Phase I-SBIR/STTR Fiscal Year 2007

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PROJECT TITLE: **Magnets for Muon 6D Helical Cooling Channels**

TECHNICAL ABSTRACT (Limit to space provided)

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

The Helical Cooling Channel (HCC), a new technique for six-dimensional (6D) cooling of muon beams using a continuous absorber inside superconducting magnets, has shown considerable promise based on analytic and simulation studies. The implementation of this revolutionary method of muon cooling requires high field superconducting magnets that provide superimposed solenoidal, helical dipole, and helical quadrupole fields.

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.

Novel magnet design concepts are being developed to provide HCC magnet systems with the desired fields for 6D muon beam cooling. New designs feature simple coil configurations that produce these complex fields with the required characteristics, where new high field conductor materials are particularly advantageous. This proposal is to develop designs and construction methods for these magnets and to design a complete magnet system for a six-dimensional muon beam cooling channel.

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

In Phase I we will complete the conceptual design of the magnets for a 6D muon cooling demonstration experiment, including the 4 m long cooling section and the upstream and downstream emittance matching magnets, in preparation for engineering designs.

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

We propose to develop the magnets needed to create bright muon beams for many applications ranging from scientific accelerators and storage rings to beams to study material properties and new sources of energy. Examples of these applications include energy frontier muon colliders, Higgs and neutrino factories, studies of rare fundamental interactions and muon catalyzed fusion.

Key Words: high temperature superconductor, muon cooling, muon-beam, collider

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

A new system of superconducting magnets is being developed to shrink the size of a beam of muons in all dimensions. The bright muon beams that will emerge from these magnets will enable new ways to investigate nature at fundamental levels at the energy frontier.

NARRATIVE SECTION

Magnets for Muon 6D Helical Cooling Channels

Table of Contents

Project Summary 1
Table of Contents 2
a. Identification and Significance of Problem or Opportunity, and Technical Approach 2
Identification of Problem 2
Technical Approach 2
Helical Cooling Channel 3
MANX Muon Cooling Channel 6
b. Anticipated Public Benefit 10
c. Phase I Technical Objectives 11
d. Phase I Work Plan 12
Details ..... Error! Bookmark not defined.
Responsibilities 12
Phase I Performance Schedule 13
e. Related Research or R & D 13
f. Principal Investigator and other Key Personnel 13
g. Facilities/Equipment 15
h. Consultants and Subcontractors 15
Appendix: Overview of Muons, Inc. Program 16
Bibliography and References 20

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

Identification of Problem

A new muon beam cooling technique, using a continuous gaseous hydrogen absorber inside a magnetic channel consisting of helical dipole and solenoid fields, has shown promise based on analytical and simulation studies. The central orbit of the muon beam in this channel is a helix, which is produced by opposing forces of the solenoid and helical dipole fields acting on the muon. The implementation of this revolutionary method of muon beam cooling requires the development of high-field superconducting magnets with relatively large apertures. These magnets are innovations in themselves.

The major significance of this muon cooling technique is to create bright muon beams with small emittance for use in particle accelerators and storage rings. A low emittance muon beam will be an essential part of muon colliders and neutrino factories based on muon storage rings. Other applications can be found in material science research, the study of rare muon decay modes, and muon catalyzed fusion.

Technical Approach

Helical Cooling Channel

A continuous energy absorber in a magnetic channel with positive dispersion can be used to cool the momentum spread of a muon beam by exploiting the fact that the higher momentum particles have longer path length and therefore larger energy loss. This approach to emittance exchange and six-dimensional cooling has been described analytically [1] and has been simulated [2] using the G4Beamline [3] and ICOOL [4] particle tracking codes. Figure 1 shows the simulation of a segment of a six-dimensional cooling channel that incorporates a continuous solenoid with helical dipole and quadrupole magnets to achieve good dispersion and acceptance.

The simulation results showing the transverse, longitudinal and 6D emittances of a muon beam as a function of position along the cooling channel are plotted in Figure 2. The cooling channel in that study was divided into four segments, each with successively smaller aperture and stronger magnets. As the emittance of the muon beam is reduced it approaches the equilibrium emittance where no more cooling can occur. By increasing the magnetic field the equilibrium emittance is reduced, allowing further cooling to take place. Table 1 summarizes the design parameters for the four sections shown in Figure 2. Also included in table are the parameters that describe the helical magnet [5] that is proposed for MANX [6], a 6D muon cooling experiment.

