectioned design approach allows independent energy extraction from the coil sections that offers a great flexibility in limiting voltages and temperatures. The relevant conductor parameters and system configuration will be determined during the quench protection analysis to limit the turn-to-turn and turn-to-ground voltages to <1 kV and coil hot spot temperature to <300 K.

VI. MUON COOLING PERFORMANCE

The proposed magnet systems were checked by the Monte Carlo beamline simulation code G4Beamline [8], using the OPERA 3D field map. The initial average momentum of 300 MeV/c reduces to 150 MeV/c at the end of the cooling section via the ionization energy loss with the liquid helium absorber. The initial momentum spread of ±13 MeV/c shrinks down to ±10 MeV/c at the end of the cooling section. On the other hand, the initial beam radius of 7 cm slightly increases to 8 cm at the end of the cooling section due to multiple scattering.

The result of beam tracing shown in Fig. 6 demonstrates the six-dimensional emittance decrease along the channel. The cooling factor, defined as the ratio between initial and final six-dimensional emittances, is 3.14 for the cooling section of the large bore system. This performance is close to the cooling factor of 3.4 obtained from the analytical field representation by Bessel functions. Based on these results, the field quality produced by the large bore magnet system seems to be adequate for the muon cooling application.

Investigation of the small bore system with the beamline simulation has recently begun. In the first step, a single particle motion was traced and found that it successfully reproduces the designed orbit. The cooling performance study will be performed after the precise matching of the helical solenoid design with the beam parameters.

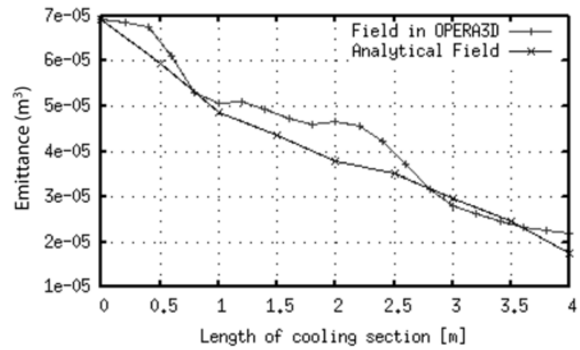


Fig. 6. 6D emittance evolution in the large bore cooling channel.

VII. CONCLUSION

The proposed NbTi magnet systems are technically feasible. The advantages of the large bore system are flexibility in dealing with uncertainties of the beam travel through the cooling channel and independent adjustment of field parameters. The small bore system has the advantages of lower cost, mass, and stored energy, but it has a fixed relation between all field components. The next step will be optimization of the matching sections for both systems. A short model and prototype fabrications and tests would be a viable approach towards verifying the magnet system performance.

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DESIGN OF 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 can realize a high sensitivity in the s-channel resonance Higgs boson production more than the electron collider. Hence the fundamental properties of the Higgs boson will be revealed with the precise measurement. This machine will also be an energy frontier machine to explorer beyond the standard model, i.e. supersymmetry, technicolor, extra dimension, grand unified theory, and so on [1]. A muon beam which is produced via the pion decay is needed a fast 6D phase space reduction to fit in the acceptance of the conventional RF acceleration cavity. The ionization cooling method is the only way to make a muon beam transverse phase space cooling within its short lifetime (2.2 μsec in a rest flame) [2]. However, it is required an emittance exchange to make a longitudinal phase space cooling.

Recently, a novel cooling scheme has been proposed [3]. A helical cooling channel (HCC) is used with a continuous ionization cooling absorber. The helical magnet consists of a helical dipole, helical quadrupole, and solenoid magnets. 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 central force which is induced by the dispersion with the helical dipole component and a attractive central force which is induced by the Larmor oscillation with the solenoid component. This realizes the continuous dispersion magnet: A particle with a higher (lower) momentum than the designed particle has a longer (shorter) path length, and loses more (less) kinetic energy in the continuous energy absorber. It is called the emittance exchange. The lost kinetic energy is compensated by the RF field. In this cooling scheme, the obtained 6D cooling factor can be 10^6 in the analytical expectation.

The simulation study has begun since 2003 and verified the helical cooling theory [4]. For the next stage, we have proposed the demonstration experiment, Muon collider And Neutrino factory eXperiment (MANX) [5]. In this article, we discuss the overview of MANX experiment and design the matching section which has been done recently.

CONCEPTUAL DESIGN OF MANX COOLING SECTION

Figure 1 shows the conceptual picture of the MANX cooling section. The cooling section consists of the helical cooling channel (red) and the upstream and downstream matching magnets (light blue). The cooling absorber is filled in the cooling channel. The matching magnet is assumed to be vacuum condition. There is a thin Al window between cooling and matching magnets to isolate thermal and vacuum conditions.

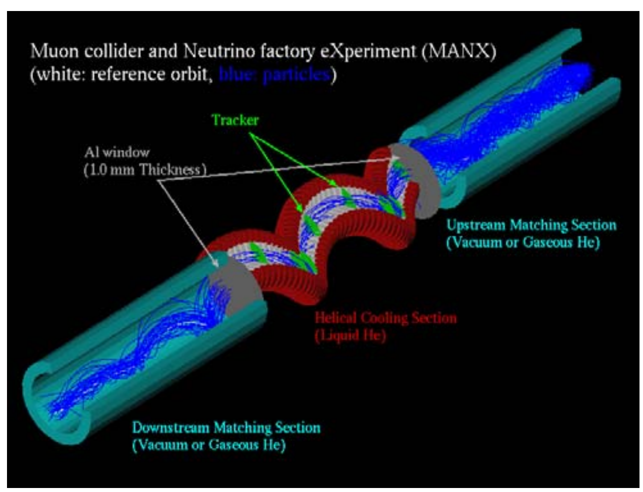

Figure 1: Conceptual picture of the MANX cooling section.

In the original MANX design, the RF cavity is removed for simplicity. Hence the magnetic field strength in the cooling channel has the momentum dependence along with the channel length. Figure 2 shows the designed field strength as a function of the length of channel. The initial and final mean momenta of the muons are 300 MeV/c and 150 MeV/c in the channel length of 3.2 m, respectively.

The liquid helium is chosen as the ionization cooling absorber in the current design because of the safety issue and usage of the liquid helium as a coolant for the magnet conductors. Table 1 has a summary of the design parameters of MANX channel.

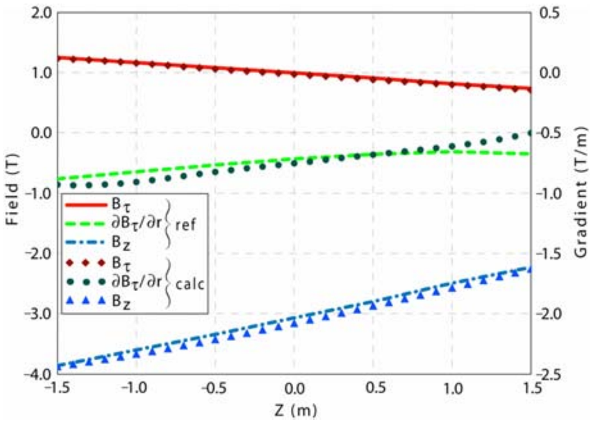

Figure 2: Field configurations of the designed particle in the cooling channel. The circle, square, and triangle lines are the required analytical field configurations and red, green, and blue lines are calculated field configurations in FEA. The conductor design is shown in Figure 3.

Table 1: MANX design parameters. Helical Pitch, κ, is defined as 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:	**B**	-3.8 T -1.6 T
Initial helical dip. strength: Final helical dip. strength:	**B**	1.0 T 0.5 T
Initial helical quad. strength: Final helical quad. Strength:	**b’**	-0.8 T/m -0.4 T/m

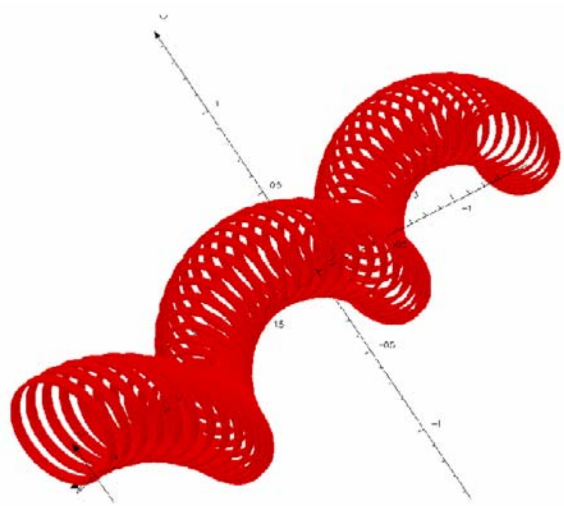

Figure 3: Layout of helical solenoid coils.

We brought up two different magnet designs to realize the helical magnet. One is the conventional helical magnet, so called as “Siberian Snake type” which exists for the spin rotator magnet. On the other hand, a new helical magnet design has brought up recently. It is called “helical solenoid magnet” as shown in Figure 3. It consists of the solenoid coils. The position of the coil center is following with the helical orbit. The helical dipole and the solenoid components can be generated naturally. In addition, by adjusting the helical pitch, this system can induce the required quadrupole component, too. The detailed discussion will be done in Ref [6].

The function of the matching magnet is to connect between the coaxial beam into the helical orbit. 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 trial was using the adiabatic ramping of a helical dipole and quadrupole components with a constant solenoid. The result was that the required matching length is more than 10 m. But it makes a perfect matching. The period of the beta beat induced by the ramping magnet is observed 1.5 λ without any strong dependence neither on the ramping rate and magnetic field strength. Hence, we considered that the transverse momentum kick should be taken place during one beta beat and keep the beam stability by tuning the solenoid field strength. Figure 4 shows a whole magnetic field configuration in the MANX cooling section.

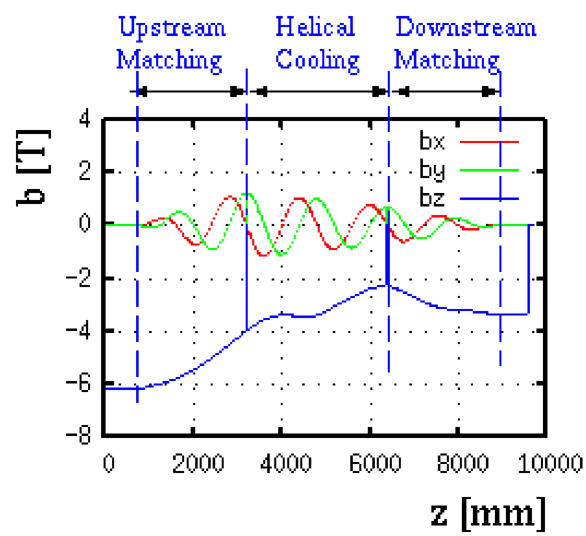

Figure 4: Measured field strength of the reference particle in a whole cooling channel.

Figure 4 shows the measured field strength of the reference particle in a whole cooling channel. The field parameters are slightly different from the designed values because of the imperfection of the beta beat tuning in the matching magnets. The average beam position at the end of the cooling channel is ~10 mm in x and y directions.

SIMULATION RESULT

Figure 5 shows the evolution of the normalized rms 6D emittance down the length of the whole cooling channel.

The obtained cooling factor in the transverse and longitudinal directions are equally 1.3, hence the obtained cooling factor of 6D emittance is approximately 2.

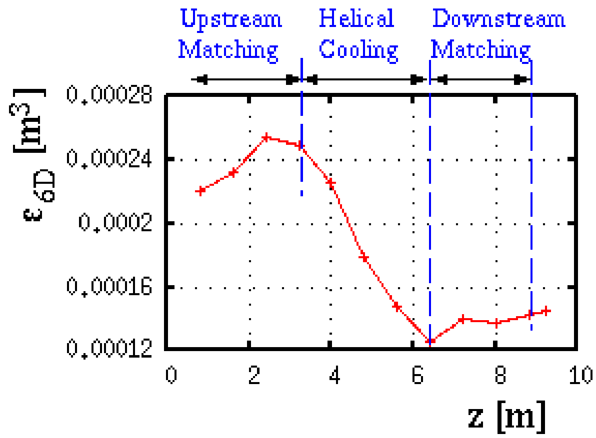

Figure 5: Emittance evolution in the MANX cooling section.

The initial condition of the injected beam (see Table 2)has a very wide phase space to occupy the acceptance of the cooling channel. The particle to make a plot in Figure 5 is chosen when it can pass through the whole cooling channel. Hence, it includes the non-linear effect of the magnet. As a result, we observe the big fractions of 6D emittance in the matching magnet.

Table 2: The initial beam profile in this simulation.

σx, σy	± 60 mm
σx', σy'	± 0.4
Δp/p	± 40/300 MeV/c
Transmission efficiency	30 %
6D cooling factor	2.1

ANOTHER ISSUES

Spectrometer

The longitudinal emittance cooling measurement is essential for the proof of the emittance exchange. Therefore, the momentum reduction and evolution of time structure measurements through the cooling channel are crucial. We start investigating what is the required time resolution in the time of flight measurements.

Muon beam line/transport line

Design of the pion production target, the pion decay channel, and the beam transport system are in progress [7].

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Delivering Muons to the MuCool Test Area

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March 22, 2007

Abstract

A new way to produce a muon beam for the MuCool Test Area is described. The key idea is to use existing Linac beam-splitting capabilities, based on a fast electrostatic chopper, to split individual 15-Hz Linac beam pulses between the Booster and the MTA, thereby taking advantage of the ability of the Linac to deliver longer beam pulses than the Booster can accelerate. The momentum-analyzing bend at the end of the Linac would be extended so that the 400-MeV H^- beam is steered past the momentum dump toward the MTA. Then it would strike a pion production target to generate muons. Such a beam line, located in existing enclosures, could parasitically deliver at least 50 μs of spill containing up to 1.4×10^{13} protons to the production target at a 15 Hz rate (i.e. 0.75 ms of spill and 2.1×10^{14} protons per second). Linac pulse length extensions could provide further improvements.

Introduction

The MuCool Test Area (MTA) [1] is designed to support a variety of activities related to muon cooling research and development. Before the end of this year, a new beam transfer line [2] will be installed to deliver 400-MeV H^- beam from the Linac to the MTA. The implementation of that line will allow individual 15-Hz Linac beam cycles not needed by the Booster to be sent to the MTA. A primary purpose of the initial experimental program with H^- beam is to assess the response of muon cooling devices such as pressurized RF cavities [3] to ionizing radiation. Although that program typically requires high instantaneous fluxes, low duty cycles and repetition rates of order 1 Hz are acceptable.

Recently thoughts have turned to the possibility of producing a low-energy muon beam for additional tests of muon cooling concepts and techniques. That experimental program would benefit from higher duty cycles and repetition rates. One possibility that has been investigated [4] is to use the 400 MeV H^- beam from the Linac to produce muons in the MTA where suitable cryogenics, RF, and hydrogen facilities already exist. However, if the beam were extracted from the Linac using the magnets [2] now being installed to transfer H^- beam into the MTA, there would be limitations in beam current and duty factor, since only those Linac pulses not destined for the Booster can be delivered by that means to the MTA. For example, if the Booster is using 13 pulses per second, only two MTA pulses of 80 μs and 2.25×10^{13} protons per second would be available (i.e. 0.16 ms of spill and 4.5×10^{13} protons per second).

The concept that is described in this note could increase the spill length and proton intensity available to the MTA by almost a factor of 5 compared to the example above. If the Linac pulse can be made longer than 80 μs, the improvement can be larger.

Reasonable modifications could extend the Linac pulse length to 110 μs, which implies an improvement factor of 5.5 and a spill length of 1.65 ms per second. For comparison, the MICE apparatus is designed to record 600 muons per second using the ISIS beam spill length of 1 ms per second [5]. The improvement factor applies both to a muon experiment such as MICE that uses the single-particle analysis technique and to the macro-particle approach that is being investigated at Fermilab [4].

Present Linac Operation

The Fermilab 400 MeV Linac can accelerate 80 μs H^- beam pulses, with 45 mA peak current, at a 15 Hz repetition rate. The 400 MeV beam is transferred to the Booster using the switchyard located in the Linac diagnostic area. To provide flexibility of operations and to insure the best possible beam and desired intensity, two electrostatic choppers and a Lambertson magnet are used to send the beam to the Booster. Currently, the length of the pulse to be accelerated in the Linac is determined by the Booster intensity requirement. Figure 1 shows the beam current in the different parts of the switchyard.

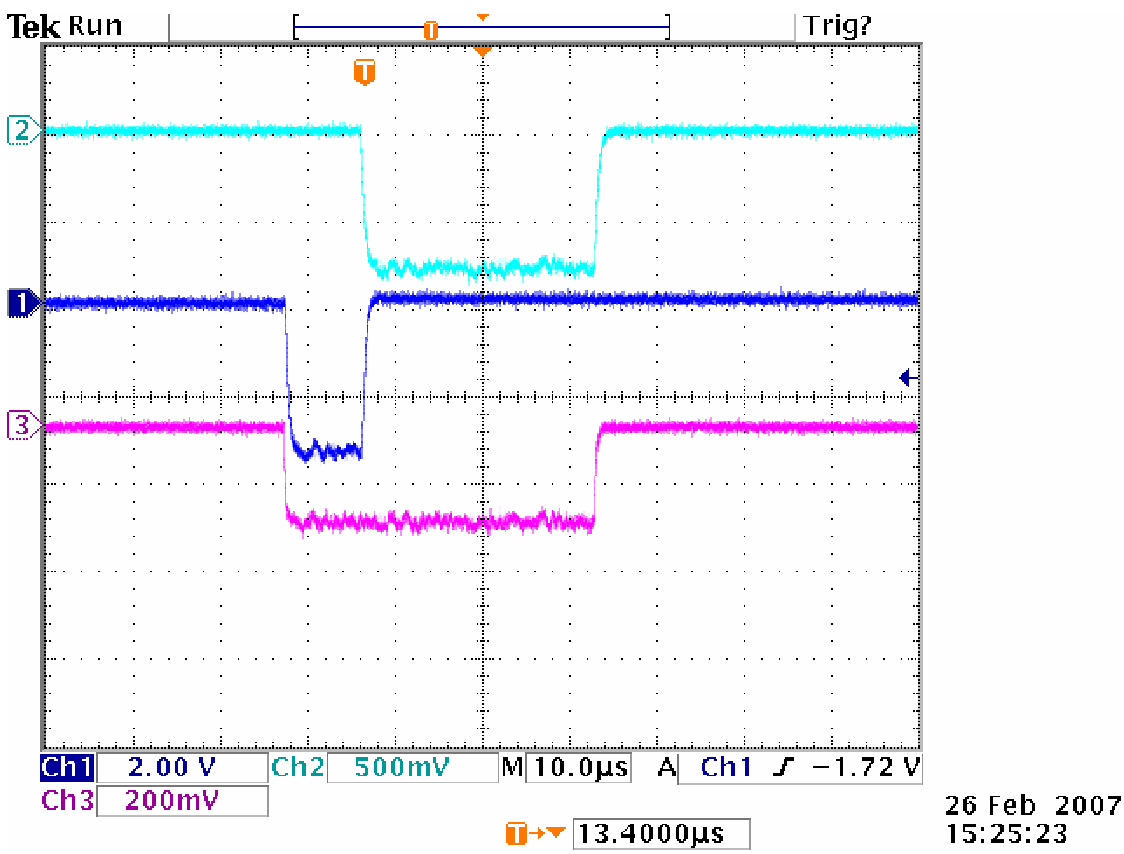

Figure 1: Present switchyard operation: the Magenta trace is the Linac pulse, the Blue trace is the beam pulse directed to the momentum dump and the Cyan trace is the beam pulse directed to the Booster. In the technique proposed in this paper, the Blue and Magenta pulses would be extended an additional 50 μs (at the 30 μs point of the display) and the Cyan pulse to the Booster would be delayed by 50 μs. The beam heading for the momentum dump would be redirected to the MTA muon production target.

During normal operation, the ion source produces a 90 μs H^- pulse with 45 mA peak current. At the upstream end of the Linac, at 750 keV, the low energy chopper removes the initial 6 μs of H^- beam. This part of the pulse is considered not useful because it is produced during the time needed by the source to reach a steady state. At the downstream end of the Linac, the first 5 μs of the remaining beam pulse is chopped by the high energy chopper and directed to the so-called momentum dump, and the rest of the beam is sent to the Booster. (The first 5 μs of the pulse is considered to be damaged in the 750 keV line during the process of charge neutralization and along the Linac due to the slow response of regulation loops.)

The high energy chopper is also used to define the exact amount of beam needed for the Booster, so that the tail of the beam pulse (normally only a fraction of a μs) is sent to the momentum dump. The length of the tail is defined by the low energy chopper and can be extended. For pbar production, which is the most demanding mode of operation, 5×10^{12} protons are accelerated in the Booster using a 28 μs, 35 mA peak current Linac pulse. Even in the pbar production mode of operation there are about 80-28=52 μs of Linac beam that are potentially available.

Overview of Switchyard and H^- Beam Extraction to the MTA

As described above and as shown in Figure 2 below, in normal operation the beam pulse is split at the end of the Linac using the high energy chopper. Most of the H^- beam goes to the 400 MeV transfer line for injection into the Booster. The front and tail of the beam are sent to the Diagnostic Line, where they are bent by the spectrometer magnet and deposited in the momentum dump.

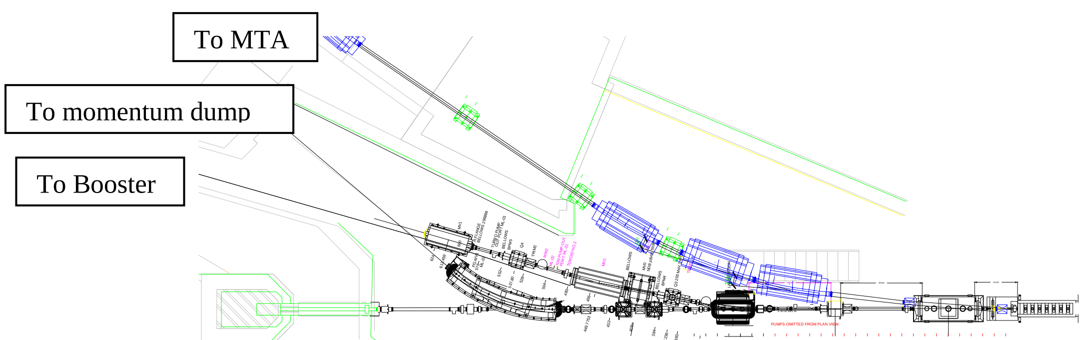

Figure 2: The switchyard as envisioned at the end of 2007 (without the modifications proposed herein). The elements shown in blue are part of the new beam line to send H^- beam to the MTA.

This year an additional transfer line will be built to take individual Linac H^- pulses and transfer them to the MTA. The beam will be bent just before and after the high energy chopper using two pulsed magnets as shown in Figure 3. The rest of the beam line to the MTA is similar to the line shown in blue in Figure 2.

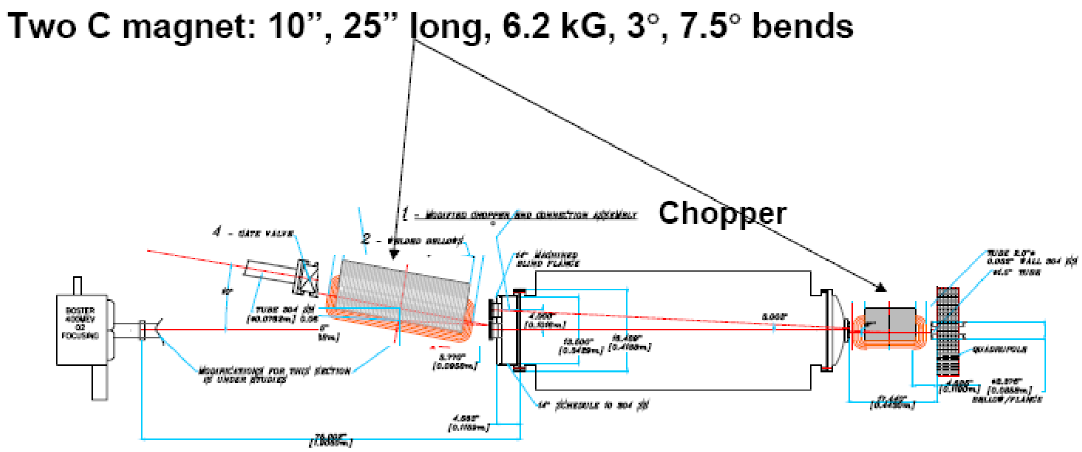

Figure 3: Pulsed magnets before and after the high-energy chopper are used in the H⁻ transfer line for the MTA. These magnets are fast enough to select individual 15 Hz pulses from the Linac, but they cannot direct parts of a single pulse to be deflected toward the MTA.

The Proposed Muon Beam Production Scheme

All of the Linac beam that is not needed by the Booster can be deflected to the MTA using the scheme indicated in red in Figure 4. As described above and indicated in Figure 1, we can use the front portion of about 50 μs of the beam for the MTA even if the Booster is taking beam at a full 15 Hz rate.

To connect the beam line after the spectrometer magnet to the beam line in the MuCool transfer hall we will need to drill a hole in the wall and add two bending magnets (red elements in Figure 4) and one quad magnet (green element in Figure 4).