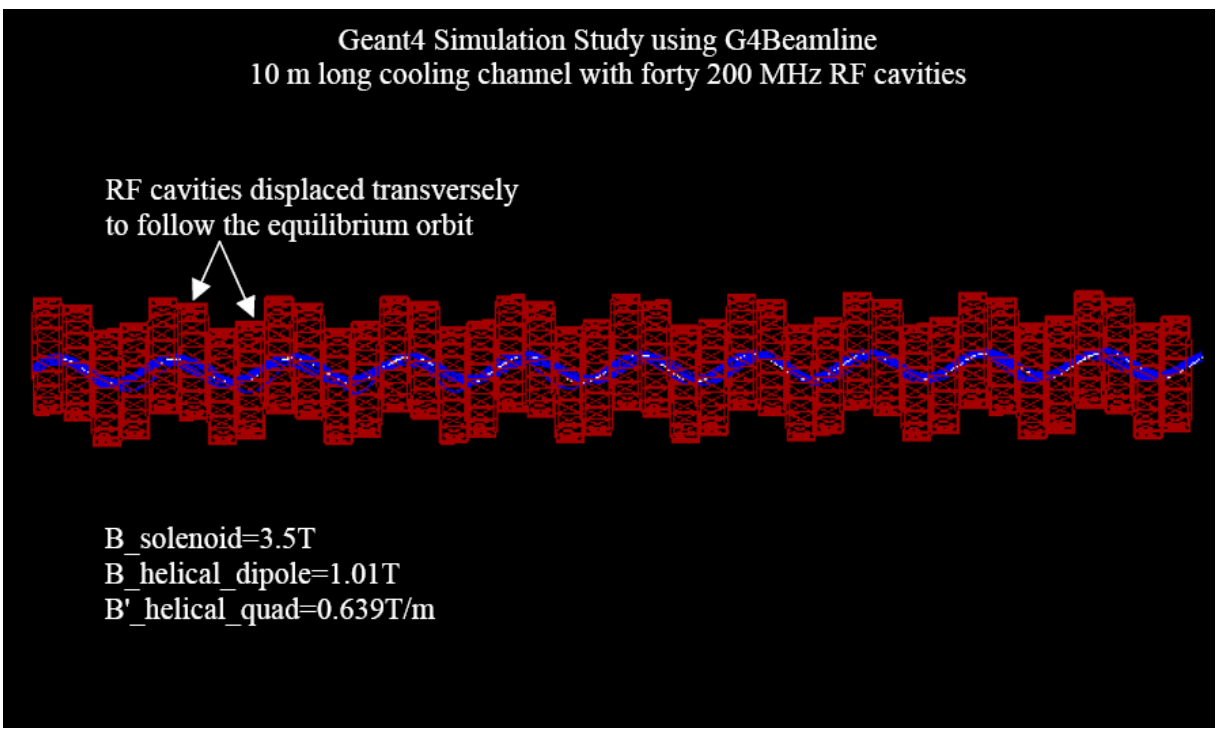

Figure 1: G4Beamline display of the helical channel that was simulated. In the simulation, solenoidal and helical components of the superimposed magnetic fields provide focusing and dispersion as muons pass through the hydrogen filled RF cavities.

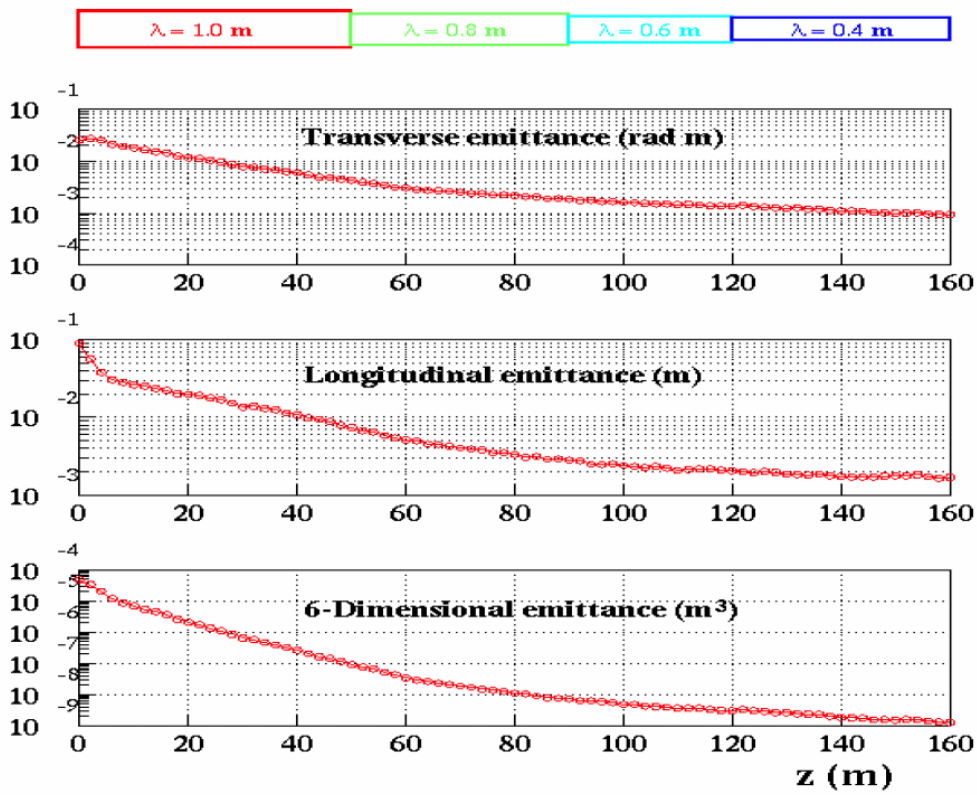

Figure 2: Emittance evolution of a muon beam in 4 sequential HCC segments. A 6D cooling factor of 50,000 has been achieved in the total channel length of 160 m.

Series HCCs							
Parameter			**Segment**				**Manx**
			1st	**2nd**	**3rd**	**4th**	
L	Length	m	50	40	30	40	4
λ	Helix period	m	1.0	0.8	0.6	0.4	2
a	Ref. orbit radius	m	0.16	0.13	0.095	0.064	0.255
κ	Helix pitch		1.0	1.0	1.0	1.0	0.8
$\mathbf{B_s}$	Solenoid field	T	-6.95	-8.68	-11.6	-17.4	-4.39
$\mathbf{b_d}$	Helix dipole	T	1.81	2.27	3.02	4.53	0.946
$\mathbf{b_q}$	Helix quad	T/m	-2.19	-3.38	-6.21	-13.75	2.36
$\mathbf{b_s}$	Helix sextupole	T/m^2	1.21	2.31	5.65	18.8	0

Table 1: Parameters for the different segments of HCC muon cooling channel. The field strengths are quoted at the radius of the helical reference orbit. ***B*** *and* $\mathbf{b_d}$ *are in T,* $\mathbf{b_q}$ *is in T/m and* $\mathbf{b_s}$ *is in* T/m^2*. The coil radius is approximately twice the reference orbit radius.*

We assume that inner coils of the magnet start at a radius of 2**a** (twice the reference orbit radius). The field from a helical dipole can be calculated analytically [1] giving:

$$b_\phi = 2b_d I_1(k\rho)\cos\psi / k\rho$$
$$b_\rho = 2b_d I_1'(k\rho)\sin\psi$$
$$b_z = -k\rho b_\phi$$

where $\psi = \phi - kz$ is the azimuth in the local rotated frame. Similarly the helical quadrupole field is described by

$$b_\phi = b_q I_2(2k\rho)\cos 2(\psi - \psi_2)/k^2\rho$$
$$b_\rho = \frac{b_q}{k} I_2'(2k\rho)\sin 2(\psi - \psi_2)$$
$$b_z = -k\rho b_\phi$$

where $b_q = (db_\phi/d\rho)$ and ψ_2 is a phase describing the quadrupole axis where $\psi_2 = 0$ describes the normal quadrupole. Table 2 shows the calculated maximum field from the solenoid and dipole windings at the inner and outer coil radii. The fields are calculated using the above analytic expressions excluding the helical quadrupole and sextupole windings. The solenoid thickness is calculated for the $\mathbf{B_s}$ using the effective current density for HTS in that field. The table shows maximum values for the components $\mathbf{B_\phi}$, $\mathbf{B_\rho}$, and $\mathbf{B_z}$. The z-component at the inner coil radius includes the solenoid contribution, but does not for the outer coil radius since the solenoid contribution is almost zero. The maximum contributions from the different components do not occur at the same location. From the field values shown in Table 2, the magnet for the MANX experiment can be built using NbTi superconductor, where as the magnets used in segments 1 and 2 require using Nb_3Sn conductor, and the magnets used in segments 3 and 4 would require HTS conductor.

Maximum Fields						
Field		**Segment**				**Manx**
		1st	**2nd**	**3rd**	**4th**	
Solenoid Thickness	cm	2.2	2.8	3.7	5.5	1.4
Inner Coil Radius	cm	32	26	19	12.8	50
Inner Coil B_ϕ	T	2.89	3.68	4.78	7.24	1.27
Inner Coil B_ρ	T	5.42	6.98	8.89	13.57	1.98
Inner Coil B_z	T	-12.77	-16.19	-21.11	-31.95	-6.39
Outer Coil Radius	cm	34.2	28.8	22.7	18.3	51.4
Outer Coil B_ϕ	T	3.08	4.06	5.72	11.17	1.29
Outer Coil B_ρ	T	6.10	8.40	12.38	29.0	2.05
Outer Coil B_z	T	-6.62	-9.17	-13.58	-32.16	-2.08

Table 2: Maximum field seen in the helical cooling channel at the inner and outer radii of the solenoid. The helical dipole contribution is calculated using the analytic expressions. The solenoid thickness is calculated using the effective current density of HTS Bi-2223 tape.