One immediate user of the suggested extraction system can be the recently proposed Macroparticle Muon Cooling Experiment [4]. That experiment needs as many protons as possible and a long pion decay channel to reduce pion contamination in the muon beam. An initial estimate is that the 400 MeV proton beam on a 40 cm carbon target can produce enough muons for the experiment [6]. The target has a 5 mm radius and is embedded in a 5 T solenoidal field. The pion decay channel is assumed to be more than 20 meters long.

To satisfy these requirements, the first bending magnet is a combined-function 40-degree bend and the second bend is a 40-degree pure dipole with a larger gap. Each of these magnets can be like the existing spectrometer magnet. The pole tip of the combined function magnet will be machined according to the required focusing strength. We may be able to use the existing MTA 5 T superconducting solenoid around the target. It is 60 cm long with 44 cm inner diameter. The bore is big enough to contain the target and thermal and radiation shields.

Initial Trace3D simulations show that the H⁻ beam can be focused to a radius of less than 5 mm at the entrance to the solenoid. Figure 5 shows the Trace3D model with final beam ellipses at the entrance to the solenoid. Figure 6 shows a Trace3D calculation of pion beam optics.

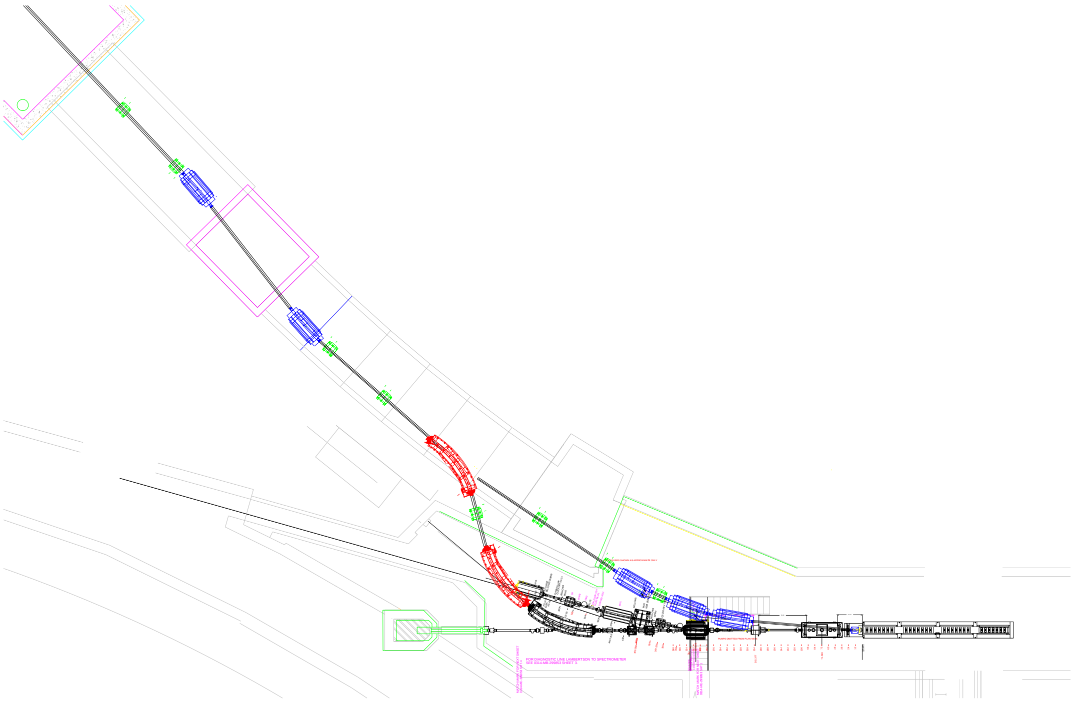

Figure 4. The elements drawn in black are the existing beam lines and the Linac. The blue elements are part of the new H$^-$ beam line now under construction. The red elements are part of the muon production system proposed in this note.

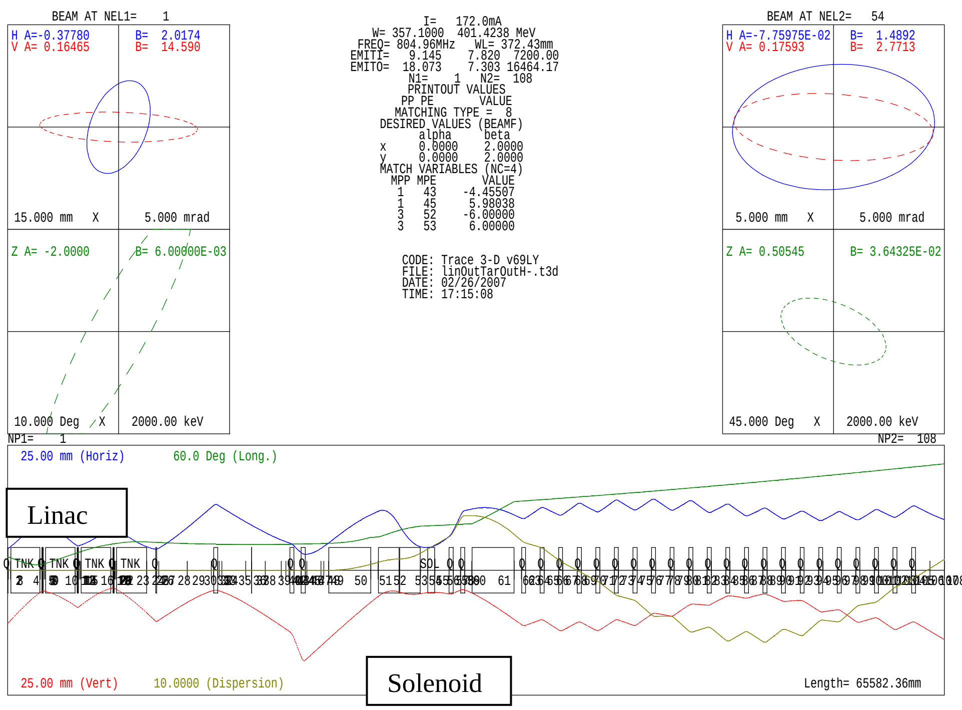

Figure 5: H$^-$ beam from the last Linac accelerating module to the MTA hall with target removed. The blue and red traces are horizontal and vertical beam envelopes (95%). The green and brown lines are bunch length and horizontal dispersion. The input beam ellipses are from beam measurements.

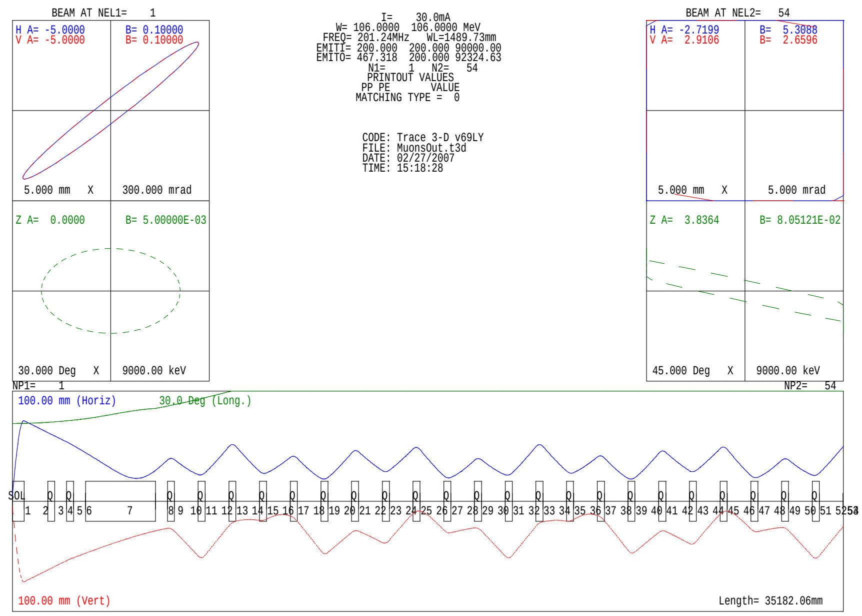

Figure 6: Pion beam with 200 MeV/c momentum collected off the target using a 5 Tesla Solenoid. The large box represents a 40 degree dipole. The rest of the line is a pion decay channel.

Conclusion

A relatively straightforward modification to the Linac switchyard allows a significant improvement in the duty factor and flux of protons on target to produce muons for the MTA.

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[5] Alan Bross, private communication.
[6] Mokhov et al., http://www.muonsinc.com/mcwfeb07/presentations/Mokhov_021307.pdf

STOPPING MUON BEAMS*

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Mary Anne Clare Cummings and Rolland P. Johnson, Muons, Inc, Batavia, IL 60639, USA.

Abstract

The study of rare processes using stopping muon beams provides access to new physics that cannot be addressed at energy frontier machines. The flux of muons into a small stopping target is limited by the production process and by stochastic processes in the material used to slow the particles. Innovative muon beam cooling techniques are being applied to the design of stopping muon beams in order to increase the event rates in such experiments. Intense stopping muon beams will also aid the development of applications such as muon spin resonance and muon-catalyzed fusion.

INTRODUCTION

The high energy physics community faces the challenge of finding affordable ways to explore the physics beyond the Standard Model. Recent developments in muon cooling hold out the promise of muon colliders to extend the energy reach of the International Linear Collider and of neutrino factories based on muon storage rings to explore the underlying physics. But energy frontier facilities are very expensive, and affordable R&D programs that can give access to new physics are also important. Fortunately, there are fundamental physics issues that are best addressed by "low energy" and non-accelerator experiments. These topics are most often related to the replication of leptons and quarks in generations: the quark and lepton mass spectra, the mixing of flavors, and the CP violation induced by the mixing. These physics issues can be addressed by intense stopping muon beams to support experiments studying rare processes with exquisite sensitivity.

Since neutrino oscillations establish lepton flavor violation (LFV) in the neutrino sector, the next logical search is for observable LFV in the charged lepton sector. An intense stopping muon beam would allow sensitive searches for such phenomena. Work is currently underway to use muon cooling design tools and innovations developed by Muons, Inc. [1], in the context of proposed improvements to the beam facilities available at Fermilab [2], to design a stopping muon beam to enhance the feasibility and improve the sensitivity of a muon to electron conversion experiment, a sensitive probe of LFV in the charged lepton sector which may run at Fermilab in parallel with the future neutrino program.

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TECHNICAL APPROACH

A muon-to-electron conversion experiment called MECO was proposed at Brookhaven [2] as part of the RSVP (rare symmetry-violating processes) project. The physics case for the experiment was compelling, but high costs led the National Science Foundation to terminate the RSVP project. The MECO concept, shown in Figure 1, includes three large superconducting magnets: solenoids for muon

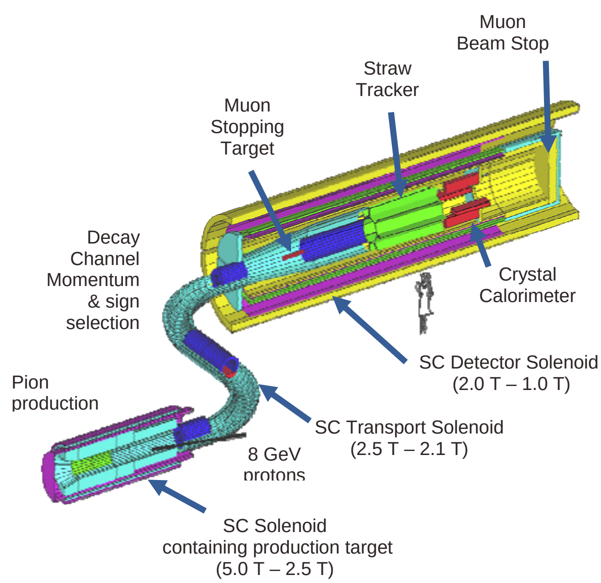

Figure 1: Conceptual picture of the MECO experiment at Brookhaven.

production, transport, and analysis. Protons incident on the production target (from the right, not shown in the figure) produce negative pions. Those pions with transverse momenta < 180 MeV/c travel within the 30 cm inner radius of the magnet, and most decays to muons occur in the production region. The muons, following helical trajectories along the magnet axis, are captured in the production solenoid and transported by the bent solenoid to the stopping target. The magnetic field along the axis of the system has regions of uniform field connected by regions of monotonically decreasing strength as shown in Figure 1. Both the trigger and tracker are high-rate detectors located far from the solenoid axis to intercept conversion electron helices and avoid lower-momentum particles resulting from beam interactions or ordinary muon decays. The negative muons are captured into orbits around nuclei in the stopping target. Rarely, a muon may convert directly to an electron in the field of a nucleus. Such an electron is emitted with an energy of about 105 MeV, almost the full rest energy of the muon: a striking kinematic signature. The detector is optimized to measure the high-energy electrons, while the low-energy ones are confined to the central region of the detector solenoid.

Beamline at FNAL

The primary proton beam for MECO was to be provided by the Alternating Gradient Synchrotron (AGS), with 40×10^{12} protons delivered at a one Hz rate. The choice of beam energy, 7-8 GeV, optimizes pion production and minimizes antiproton production (a potential background source). The 8 GeV energy of the Fermilab Booster proton beam is thus close to optimal. Two 8-GeV storage rings presently used for accumulating antiprotons can be reused for protons. Figure 2 shows the proton distribution to the FNAL physics program at that time. The idea is that 4 of the 22 Booster batches per Main Injector (MI) cycle will be available for muon production while 18 batches are used for the neutrino program. In contrast to the MECO reflecting solenoidal production channel, a forward production target is being considered, in which case the muon production system would be similar to current neutrino factory and muon collider front end designs.

Momentum-dependent Helical Cooling Channel

We propose to explore ways to improve the capabilities and reduce the direct costs of a muon-to-electron conversion experiment by using muon beam cooling techniques to enhance the sensitivity of the experiment and to reduce the cost of the magnet system. Ionization cooling ordinarily shrinks only transverse emittances, so emittance exchange is necessary for longitudinal cooling. In earlier concepts, emittance exchange was accomplished by using a dipole magnet to create an energy-position correlation of the beam in a wedge-shaped absorber. Higher energy particles pass through the thicker part of the wedge and suffer greater ionization energy loss, thus producing a more mono-energetic beam. The conceptual innovation developed by Muons, Inc. is to fill the bending magnet with a continuous, homogenous absorber such as dense hydrogen gas. Higher-momentum particles lose more energy because they have longer path lengths in the gaseous absorber, thereby reducing the beam energy spread and hence the longitudinal emittance. This concept of a continuous absorbing medium was refined by the development of the Helical Cooling Channel (HCC)[4], invented by Yaroslav Derbenev, comprised of superposed

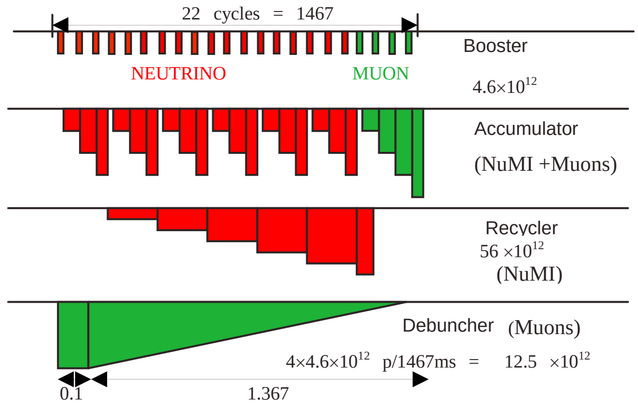

Figure 2: Fermilab Proton source ring usage.

solenoid, helical dipole, and quadrupole magnets. The HCC-type magnet has been adapted for front end designs of a neutrino factory and muon collider, as illustrated in Figures 3a and 3b. One HCC variation has been proposed for a cooling demonstration, 6DMANX,[5] employing ionization cooling and emittance exchange to achieve reduction in normalized emittance in six dimensions.

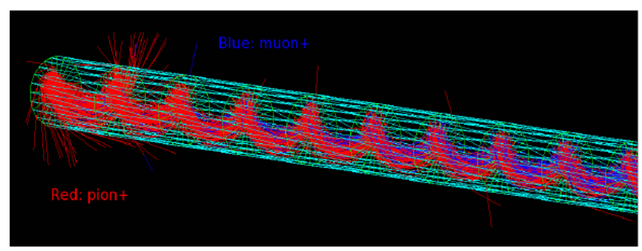

Figure 3a: G4Beamline simulation of muon (blue) and pion (red) orbits in a HCC-type magnet that is adapted as a decay channel.

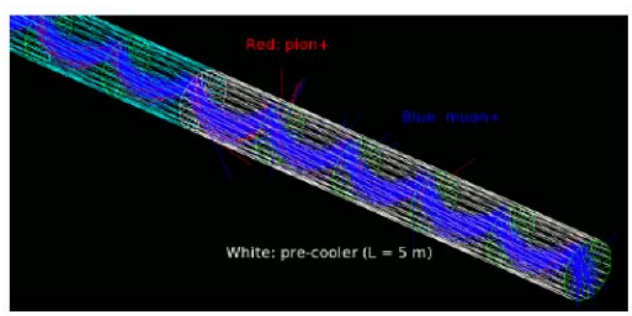

Figure 3b: The decay channel in Fig. 3a ends in an absorber-filled HCC which is a precooler.

FNAL μ/e Conversion Experiment

The approach of the FNAL experiment will be to increase the stopped muon/proton ratio from the 0.25% accepted by the MECO design by using the higher-energy, higher flux part of the pion/muon production spectrum. The beam will be slowed by passing through a HCC segment that is much like the 6DMANX apparatus, which could be filled with liquid helium or hydrogen. After the beam has been slowed from about 300 MeV/c to 100 MeV/c, another HCC with a less dense absorber will be used to slow the beam to about 50 MeV/c before it is transported to the experimental stopping target.

The use of longitudinal beam cooling overcomes the large momentum spread that results from the strong negative slope of the dE/dx versus momentum curve at low energy; this is what motivativated MECO's choice of the low energy tail of the production spectrum, with its lower stopped-muon/proton yield. The idea of tapering the density of the absorber is an innovation in the theory of the HCC. In order to be effective, the magnetic dispersion, which provides the momentum or path-length dependent ionization energy loss, must increase as the beam slows and the slope of dE/dx versus E increases. However, when the magnetic dispersion is increased too far, the required magnetic fields cause the beam stability and channel acceptance to suffer. Reducing the density of the energy absorber overcomes this problem. Possible lower dE/dx absorber alternatives include high-pressure gas, and low density inserts (e.g. Styrofoam) into the liquid hydrogen or helium absorber.

A first attempt to use a simple, tapered-density HCC approach, where absorbers with different density are used to cool and degrade a beam produced by 8 GeV protons was simulated with a Geant4-based program called G4Beamline[6], shown in Figure 4. Figure 5a shows the entire momentum spectrum of produced muons and pions, and the subset (hatched area) that enters the first HCC

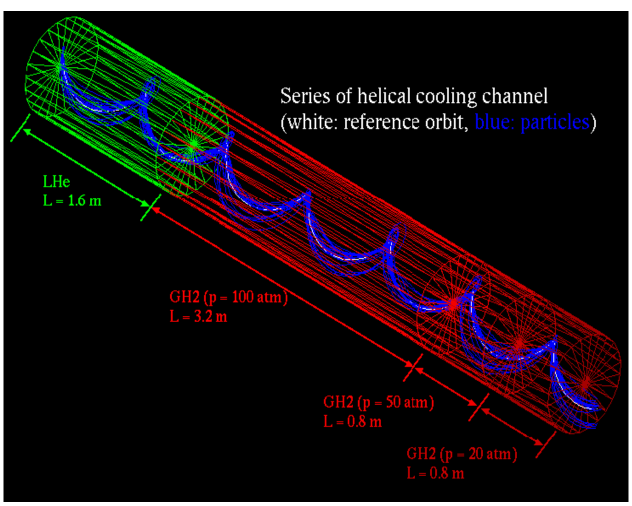

Figure 4: HCC with decreasing density used for first simulations.

segment at the left of Figure 4, which is at Z=0. Figure 5b shows the evolution of the momentum distribution as the beam is degraded and cooled in the HCC in a series of segments shown in Figure 4 with decreasing density. The reduction in flux as the beam passes down the channel is due to the reduced acceptance caused by the required dispersion. The acceptance will be improved by further theoretical analysis and numerical simulation studies. But already this first, non-optimal study shows the muon/proton ratio of muons stopping in a 50 mm Al target is 1.2%, almost 5 times larger than in the baseline MECO design. This is encouraging, and a more optimized study of transverse distributions, backgrounds, and the use of a stronger capture solenoid should yield significant improvements.

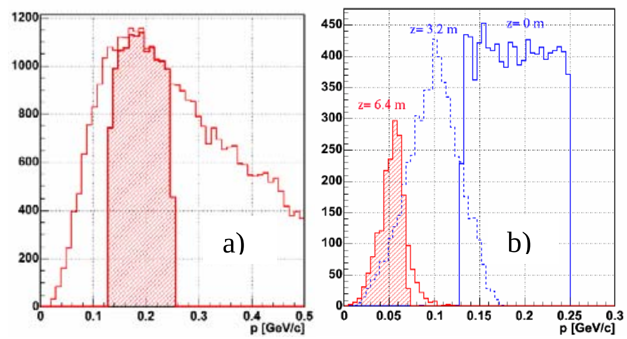

Figure 5: (a) A plot of the π/μ flux from the target produced by an 8 GeV proton beam and the subset (hatched area) that enters the first HCC segment. (b) A plot of the evolution of the muon momentum spread from the start of the cooling channel (z=0) through a series of HCC segments with reduced hydrogen absorber density to the stopping target at z=6.4 m.

SUMMARY

The flux of stopping muons for the study of rare processes such as muon-to-electron conversion can be improved by the use of innovative muon cooling concepts originally developed for muon colliders and neutrino factories.

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[2] C. Ankenbrandt et al, "Using the Fermilab Proton Source for a Muon to Electron Conversion Experiment". http://lanl.arxiv.org/ftp/physics/papers/0611/0611124.pdf

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APPENDIX A. U.S. DEPARTMENT OF ENERGY COVER PAGE FOR SMALL BUSINESS INNOVATION RESEARCH (SBIR) AND SMALL BUSINESS TECHNOLOGY TRANSFER (STTR) PROGRAMS

DE-FG01-05ER05-28

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TITLE: **Development and Demonstration of 6-Dimensional Muon Beam Cooling**	Topic No.: **38**	Subtopic: **b**
	Amount Requested (not to exceed $100,000):	$100,000

SMALL BUSINESS

FIRM NAME:	I.R.S Entity ID or SSN:	ADDRESS:
Muons, Inc.	**36-4488857** DUNS #: 117921259	ADDRESS: 552 N. Batavia Ave. CITY: Batavia STATE: IL ZIP: 60510 Web Address:

Principal Investigator (See Requirements in Sec. 1.5.2)	Corporate/Business Authorized Representatives
Dr. Rolland P. Johnson	Dr. Rolland P. Johnson
Title: Scientist Phone Number: (757) 870-6943 E:mail address: roljohn@aol.com	Title: President Phone Number: (757) 870-6943 E:mail address: roljohn@aol.com

Certification and Acceptance: I certify that the statements herein are true and complete to the best of my knowledge, and accept the obligation to comply with DOE terms and conditions if an award is made as the result of this submission. A willfully false certification is a criminal offense. (U.S. Code, Title 18, Section 1001)

Signature: ROLLAND JOHNSON Date: 11/30/2005	**Signature: ROLLAND JOHNSON Date: 11/30/2005**

RESEARCH INSTITUTION

Check YES or NO: This grant application contains substantial collaboration with a research institution (see definition Sec. 2.9 and Sec. 1.5.3).

X YES __ NO

If yes, check one:
__ STTR only.
X both SBIR and STTR.

If no, check below:
__ SBIR only.

NAME OF RESEARCH INSTITUTION:	
Fermi National Accelerator Laboratory	$30,000 Amount of Subcontract

ADDRESS: P. O. Box 500
CITY: Batavia STATE: IL ZIP: 60510

Certifying Official: Dr. Bruce Chrisman

Title: Associate Director Phone Number: (630) 840-6657
E:mail address: Chrisman@fnal.gov

Certification: If this grant application is selected for award, I certify that the above research institution will conduct the work herein attributed to it.

Signature: BRUCE CHRISMAN Date: 11/30/2005

OTHER SUBCONTRACTORS: INDICATE NAME AND DOLLAR AMOUNT

None.

CERTIFICATIONS AND QUESTIONS: ANSWER Y (YES) OR N (NO)

Y 1. The applicant organization certifies that it is a small business and meets the definition stated in Section 2.3.

Y 2. The applicant will comply with the provisions regarding: (1) lobbying, (2) debarment, suspension, and other responsibility matters, and (3) drug-free workplace requirements. (See Certifications Section.) Inability to certify to any or all statements requires explanation.

Y 3. The Principal Investigator will have his/her primary employment with the small business at the time of award (see Section 1.5.2).

Y 4. The application includes a subcontract with a Federal lab (See Section 1.6.2).