MANX Muon Cooling Channel

MANX is an experiment that is being proposed to demonstrate the cooling of muon phase space using a four-meter long helical cooling channel. Tables 1 and 2 show the parameters and the maximum fields expected for the MANX experiment in the rightmost column. The region of the bore of the MANX magnet will be filled with liquid helium as an absorber for the muon cooling process. Because there is no RF to replace the energy lost in the absorber, the MANX magnet will be designed so that the magnet field falls off with distance as the muons lose momentum. The values of field listed in the table are valid at the entrance to the channel.

Two approaches are being investigated for the MANX HCC magnet. Figure 3 shows a design where helical dipole coils are wound around the outside of a solenoid. There are several helical dipole coils of different lengths superimposed in order to allow the dipole field to fall with length. A TOSCA analysis of this configuration produces a field along the reference particle orbit with good agreement to the analytic fields used to describe the magnet as is shown in Figure 4.

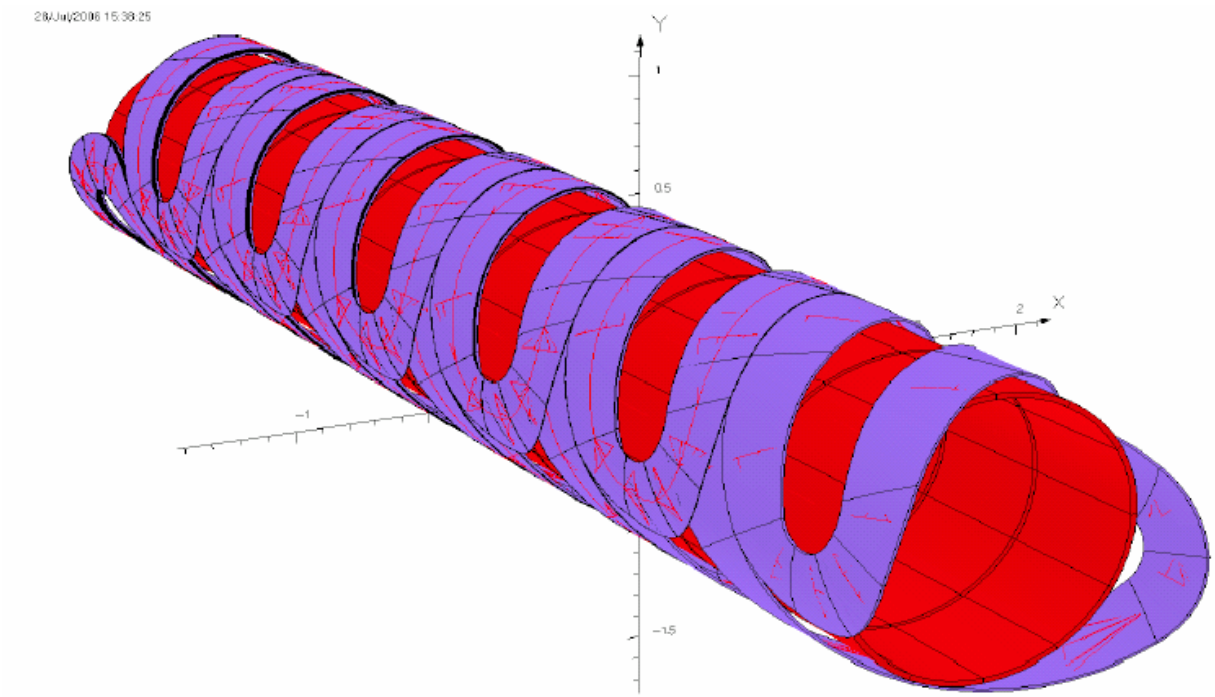

Figure 3: Drawing of helical dipole coils wound around solenoid coils. This is a possible coil configuration for the MANX magnet system.