N 5. The applicant has received more than 15 Phase II SBIR awards in the preceding five fiscal years. **(If yes, please provide information requested in Section 3.3.7.)**

N 6. The applicant and/or Principal Investigator has submitted applications containing a significant amount of essentially equivalent work under other federal program solicitations, or received other federal awards containing a significant amount of equivalent work? **If "yes", the application must include the required information requested in Section 3.3.4.**

Y 7. If the proposed project does not result in an award, does the applicant permit the government to disclose the technical abstract of the application, and the name, address, and telephone of the business official to any inquiring parties?

N 8. The applicant is delinquent on a Federal debt? (If "yes," please attach an explanation.)

Y 9. All research by the applicant and all subcontractors will be performed within the United States.

PROPRIETARY NOTICE (SECTION 5.4) For any purpose other than to evaluate this submission, these data shall not be disclosed outside the Government and shall not be duplicated, used, or disclosed in whole or in part, without written consent from the applicant. Provided that a grant is awarded to this applicant as a result of or in connection with the submission of these data, the Government shall have the right to duplicate, use, or disclose the data to the extent provided in the grant. This restriction does not limit the Government's right to use information contained in the data if it is obtained from another source without restriction. The data in this submission subject to this restriction are contained on pages ______________________

SMALL BUSINESS INNOVATION RESEARCH PROGRAM
SMALL BUSINESS TECHNOLOGY TRANSFER PROGRAM
SOLICITATION NO. DOE/SC-0075
PROJECT SUMMARY
Phase I

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09/10/03

Topic No.: **38** Subtopic: **b**

(All information provided on this page is subject to release to the public.)

FIRM NAME: **Muons, Inc.**	RESEARCH INSTITUTION: **Fermi National Accelerator Laboratory**
ADDRESS: 552 N. Batavia Ave., Batavia IL 60510	ADDRESS: P. O. Box 500, Batavia IL 60510

NAME of PRINCIPAL INVESTIGATOR: Dr. Rolland P. Johnson PHONE NUMBER: (757) 870-6943 (mobile)

PROJECT TITLE: Development and Demonstration of Six-Dimensional Muon Beam Cooling

TECHNICAL ABSTRACT (Limit to space provided)

Statement of the problem or situation that is being addressed - typically, one to three sentences.

Ionization cooling, a method for shrinking the size of a particle beam, is an essential technique for future particle accelerators that use muons. Muon colliders and neutrino factories, examples of these future accelerators, depend on the development of robust and affordable techniques for ionization cooling

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, two sentences.

This proposal is to develop an experiment to prove that effective six-dimensional (6D) muon beam cooling can be achieved using an ionization-cooling channel based on helical and solenoidal magnets in a novel configuration. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood, thereby overcoming a critical roadblock to intense neutrino factories and high-luminosity muon colliders.

What is planned for the Phase I project (typically, two to three sentences).

In Phase I a preliminary simulation of a complete experiment will be performed based on GEANT4 that will include spectrometers upstream and downstream of the specially-designed HCC. Experimental significance can then be studied as a function of detector resolution, particle identification efficiency, magnetic field parameters, and absorber characteristics using the numerical simulation. Critical technical issues will be identified for computational and experimental investigation in Phase II.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

The applications of the new techniques that will be developed and proved by this project involve very bright muon beams for fundamental research using muon colliders, neutrino factories, and muon beams with new characteristics. The most important application will be an energy frontier muon collider which achieves high luminosity by virtue of small emittance rather than large muon flux. The small emittance in all dimensions that is possible as shown by this project will allow high-frequency ILC RF structures to be used for such a collider and also for a high flux muon beam that could supply a storage ring used as a neutrino factory.

SUMMARY FOR MEMBERS OF CONGRESS: (LAYMAN'S TERMS, TWO SENTENCES MAX.)

An energy frontier muon collider, potentially the most powerful subatomic micoscope, becomes a realistic machine if muon beams can be made small enough in their short lifetime. This project is to develop the required techniques to cool muon beams and design an experiment to prove that the techniques work.

Development and Demonstration of Six-Dimensional Muon Beam Cooling

Table of Contents

Overview

The projects discussed below are to improve the cooling of intense muon beams, which could reduce the cost of neutrino factories and facilitate the design of high-intensity muon colliders. These SBIR and STTR projects represent a coherent plan and innovative program to develop a muon source to be used in these and other projects. For United States High Energy Physics, an energy frontier muon collider is an alternative or follow-on to the present plan based on the International Linear electron positron Collider (ILC). In fact, we are convinced that the work described here adds to the importance of the ILC effort since we can use (shorter) sections of their accelerating structures to recirculate muons to even higher energy to achieve a higher energy frontier lepton collider at less cost. The demonstration experiment described in this proposal is an essential step to a convincing case for a muon collider. It is also required for the case of neutrino factory based on ILC accelerating structures.

Muons, Inc. started with the idea that a gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve. This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Additionally, use of a continuous gaseous absorber presents other practical advantages that make it a simpler and more effective cooling method compared to short liquid hydrogen flasks in the conventional designs.

Measurements by Muons, Inc. and the Illinois Institute of Technology (IIT) at Fermi National Accelerator Laboratory (FNAL) have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure. Consequently, a higher gradient is possible in a hydrogen-filled RF cavity than that needed to overcome the energy loss from ionization cooling. Hydrogen is twice as good as helium in ionization cooling effectiveness, viscosity, and heat capacity. These facts and a possible future hydrogen economy make it our energy absorbing material of choice.

Subsequent to the idea of pressurized RF cavities, we introduced the concept that a cooling channel filled with a continuous homogeneous absorber could provide longitudinal ionization cooling by exploiting the path length correlation with momentum in a magnetic channel with positive dispersion. We applied this approach to a helical cooling channel (HCC), invented by Yaroslav Derbenev, to use this concept of a continuous homogeneous energy absorber to allow emittance exchange and excellent 6D muon beam cooling.

A new idea, explored in the course of an SBIR Phase I project that did not continue into Phase II, is that the HCC concept can be extended to the case of magnetic fields that change amplitude and direction along the *z*-axis (the beam direction). In this case, the beam momentum can change and the conditions for 6D cooling can still be met as a beam slows down in a very dense continuous absorber. This concept leads to several new applications, including an economical and striking experiment to demonstrate the effectiveness of the HCC to cool all (6) dimensions of a muon beam – the subject of this proposal.

These paths to an affordable neutrino factory and to a compelling design of a muon collider have complementary projects that Muons, Inc. is pursuing with SBIR/STTR grants and proposals:

Phase II Projects

1) The development of Pressurized **High Gradient RF Cavities** is the subject of an STTR grant with IIT (Prof. Daniel Kaplan, Subcontract PI), which began in July 2002 and ended in September 2005. In Phase I of this project, Muons, Inc. built an 805 MHz test cell (TC) and used it to measure the breakdown voltages of hydrogen and helium gases at FNAL with surface gradients up to 50 MV/m on copper electrodes. Phase II started in July 2003 to extend the measurements at Fermilab's Lab G and the MuCool Test Area (MTA) to include effects of strong magnetic fields and ionizing radiation at 805 MHz. By the end of November 2003, a new test cell was built under this grant, passed safety requirements associated with the high pressure hydrogen, and was used to extend Paschen curve measurements for hydrogen beyond 60 MV/m surface gradient (20μs pulse width) using electropolished molybdenum electrodes [1]. The new

test cell is capable of 1600 PSI operation in the 5 Tesla LBL Solenoid, recently installed in the MTA, with ionizing radiation from the 400 MeV H^- Linac. IIT, Muons, Inc. and Fermilab staff members prepared a design [2] for a beam line from the Linac to the MTA using available magnets and other components, however, the beam line has yet to be implemented. We planned to have a demonstration of pressurized high-gradient RF cavities operating in intense magnetic and radiation fields by the end of the STTR Phase II grant period, however the Lab G work was terminated when Fermilab operations removed the klystron from Lab G in January 2004. The klystron was made available to us in the MTA in the summer of 2005 without the Solenoid or the implementation of the beam line. The Solenoid will be available in the MTA sometime near the end of 2005, when we can operate the TC in it. We are exploring other ways to operate the test cell in a beam, perhaps in front of the Linac Dump, as part of the Phase II phase rotation grant described below. IIT supported a post-doc to work on this project under this grant. The results of this project and others below can be found at http://muonsinc.com

2) **Six-Dimensional (6D) Cooling** using gaseous absorber and pressurized high-gradient RF is the subject of an SBIR grant with Thomas Jefferson National Accelerator Facility (Dr. Yaroslav Derbenev, Subcontract PI), which began in July 2003 and will end in July 2006. A magnetic field configured such that higher energy particles have a longer path length can be used to generate the momentum-dependent energy loss needed for emittance exchange and six-dimensional cooling. In the 6D channel, helical dipole and solenoidal magnets and the RF cavities in them are filled with dense hydrogen so that higher energy particles then have more ionization energy loss. A paper describing the concepts and dynamics of this Helical Cooling Channel (HCC) grew out of the proposal for this grant and has been published in PRSTAB [3]. Recent simulations of a series of four such HCC segments have shown cooling factors of more than 50,000 in a 160 m long linear channel [4]. The 6D grant itself is to support the simulation of the channel by modifying existing computer codes and to optimize the design of the channel.

3) **Hydrogen Cryostat for Muon Beam Cooling** is an SBIR project begun in July 2004 and now funded to July 2007 with Fermilab (Dr. Victor Yarba, Subcontract PI) to extend the use of hydrogen in ionization cooling to that of refrigerant in addition to breakdown suppressant and energy absorber. The project is to develop cryostat designs that could be used for muon beam cooling channels where hydrogen would circulate through refrigerators and the beam-cooling channel to simultaneously refrigerate 1) high-temperature-superconductor (HTS) magnet coils, 2) cold copper RF cavities, and 3) the hydrogen that is heated by the muon beam. In an application where a large amount of hydrogen is naturally present because it is the optimum ionization cooling material, it seems reasonable to explore its use with HTS magnets and cold, but not superconducting, RF cavities. However, the Helical Cooling Channel (HCC) cryostat to be developed in Phase I, because of new inventions in the last year, now has more variations than were originally envisioned and there are now several cryostat designs to be optimized. In Phase I we developed computer programs for simulations and analysis and started experimental programs to examine the parameters and technological limitations of the materials and designs of HCC components (magnet conductor, RF cavities, absorber containment windows, heat transport, energy absorber, and refrigerant). As an example, we could design the cryostat for the 6DMANX cooling demonstration experiment.

4) **Ionization Cooling using Parametric Resonances** is a project begun in July 2004 and funded to July 2007 with Jefferson Lab as a research partner (Dr. Yaroslav Derbenev, Subgrant PI). The excellent 6D cooling expected from the SBIR Project 2) above leaves the beam with a small enough size and sufficient coherence to allow an entirely new way to implement ionization cooling by using a parametric resonance. The idea is to excite a half-integer parametric resonance in a beam line or ring to cause the usual elliptical motion on a phase-space diagram to become hyperbolic, much as is used in half-integer extraction from a synchrotron. This causes the beam to stream outward to large x' and/or y' while the spatial dimensions x and/or y shrink. Ionization cooling is then applied to reduce the x' and y' angular spread. The Phase II grant is to study the details of this new technique and to develop techniques for correction of chromatic and spherical aberrations and other higher-order effects using analytical calculations and numerical simulations.

New Muon Cooling Phase I Projects Granted in 2005:

5) Reverse Emittance Exchange for Muon Beam Cooling, with Jefferson Lab (Dr. Yaroslav Derbenev, Subgrant PI) is a Phase I STTR project begun in July 2005 to develop a technique to shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider. After the 6D cooling described in Project 2) above, the longitudinal emittance is small enough to allow high frequency RF for acceleration. However, the longitudinal emittance after the beam has been accelerated to collider energy is a thousand or more times smaller than necessary to match the beta function at the collider interaction point. We plan to repartition the emittances to lengthen the muon bunch and shrink the transverse bunch dimensions using linear cooling channel segments and wedge absorbers.

6) Capture, Bunching, and Precooling using High-pressure Gas-filled RF Cavities, with Fermilab (Dr. David Neuffer, Subgrant PI) is a Phase I STTR project begun in July 2005 for simultaneous muon capture, RF bunch rotation, and precooling in the first stage of a muon beam line. The project has computational and experimental parts. The concept of the use of gas filled RF cavities close to the pion production target for phase rotation and beam cooling will be simulated. In parallel, the project will also involve a continuation of the experimental development in the Fermilab MuCool Test Area of high-gradient high-pressure RF cavities operating in a high radiation environment and in strong magnetic fields.

New Muon Cooling Phase I proposals for 2006:

7) Development and Demonstration of Six-Dimensional Muon Beam Cooling with Fermilab, this proposal. This proposal is to develop an experiment to prove that effective six-dimensional (6D) muon beam cooling can be achieved using an ionization-cooling channel based on a novel configuration of helical and solenoidal magnets. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood sufficiently well to become an enabling technology for intense neutrino factories and high-luminosity muon colliders.