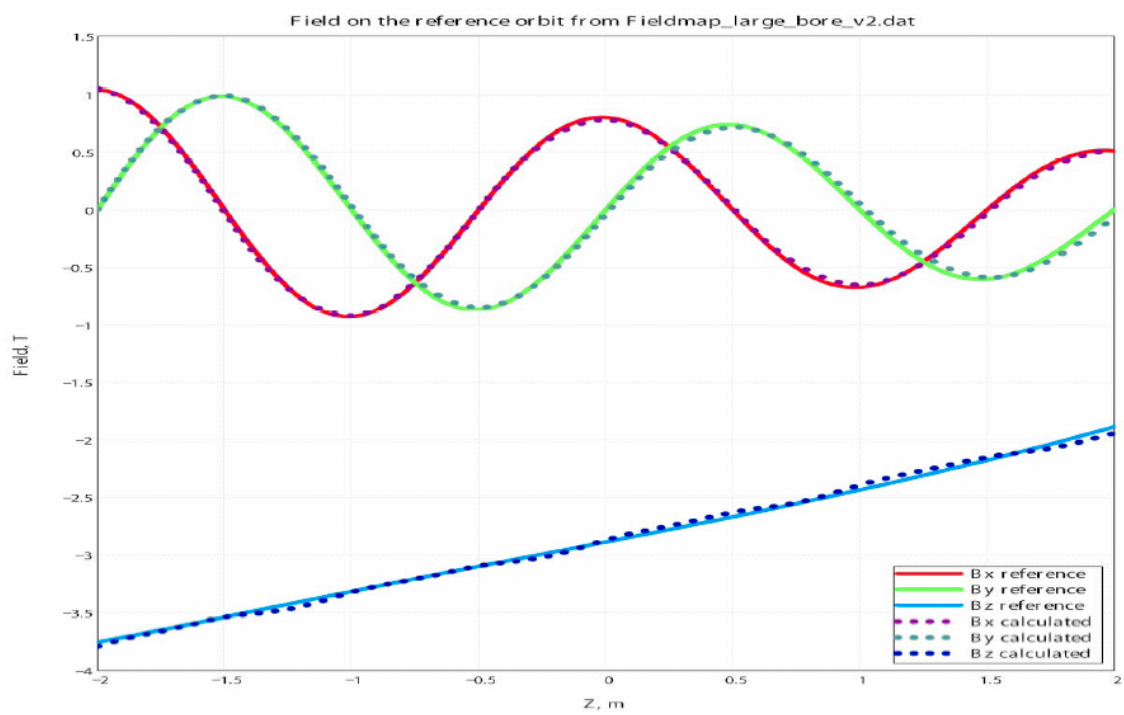

Figure 4: The field calculated with TOSCA is compared to the field from the analytic formulae.

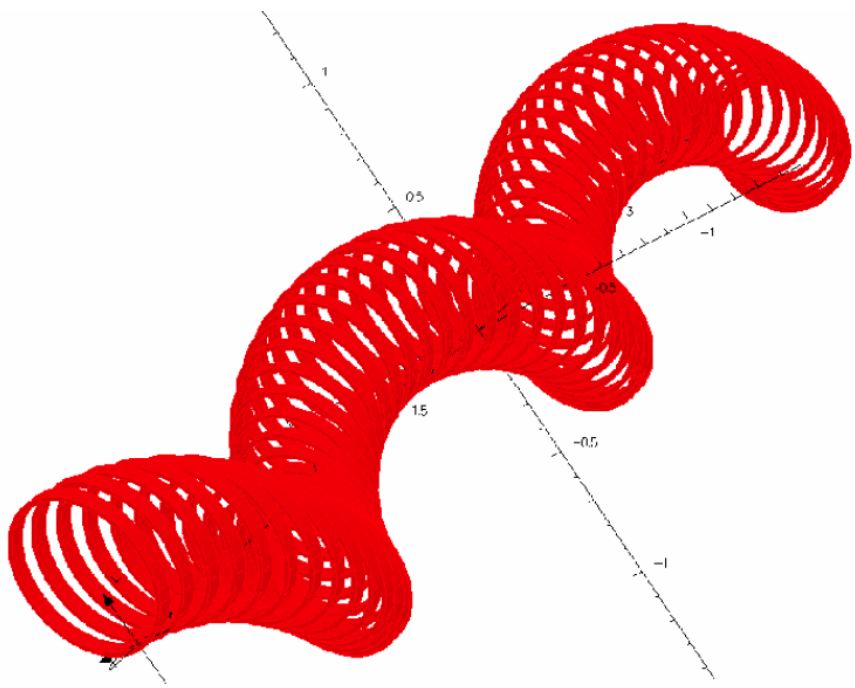

Figure 5: Arrangement of coils to form a helical solenoid channel for use with MANX. This configuration produces both the desired solenoid and helical dipole field.

Another more innovative approach is to construct the HCC out of current rings. Figure 5 shows a drawing of the helical solenoid channel built out of current rings. The geometrical placement

of the current rings is such that the desired solenoid and the helical dipole and helical quadrupole fields are generated. This magnet design was reported at the last Applied Superconductivity Conference [5], where that effort was supported by the STTR project 3 described in the appendix below. There are several important advantages to this idea: 1) the aperture is half the value in the previous design shown in figure 3, 2) the maximum field at the coils is also significantly reduced, and 3) the extent of the fringing fields at the entrance to the channel is shorter making the matching problem easier.