8) 50 Tesla HTS Magnets for Muon Beam Cooling with BNL. High-field High-Temperature Superconductor (HTS) solenoids operating at 4 K can provide the transverse cooling needed to bring the emittance down from the value reached by a Helical Cooing Channel to that which is needed for effective Parametric-resonance Ionization Cooling. An innovative magnet design is proposed to achieve extreme fields for this HEP application.

9) Interactive Design and Simulation of Beams in Matter with IIT. G4BeamLine (G4BL*), a beam line design program based on GEANT4 for beams with significant interactions with matter, has been the workhorse for Muons, Inc. and the International Muon Ionization Cooling Experiment (MICE) [5] collaboration to simulate muon cooling channels to explore new techniques. This proposal is to improve the program for more general use, adding a Graphical User Interface and several new and enhanced capabilities.

10) High Power RF couplers for the ILC with JLab. Sufficiently cooled muon beams can be accelerated in 1.3 GHz Tesla-style RF modules for uses in Muon Colliders or Neutrino Factories. However, to achieve the highest average collider luminosity or neutrino flux, higher repetition rates will be required than are contemplated with the ILC. We propose to improve the present ILC RF coupler design with lower cost, innovative RF windows for the benefit of the ILC, other 1.3 GHz accelerators, and future muon-based programs.

11) Compact, Tunable RF Cavities for FFAG Synchrotrons with Fermilab. Fixed Field Alternating Gradient machines are being studied as a means to accelerate particles so quickly that ramping magnets are not possible. The potential applications for such rapid-cycling machines include high-intensity proton drivers for muon and neutron production, heavy-ion cancer therapy, and muon acceleration. We propose to develop a novel RF cavity design that will have fast tuning, operate over a wide frequency range, and will be well-suited to an FFAG.

Although each of these projects is independent, taken together they represent a coherent plan to generate a compelling design for an intense muon source. Muons, Inc. now has enthusiastic collaborators from IIT, Jefferson Lab, Fermilab, and Brookhaven who are part of this effort. The grants described above now support five young accelerator scientists. We hope that recent simulation results showing 6D cooling factors of 50,000 for a 4-section helical cooling channel will reenergize the muon collider community. The Linac community has likewise shown interest in the pressurized cavity development. This is a lively, creative collaboration dedicated to developing new options for the physics community.

* http://g4beamline.muonsinc.com

a. Identification and Significance of Problem or Opportunity, and Technical Approach

Identification of Problem

Ionization Cooling (IC) is currently the only practical technique fast enough to cool a muon beam. An experiment to show that adequate ionization cooling can be achieved in a practical device has yet to be made.

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

Significance

Muon beams with low transverse and longitudinal emittance are needed for **muon colliders** in order to get the highest luminosity with the fewest number of muons. We would like to emphasize that the strong reduction of emittance has at least nine very beneficial consequences for a muon collider. The reduction of the required muon current for a given luminosity diminishes several problems:
1) radiation levels due to the high energy neutrinos from muon beams circulating and decaying in the collider that interact in the dirt near the site boundary;
2) electrons from the same decays that cause background in the experimental detectors;
3) difficulty in creating a proton driver that can produce enough protons to create the muons;
4) proton target heat deposition and radiation levels;
5) heating of the ionization cooling energy absorber and
6) beam loading and wake field effects in the accelerating RF cavities.
Smaller emittance also:
7) allows smaller, higher-frequency RF cavities with higher gradient for acceleration;
8) makes beam transport easier; and
9) allows stronger focusing at the interaction point since that is limited by the beam extension in the quadrupole magnets of the low beta insertion.

Reasons 7) and 8) also apply to affordable **neutrino factories** based on muon storage rings. The costs of the acceleration systems for past neutrino factory design studies have been a large fraction of the totals and would have benefited from higher frequency RF systems with their higher gradients and lower component costs. Reference [6] describes how a future Fermilab proton driver [7] based on TESLA superconducting linac modules can perform as both the source of protons to produce the muons and as the accelerator of the muons to be used for a neutrino factory or muon collider, allowing a single linac to serve the dual function of production and subsequent acceleration of the muons. Recent advances in muon cooling [8] have the promise of muon emittances that are compatible with the 1300 MHz accelerating structures that are the basis for the ILC design. In the design described in reference [7], H^- ions are accelerated to 8 GeV in the superconducting Linac, stripped and stored as protons in a ring, then bunched during the 300 microseconds it takes the Linac cavities to be rephased for muon accleleration. The protons are then extracted from the ring to produce pions and muons which are cooled in a few hundred meters, accelerated to a few GeV and injected back into the Linac at the $\beta = 1$ point for acceleration to add 7 GeV. By recirculating the muons in the constant frequency section of such a proton driver Linac, even higher energies can be achieved quickly so that losses from muon decay are minimized. Additional RF power and refrigeration can increase the repetition rate of the Linac to make large increases in the average flux of a neutrino factory and the average luminosity of a muon collider.

Other important uses for bright muon beams range from basic studies of fundamental interactions to muon catalyzed fusion.

Opportunity

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

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

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

Technical Approach

Helical Cooling Channel (HCC) with Z-dependent Field Amplitudes

As discussed in the Overview section above, the results of analytical and numerical simulation calculations 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 [3] ;

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa}b\right], \tag{III.12}$$

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

The new idea that is the basis for this proposal is that equation (III.12) 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 you would like the momentum and/or radius of the equilibrium orbit to change for various purposes. Examples of these purposes that we have started to examine include:

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

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

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

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

Additional constraints to equation (III.12) are needed to determine the cooling properties of the channel. For example, to achieve equal cooling decrements in the two transverse and the longitudinal coordinates:

$$q \equiv \frac{k_c}{k} - 1 = \beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}}, \tag{IV.21}$$

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

HCC Precooling Examples

Figure 1 shows the G4BL simulation of a combination decay (40 m) and precooler (5 m) HCC example. Pions and muons are created in the vacuum of the decay channel and captured in the HCC. At the end of the decay region, the muons pass through a thin aluminum window into a region of liquid energy absorber. By having a continuous HCC for the two sections, the problem of emittance matching into and out of the precooler has been avoided. Simulation studies of various precooler dimensions and magnet strengths have been done.

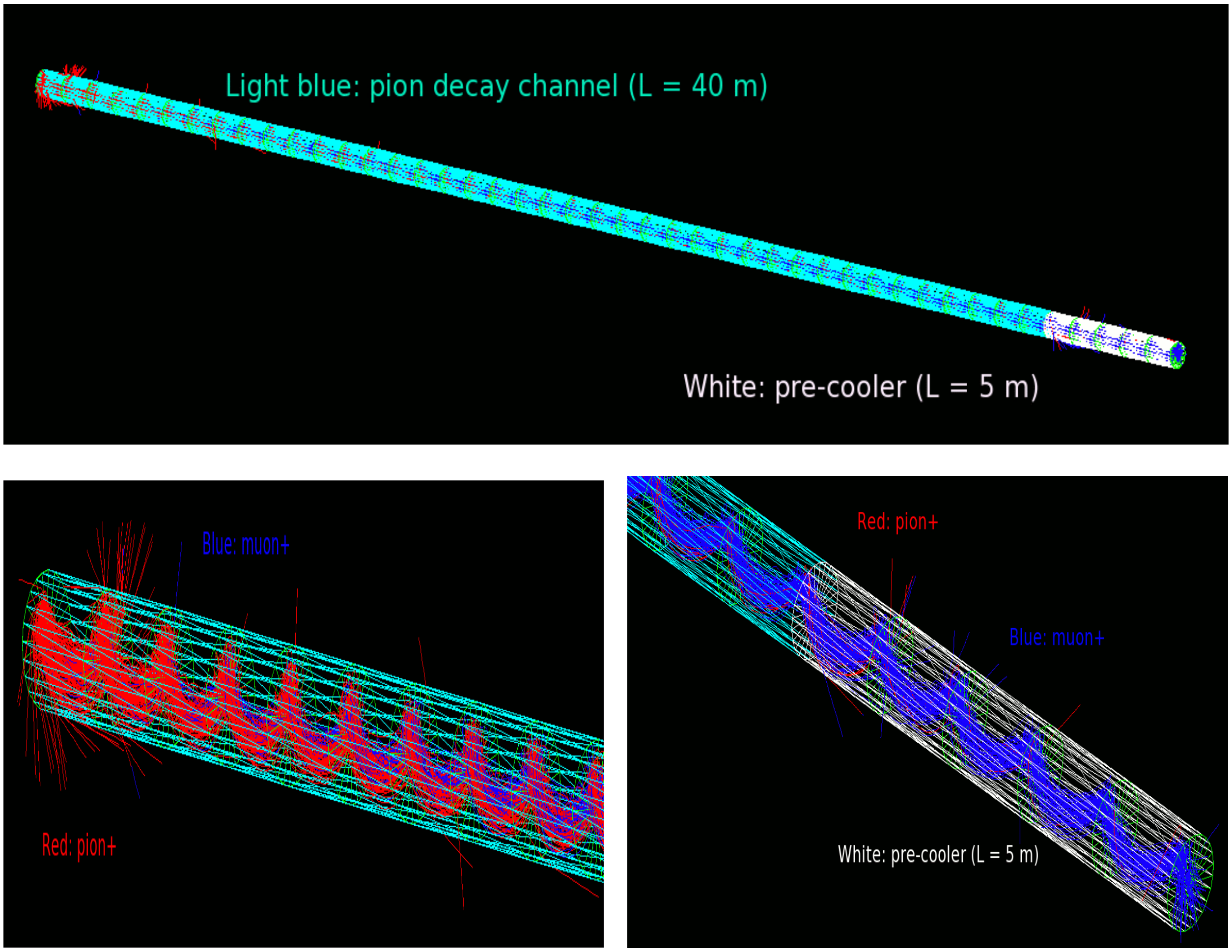

Fig. 1: G4BL display of a pion decay HCC (light blue) followed by a 5 m precooling (white) HCC. The top display shows the whole layout, the lower left display is the beginning of the decay channel, and the lower right display shows the precooler end. The red and blue lines show the pion and muon tracks,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

Figure 2 shows the normalized transverse (only the average transverse plot is shown), longitudinal, and 6D emittances plotted as a function of the distance down the channel to study the use of liquid hydrogen and liquid helium and the effects of the aluminum containment windows of a 6 m long precooler section. In this simulation, 400 MeV/c muons are degraded to less than 200 MeV/c in making 6 turns in a HCC filled with liquid hydrogen or liquid helium, without or with 1.6 mm aluminum windows on each end of the section. Far from the equilibrium emittances, the cooling with liquid helium absorber is almost as good as with liquid hydrogen. The aluminum windows do not significantly degrade the cooling.

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 the RF cavities, while the two thin windows needed for this precooler design are negligible in their heating effect compared to the length of the liquid absorber. This precooling example inspired the idea of a 6D cooling demonstration experiment that is described below. In fact, the device that we propose to design as a 6D demonstration experiment also serves as a precooler prototype.

The goal of Phase II of the project is to create a realistic design for a cooling channel experiment which can be built with available technology and to demonstrate by computer simulation that it will be a striking proof of the concepts we are developing.