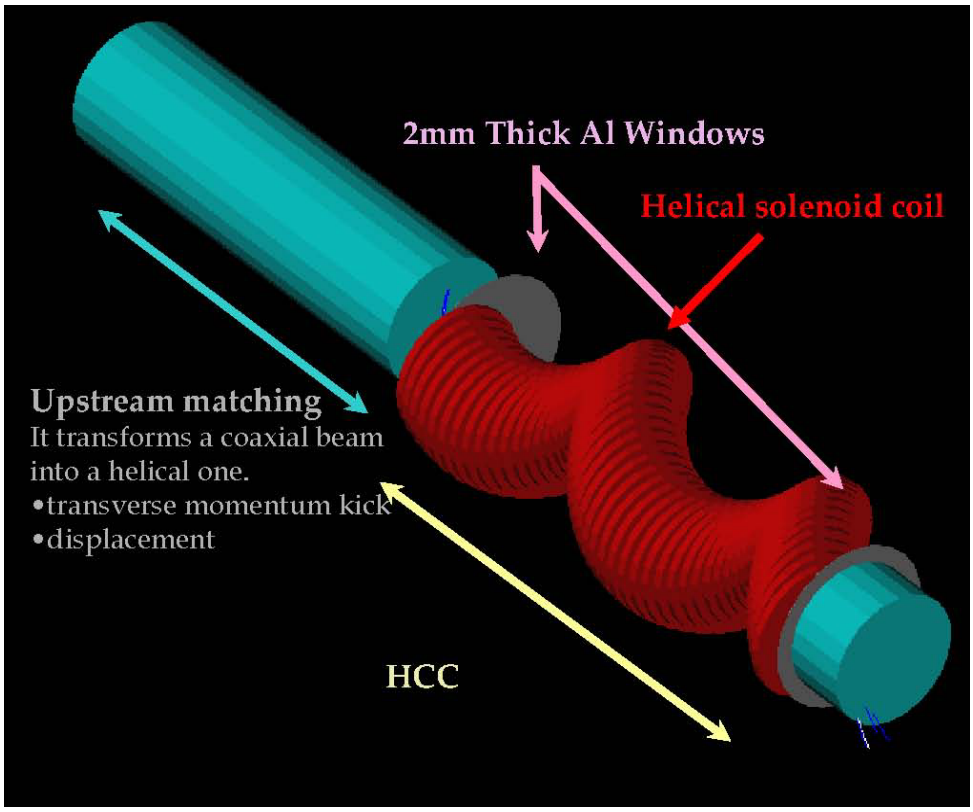

Figure 6: Conceptual picture of the MANX magnet system.

Figure 6 shows one possible configuration of the MANX magnet system. The magnetic fields for the upstream matching and momentum-dependent HCC sections are shown in figure 7. The simulation plots of the emittance evolution of this version of MANX are shown in figure 8. These indicate that the 6D invariant emittance will be cooled by about a factor of 4 in this experiment. The upstream matching section magnets transform a 300 MeV/c coaxial muon beam into a beam that enters the (red) helical cooling channel magnets onto the proper orbit for cooling. The downstream matching section magnets are used to match the cooled 150 MeV/c beam into a spectrometer and particle identification devices and are not yet included in the simulation. Although the matching section field specifications have been determined, and been used in simulations, the required coil configurations are yet to be designed.