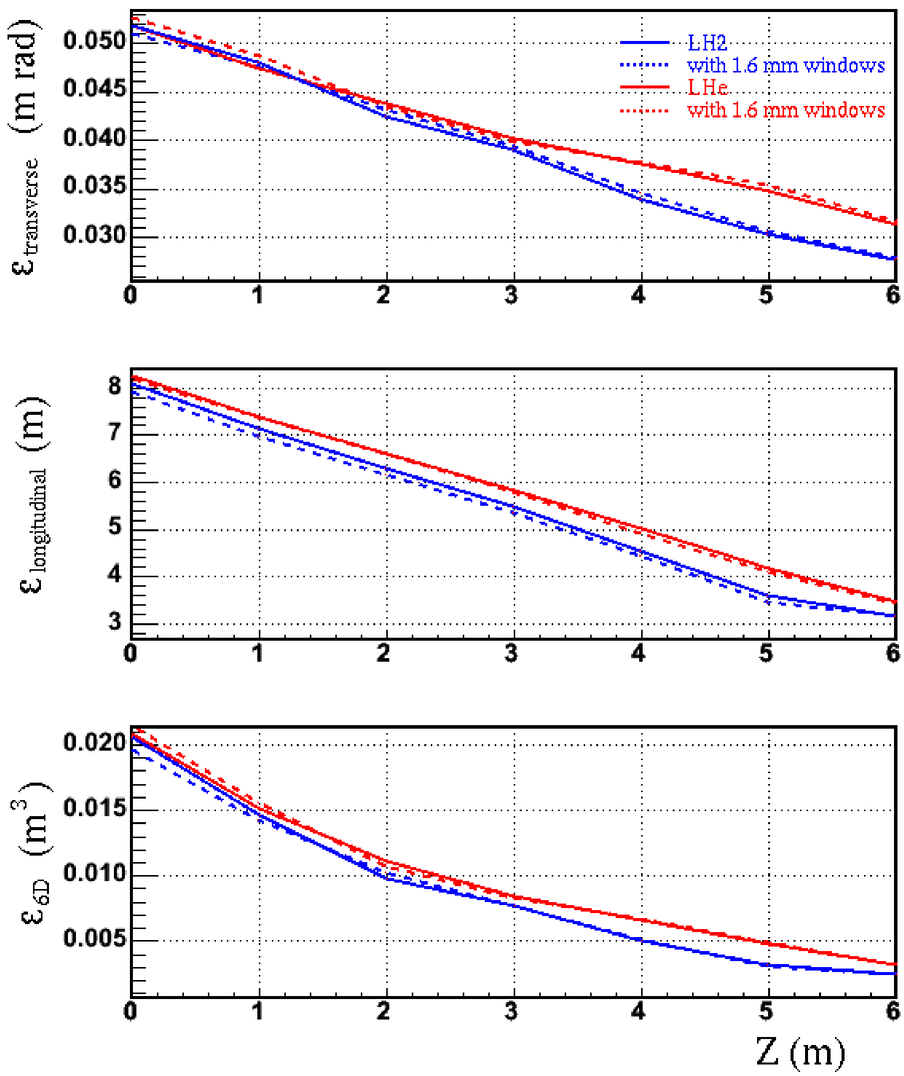

Fig. 2. Simulations showing emittance evolution for particles that survive to 6 m for a HCC precooler filled with liquid hydrogen (blue) or liquid helium (red), with (dashed) and without (solid) 1.6 mm thick aluminum windows on each end.

b. Anticipated Public Benefits

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

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

The Phase I Project

c. Phase I Technical Objectives

In Phase I a preliminary simulation of a complete experiment will be performed that will include spectrometers upstream and downstream of the specially-designed HCC. In preparation for this simulation, a specific objective is to understand the beam transport through the spectrometers and the HCC test device, including fringe fields, such that the beam emittance is not distorted and beam cooling measurements will be clear and unambiguous. Based on this analysis and simulation, at least one base design of the 6DMANX will be developed.

The technical objectives of the Phase I project include:

1. Develop an analytic understanding of the matching between the HCC and spectrometers using the techniques developed in part by our collaborators Bogacz and Derbenev.

2. Using the analytic treatment for guidance, develop a numerical simulation of the complete 6DMANX experiment using G4BL.

3. Use the G4BL program to start the optimization of the experiment.

4. Identify critical issues of prototype development and engineering concerns.

5. Prepare a plan for Phase II development.

d. Phase I Work Plan

6DMANX, the 6D HCC Demonstration Experiment

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

A conceptual picture of a 6DMANX demonstration experiment is shown in figure 3 based on using the MICE spectrometers at Rutherford Appleton Laboratory (RAL). The gray cylinder represents the HCC, which is the new device to be built. It is a solenoid with transverse helical dipole and quadrupole magnets that is filled with liquid helium or hydrogen. Muons enter from the left of the picture and pass through the (yellow) solenoidal spectrometer section instrumented with scintillating fiber detectors that are being built for the MICE experiment.

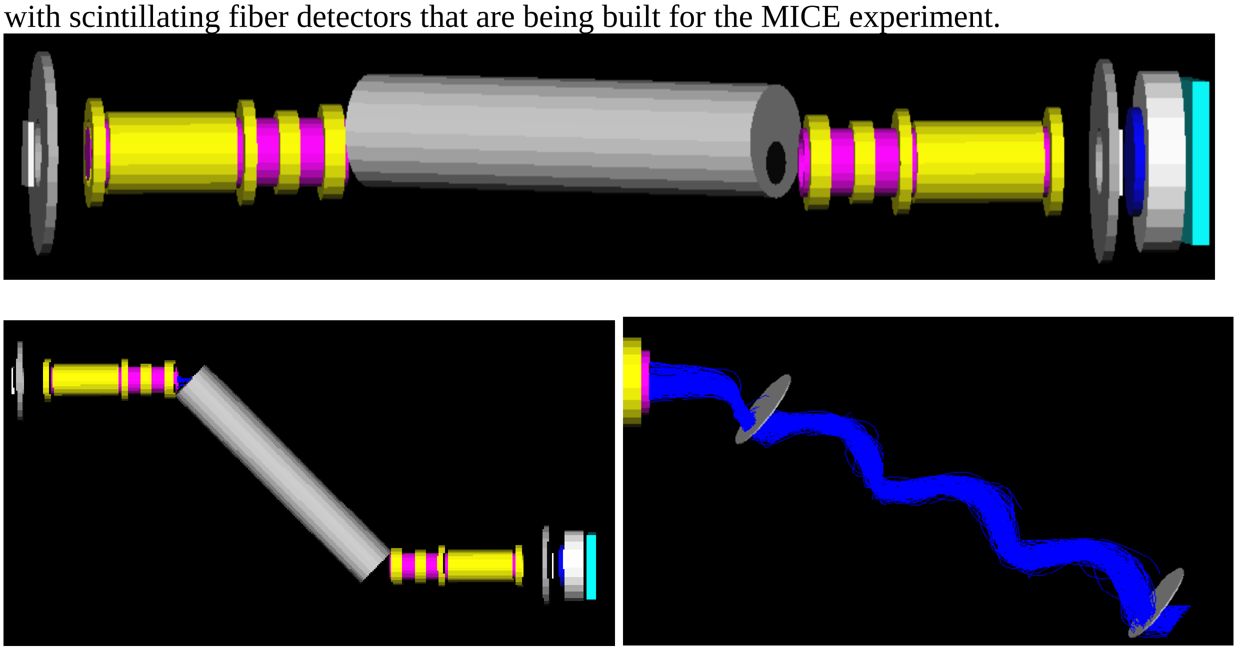

Fig. 3. G4BL simulation program displays of the elevation (upper), plan (lower left) and beam trace (lower right) views of the 6DMANX HCC using the MICE spectrometers. The yellow devices correspond to the matching coils and spectrometer magnets of the particle measurement sections of the MICE experiment. The gray cylinder is the HCC that is the heart of 6DMANX.

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

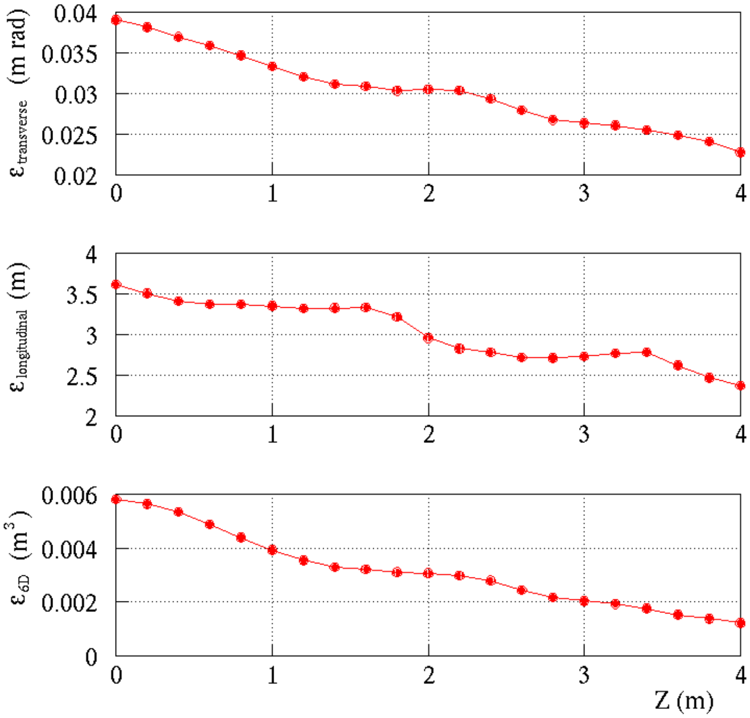

Fig. 4 G4Beamline Simulation of a liquid helium filled 6DMANX section with reduced field requirements. The initial momentum has been decreased from 400 to 300 MeV/c (as required for the RAL beam), λ has been increased from 1 to 2 m, and κ decreased from 1 to 0.8. The maximum field at a conductor has thereby been reduced to 5.2 T. The cooling factors are: average transverse 1.7, longitudinal 1.5, and 6D 4.7.

Latest Iteration of 6DMANX Design

The magnetic field strengths for the first studies of the precooler and the demonstration experiment were very large at the coils and would require the use of HTS at low temperature. In order to reduce this technical problem, we have already started to study changes in the experiment to make it easier to build. Figure 4 shows the simulation results for the 6DMANX experiment based on relaxed parameters, where the magnet coils could be made of NbTi and cooled by the same liquid helium that acts as the ionization cooling energy absorber. In order to reduce the fields, the initial momentum has been decreased from 400 to 300 MeV/c (as required for the RAL beam), λ has been increased from 1 to 2 m, and κ decreased from 1 to 0.8. The maximum field at a conductor then becomes 5.2 T. The cooling factors are: average transverse 1.7, longitudinal 1.5, and 6D 4.7.

These simulations using a HCC with momentum dependent magnetic fields indicate that a device originally designed to be used as an excellent precooling device in a practical muon cooling channel can also be used to demonstrate exceptional muon beam cooling. Compared to the 10% cooling effect expected with MICE, the 470% effect of the LHe 6DMANX simulations implies a lot of room for compromise. That is, some of the parameters such as the beam momentum range, the magnet aperture, or channel length could be reduced and there would still be an impressive measurement to be made. For example, it may be possible to make a conventional emittance measurement (using an ensemble of muons rather than one particle at a time) as a cheap, preliminary measure of emittance reduction, further reducing costs. These options can be considered in detail when the more general matching problems are understood.

Analytic Understanding and Numerical Simulation

The tranport of the beam through the upstream spectrometer, a matching section, the HCC, a second lower energy matching section and the downstream spectrometer will first be optimized analytically and then verified by G4Beamline simulations. We note that Derbenev and Bogacz, two of our close collaborators, have worked on the general solution for matching between solenoidal lattices and those based on quadrupole and dipole magnets [9, 10, 11]. The effectiveness of this approach has been seen in the development of techniques for flat beams for linear colliders and most recently for the electron cooling of the antiproton beams for the Fermilab Tevatron Collider.

In Phase I we will solve the matching problem and get a start on studying experimental significance as a function of detector resolution, particle identification efficiency, magnetic field parameters, and absorber characteristics using the numerical simulation.

Critical Concerns/Planning for Phase II

The HCC with a continuous homogeneous absorber is a technical breakthrough in the technology of muon beam cooling. The extension of this idea to a HCC with z-dependent magnet strengths represents another technical breakthrough. The development and optimization of the 6DMANX experiment involves many parameters, many of which will come down to the size of and confidence in the cooling signal versus the cost and timeliness of the experiment. The effort to get the best possible parameters will be the concern of the second phase of the project.

6DMANX Conceptual design
Work to be performed by Rolland Johnson, Mary Anne Cummings, and Thomas Roberts of Muons, Inc., and Charles Ankenbrandt, Al Moretti, Milorad Popovic, Gennady Romanov, Alexander Zlobin, Vladimir Kashikhin, Katsuya Yonehara, and Victor Yarba of Fermilab. Work performed at Muons, Inc. and Fermilab.

Computer simulations
Work to be performed by Rolland Johnson, Mary Anne Cummings, and Thomas Roberts of Muons, Inc. and Katsuya Yonehara and Milorad Popovic of Fermilab. Work performed at Muons, Inc. and Fermilab.

Responsibilities

Muons, Inc.: The direction of the project is the responsibility of the company and the PI. The development of the computer representation of the conceptual design and the maintenance of the database of scientific and engineering parameters will be the responsibilities of Dr. Roberts.

Fermilab: Victor Yarba will be responsible for the Fermilab subcontract. The engineering questions related to the design of 6D MANX will be addressed by the Technical Division engineers for further study and perhaps prototypes as well as preliminary cost studies.

Phase I Performance Schedule

Two months after start of funding:
1) Analytical description of matching between HCC and spectrometers formulated
2) Possible experimental environments investigated; muon beam energy, flux, location
3) Engineering limitations and possible simplifications investigated

Four months after start of funding:
1) First G4BL simulations of matching problem guided by analytic description
2) Baseline experimental layout defined, entered into simulation program

Six months after start of funding:
1) Simulations used for first studies of experimental significance as functions of beam parameters, detector characteristics, and HCC choices such as length, radius, field magnitudes, and coil configuration
2) Critical engineering issues defined
3) Draft of Phase II proposal

Nine months after start of funding
1) Phase II proposal

e. Related Research or R&D

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

A natural extension to the 6DMANX conceptual design shown in figure 3 would be to use the eight 200 MHz RF cavities that are part of the MICE project to accelerate the muons after they have been cooled to demonstrate another stage of cooling with another HCC segment.

Much of the directly related work on muon cooling is being carried out by Muons, Inc. and our research partners in SBIR/STTR projects as was covered in the Overview section at the beginning of the proposal. To reiterate, Muons, Inc. is working on three Phase II SBIR grants and two Phase I grants to study different approaches to or aspects of muon beam cooling and is submitting 5 new SBIR/STTR proposals. These SBIR/STTR grant subjects and the work they represent are entirely complementary. There is no work that is duplicated in these projects.

f. Principal Investigator and other Key Personnel

Muons, Inc. Principal Investigator: **Dr. Rolland P. Johnson** has been actively involved in particle accelerator research and development for almost 30 years. He has worked on all aspects of synchrotrons, storage rings, and light sources at several institutions. Dr. Johnson has directed several successful accelerator R & D, construction, and commissioning projects. Examples at Fermilab include H^- injection into the Booster, new extraction kickers for the Booster, Booster RF cavity gradient improvement program, Tevatron low beta insertions, Tevatron Collider, and at LSU, the CAMD light source. He directed many software projects at Fermilab, CAMD, and CEBAF. He also provided technical oversight to several SBIR grants while on detail to the DOE. Dr. Johnson has considerable experience in the area of beam cooling, having participated in the commissioning and improvement programs of the CERN Antiproton Accumulator as well as the design of the Fermilab TeV I project. He has contributed original work involving simulations and implementations of stochastic cooling systems and of their associated RF systems. Besides work on methods to increase the proton flux for better muon production as seen in the Proton Driver Design Report and The Linac Afterburner Proposal, he has worked on improving ionization cooling.

Fermilab Subcontract PI: **Dr. Victor Yarba** will direct the activities of appropriate technical division personnel to work with the physicists and others involved in the simulation efforts to determine and optimize the engineering and construction costs of the 6DMANX conceptual design report. Fermilab will support one postdoctoral researcher on second phase of this project.

Drs. Katsuya Yonehara and **Vladimir Kashikhin** of the Fermilab TD will do much of the simulation and magnet design work for 6DMANX.

Dr. Charles M. Ankenbrandt, presently a senior accelerator physicist at Fermilab, has participated in many Fermilab construction and improvement projects, at times taking leadership roles as Leader of the Booster Synchrotron Group and Leader of the Accelerator Division Theory Group. He invented the techniques of "barrier buckets" and "slip stacking" used at Fermilab.

Dr. Milorad Popovic has worked with Drs. Johnson and Ankenbrandt on many projects. Most recently they have worked together on proton driver issues for a neutrino factory, including a proposal to upgrade the Fermilab Linac to improve the operation of the existing Fermilab accelerator complex.

Drs. Mary Anne Cummings, **Stephen Kahn, and Thomas Roberts** of Muons, Inc. are high-energy experimental physicists as well as accelerator physicists who will bring their expertise to help design 6DMANX.

C.V. Rolland P. Johnson

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Academic Background: U. of California, Berkeley Ph.D., Physics, June 1970
U. of California, Berkeley AB, Mathematics, June 1964

Work Experience: Particle accelerator design, construction, operation, and controls. Project Management. Experimental High Energy Physics Research. Teaching.

Employment Background:

2002-Present Scientist-Owner Muons, Inc.

(2002-) PI of a Phase II STTR grant with IIT to develop HP RF Cavities, PI of two Phase II SBIR grants with JLab to develop 6D cooling using helical dipoles and Parametric-resonance Ionization Cooling, and PI of a Phase II STTR grant with Fermilab to develop cryostat designs for muon cooling channels.

1996-2001 Consultant

Consulting contracts with CAMD, DOE, DESY, Fermilab, IIT, SRRC

1993-1996 Senior Staff Scientist, Thomas Jefferson National Accelerator Facility, (CEBAF)

(94-96) On Detail to DOE Headquarters, Germantown MD. Program monitor for 11 university grants. Acting Technical Topic monitor for 12 SBIR grants. Project reviewer. Member SSC equipment reallocation team.

(93-94) Head of Instrumentation and Controls Department, CEBAF Accelerator Division, Responsible for Control, Beam Instrumentation, and Safety Systems. Program coordinator for machine commissioning

1991-1992 Senior Accelerator Physicist, MAXWELL LABS, Brobeck Division

In charge of installation and commissioning the 1.4 GeV CAMD light source at LSU

1974-1991 Physicist, FERMI NATIONAL ACCELERATOR LABORATORY

(84-91) Tevatron Coordinator for Collider upgrades. Responsible for design, debugging of low beta inserts, e-s beam separation, diagnostics. Invented “double-helix” beam separation scheme. Discovered decay of persistent currents in superconducting accelerator magnets. Supervised software development. Wrote design programs for RF systems and lattice insertions. Directed machine commissioning.

(90-92) Adj. Professor, NIU. Taught "Introduction to Particle Accelerators".

(88-92) CDF Experimenter, responsible for CAMAC system, alarms and limits and high voltage control, and integration of the experiment into the accelerator control system. Contributor to luminosity and total cross-section analyses.

(88-91) Chairman, Wilson Fellows Committee to recruit, select, nurture extraordinary physicists. Thesis supervisor for two Ph. D. students. Directed experimental accelerator research using the Tevatron.

(83-84) Leader of a Tevatron commissioning team. Also wrote programs to control RF, excitation ramps, correction elements, closed orbit, monitor of cryogenics, vacuum.

- (82-83) Member of antiproton source design group. Coordinated the original design report. Specified energy, location, and stochastic cooling systems. Wrote RF control programs.
- (80-82) Assignment to CERN, Geneva, Switzerland. Participated in commissioning and initial operation of the Anti-proton Accumulator. Wrote the RF control programs. Improved 1 to 2 GHz stochastic cooling systems.
- (79-80) Assistant Head of Accelerator Division, in charge of Linac, Booster, Main Ring, Switchyard and Operations Groups. Directed the activity of about 250 people to operate and improve the accelerator fixed target program. Had record intensity levels and reliability.
- (78-79) E203 experimenter. Leader of a group of Fermilab physicists who collaborated with Princeton and Berkeley to study deep inelastic muon scattering.
- (75-78) Leader of Booster Synchrotron Group. In charge of the development and operation of the 8 GeV rapid cycling synchrotron. Increased output current by a factor of 3. Built fast bunch-by-bunch transverse dampers to control head-tail instabilities. In charge of H^- injection project. Directed RF cavity development projects.
- (74-75) Member, Main Ring group. Responsible for high field closed orbit of the 400 GEV MR synchrotron. In charge of the 8 GeV transfer line between Booster and MR.

1963-1974 Physicist, LAWRENCE BERKELEY LABORATORY

- (70-74) Postdoctoral Research Associate. Bevatron experiments: muon neutrino mass limit, muon range differences, and Kl3 form factors from muon polarization.
- (72-73) Visiting Scientist IHEP, Serpukhov, USSR. Experiments at the 70 GeV synchrotron on pion-proton interactions. Discovered h^o meson. Worked in a Russian group.
- (67-70) Graduate Student Research Asst. Ph.D. thesis experiment on rare decays of the neutral K-meson at the Bevatron.
- (63-67) Research Apparatus Operator. Programmer, data analyst.

Publications

Over 50 references in Accelerator Topics and over 80 in High Energy Physics can be found at **http://members.aol.com/roljohn**. Some recent work relevant to this proposal can be found in the reference section of this proposal.

COST AND PERFORMANCE OF RAPID-CYCLING PROTON SYNCHROTRONS, C. M. Ankenbrandt and R. P. Johnson, Proceedings of the 2001 Particle Accelerator Conference, http://pacwebserver.fnal.gov/papers/Thursday/PM_Poster/RPPH039.pdf.

A LINAC AFTERBURNER TO SUPERCHARGE THE FERMILAB BOOSTER, C. M. Ankenbrandt, J. MacLachlan, M. Popovic, and R. P. Johnson, July, 2001. **AIP Conf.Proc.642:232-235,2003**

COMMISSIONING OF THE SYNCHROTRON LIGHT SOURCE AT LSU. R.P.Johnson, et al. Berlin:EPAC 1992:197.

COMPUTER CONTROL OF RF-MANIPULATIONS IN THE CERN ANTIPROTON ACCUMULATOR. R. Johnson, S. van der Meer, F. Pederson and G. Shering, IEEE Trans. Nucl. Sci. NS-30 No. 4,(1983)2290.

C.V. Victor Yarba

Education:

D.Sc. Physics, Institute for High Energy Physics, Protvino, Russia - 1974
Ph.D Physics, Joint Institute for Nuclear Research, Dubna, Russia - 1967
M.S. Physics, Moscow State University, Moscow, Russia - 1958

Summary of Qualifications:

Has conducted research at JINR, Dubna, (1958-1969) and IHEP, Protvino, Russia (1969-1992); at CERN, Geneva, Switzerland (1965,1973); at SSC and at FNAL, USA (1992-present).

Area of physics research: Particles and light nuclei, including the discoveries of ${}_2He^8$ and double charge exchange of π-mesons on nuclei; K^+ and ν interactions with protons by using 2m and BEBC bubble chambers at CERN, MIRABEL bubble chamber at IHEP, 16 foot bubble chamber at Fermilab; pp interaction using EHS at CERN; particle accelerator technology.

Management:
(1974-1992) First Deputy Director of IHEP, Protvino, Russia
(1983-1992) project manager of the UNK 3 TeV accelerator – storage complex at IHEP
(1993) 2 TeV high energy booster at SSC, Dallas, TX, USA – Acting Machine Leader
(1994 to present) Fermi National Accelerator Laboratory
- (1994-1996) - Head of Magnet Design and Fabrication Group
- (1997-2002) - Head of Engineering and Fabrication Department
- (2002-present) – Technical Division Associate Head for R&D

Teaching: 1976-1992 (part time) Professor and Head of the High Energy Physics Department at Moscow Institute of Physics and Technology (MPTI)

Honors and Awards:
The USSR Government prize in Science and Technology
Two awards from the Joint Institute for Nuclear Research for scientific achievements (Dubna)
Two awards of the USSR for ${}_2He^8$ Discovery and for Pion Double Charge Exchange Discovery
Fellow of the American Physical Society (2004)

International Collaboration:
1974 – 1980 Co-Chairman of the CERN – Minatom USSR joint scientific committee
1974 – 1984 Co-Chairman of the CEN SACLAY, France – IHEP, USSR joint scientific committee;
1976 – 1992 Member of the USA – USSR joint coordinating committee for fundamental properties of matter;
1976 – 1982 Active organizer and member of ICFA – the International Committee for Future Accelerators

Publications: 139 publications available on SPIRES

g. Facilities/Equipment

Muons, Inc. currently occupies a building of approximately 4000 square feet of floor space equipped with computer workstations and fast internet access in Batavia, Illinois, a short drive to Fermilab. Muons, Inc. also occupies an office equipped with computer workstations in the ARC building adjacent to the Jefferson Lab campus in Newport News, Virginia. The development of designs and their analysis and simulation require knowledgeable people, places to meet, computers for simulations and CAD/CAM, and access to libraries and the web. The Phase II effort will require the facilities and equipment of Fermilab to produce and test prototypes of critical components of the demonstration experiment. The new Fermilab Muon Test Area at the end of the Linac and the shops of the Fermilab Technical Division will be essential to this effort.

h. Consultants and Subcontractors

(i) Research Institution

Fermi National Accelerator Laboratory

(ii) Other Consultants and Subcontractors

None.

i. Similar Grant Applications, Proposals, or Awards

We have submitted no similar grant applications or proposals. We have received no awards for this project.

References

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[3]Y. Derbenev and R. P. Johnson (Phys. Rev. Special Topics Accel. and Beams 8, 041002 (2005)) http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf

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[7] G. W. Foster and J. A. MacLachlan, Proceedings of LINAC 2002, Gyeongju, Korea

[8] R. P. Johnson and Y. Derbenev, Technical Challenges of Muon Colliders, NuFact05 http://www.muonsinc.com/reports/NUFACT05-Johnson.pdf

[9] Alexey Burov, Sergei Nagaitsev, and Yaroslav Derbenev, Circular modes, beam adapters, and their applications in beam optics, PHYS. REV. E **66**, 016503, 2002.

[10] A. Burov, S. Nagaitsev, and A. Shemyakin, Ya. Derbenev, Optical principles of beam transport for relativistic electron cooling, PHYS. REV. SPECIAL TOPICS – ACCEL AND BEAMS, VOLUME 3, 094002 (2000)

[11] V. A. Lebedev and S. A. Bogacz, http://www.cebaf.gov/~lebedev/AccPhys/XY_coupling.doc