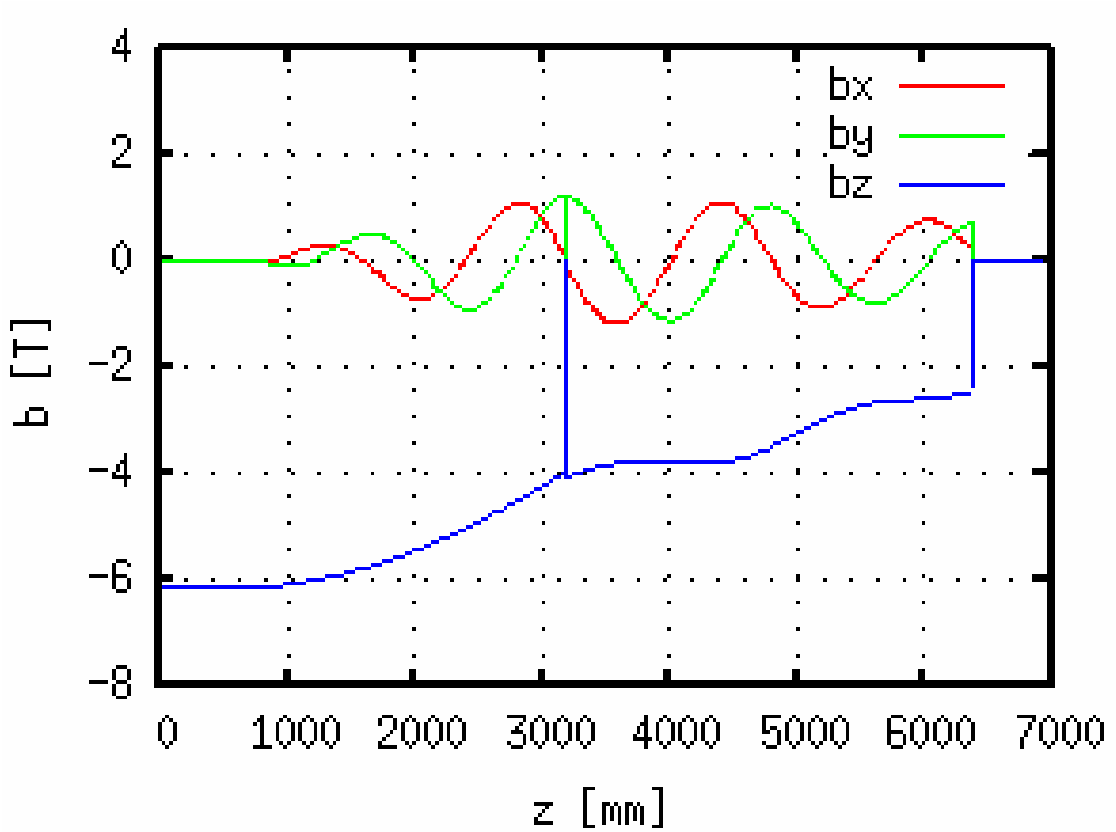

Figure 7: The solenoidal and helical dipole fields of MANX. The coaxial beam enters in a pure 6.2 T solenoidal field; the matching section starts at 0.8 m and continues to 3.2 m where it passes through a window to enter the LHe of the HCC. The emittances showing the cooling behaviour are plotted in the following figures.

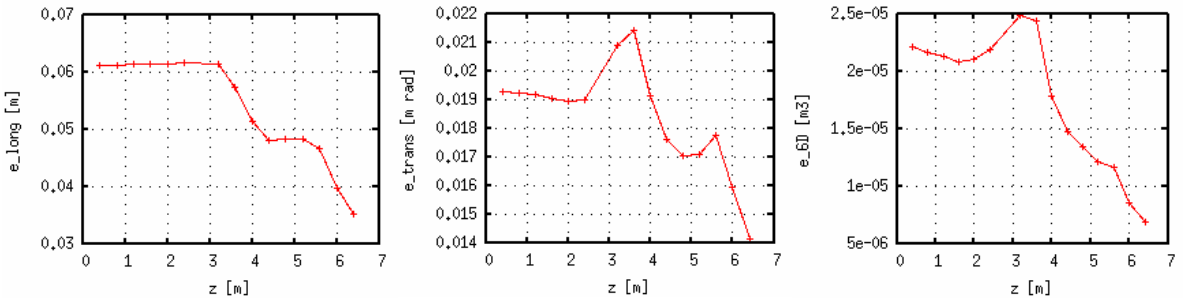

Figure 8a, b, c: The longitudinal, transverse, and 6D emittance evolution of the muon beam as simulated by G4BL for the magnet system shown in figures 6 and 7. The increase in transverse emittance at 3.2 m is due to the 2 mm thick Al window.

b. Anticipated Public Benefit

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.

Each of these opportunities depends on being able to cool muons beams quickly and efficiently. This ability is the goal of the program described in the appendix and this proposal, as well.

c. Phase I Technical Objectives

The funding for STTR project 3 described in the appendix, which includes the development of HCC magnet designs, will end in July 2007. The project we are proposing here is to continue the work that has brought us such interesting inventions and essential development as shown in figures 3 and 5. In this project we will continue the development of the HCC magnet system. In Phase I we will concentrate on the design of the magnets for the MANX 6D demonstration experiment.

In Phase I we will complete the conceptual design of the magnets for MANX experiment in preparation for engineering designs. The magnets needed for the MANX experiment include the 4 m long cooling section and the upstream and downstream emittance matching magnets. The conceptual design will include:

- A comparison of the costs, complexity, and cooling performance of the helical dipole/solenoid combination (figure 3) with the helical solenoid ring channel (figure 5)
- A conceptual design of the matching section magnets for the MANX experiment.
- A mechanical study including the calculation of the forces on the coils and the conceptual design of a support system for the coils.
- A simulation study using field errors to establish field quality specifications.

d. Phase I Work Plan

The primary objective of this proposal is to develop a conceptual design for a realizable magnet system for MANX. The preliminary work that has been done has identified two approaches for a helical channel magnet system, which have been described in the previous sections. These approaches have been modeled using the Tosca magneto-static field solver program. This program produced field maps corresponding to a realizable coil configurations and the field map from the coil configuration has been used in the G4beamline particle tracking program to evaluate the cooling performance of the helical channel lattice. The coil configurations of each of these approaches are being optimized to produce a field that closely matches the specifications of the cooling channel. G4beamline will be used to establish field quality specifications by introducing field errors into the simulations.

A realistic design of the coil configuration includes the selection of the appropriate conductor for the cooling channel and a support structure to contain the large magnetic forces on the coils. The field level assumes using NbTi superconductor for the MANX demonstration. This proposal should provide a conceptual design for the magnet system which will support the Lorentz forces and keep the coil stress/strain level below its limit.

Responsibilities

Work to be performed as a collaboration of Muons, Inc. with Fermilab:

Muons, Inc.: Stephen Kahn, Rolland Johnson, and Mohammad AlSharo'a.

Fermilab: Alexander Zlobin, Katsuya Yonehara, Vladimir Kashikhin, Vadim Kashikhin and Emanuella Barzi.

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

Fermilab: Dr. Alexander Zlobin will be responsible for the Fermilab subgrant.

Phase I Performance Schedule (Tasks and Milestones)

3 months after start of funding:

1) Establish a conceptual design of matching section magnets for both of the MANX schemes discussed in this proposal (The design should be complete enough to begin a cost analysis of the two schemes).
2) Evaluate each of these approaches using the simulation tools to see if either of these schemes produces more favorable cooling results. This should include an effort to iterate the magnet design to improve cooling performance.
3) Study the mechanical forces of the MANX magnet design to develop a structural support system for the coils.

6 months after start of funding:

1) Determine the best magnet scheme to be used for the MANX experiment.
2) Determine the critical engineering issues of the MANX magnet. Develop approaches to solve these critical issues.

9 months after start of funding:

1) Prepare an initial conceptual design report for the MANX magnet system.
2) Prepare a Phase II proposal.

e. Related Research or R & D

Muons Inc. has a program built on SBIRs to provide the R&D necessary for various topics necessary for pursuing a muon collider. This program is described in the Overview section in the appendix to this proposal. Two of the SBIR phase I proposals that are being submitted concurrently to this proposal are concerned with using HTS conductor with high field magnets. One of these proposals examines the feasibility of a 50 T HTS solenoid to be used for muon cooling. The other describes an approach to providing quench protection for HTS high field magnets. Muons Inc. has a phase II grant to examine six-dimensional cooling using gaseous absorbers, which provides the conceptual basis for muon cooling in a helical channel. There is also a phase I grant to develop a demonstration experiment to show six-dimensional muon beam cooling.

f. Principal Investigator and other Key Personnel

Muons, Inc. Scientist and Principal Investigator: **Dr. Stephen Kahn** most recently worked at the Advanced Accelerator Group at BNL on neutrino factory and muon collider R&D. His previous experience at Brookhaven has been varied, including work on high energy physics experiments (neutrino bubble chamber experiments and the D0 experiment) and superconducting accelerator magnets (for ISABELLE, RHIC, the SSC and the APT). Work to design superconducting magnets included 2D and 3D finite-element field calculations using the Opera2d and Tosca

electro-magnetic design programs and along with structural finite-element calculations with ANSYS.

Muons, Inc. Scientist **Dr. Rolland P. Johnson** has been actively involved in particle accelerator research and development for over 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 extensive 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. Dr. Johnson has experience in the design and development of magnets. He designed and built the large aperture magnets used for his thesis and was heavily involved in the commissioning of the Tevatron, where he discovered and corrected for the decay of the sextupole component of the superconducting dipoles, invented the double-helix beam separation scheme, and implemented the squeeze of the low beta interaction region quadrupoles. 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. Most recently, he has devoted much energy to the development of Muons, Inc., an organization devoted to fundamental research and accelerator R & D, where he has recruited an excellent staff.

Fermilab Subgrant PI: **Dr. Alexander Zlobin** will direct the activities of the appropriate Fermilab Technical Division personnel to work with the physicists and others involved in the helical cooling channel design effort. He has 30 years of experience in superconducting magnet technology for particle accelerators. He participated in superconducting magnet R&D programs for the 3 TeV Accelerator and Storage Complex (UNK) at IHEP (Protvino, USSR). He led the quadrupole short model R&D program at Fermilab and personally contributed to the development of large-aperture high-gradient quadrupoles (HGQ) based on NbTi superconductor for the LHC IRs including magnetic, mechanical, thermal and quench protection issues, model magnet fabrication, tests and data analysis. At the present time he is working on the development of a new generation high-field accelerator magnets based on Nb_3Sn superconductor for High Energy Physics including LHC luminosity and energy upgrades (LARP), VLHC and the Muon Collider. He is also promoting superconductor R&D at Fermilab to study and develop in collaboration with industry new alternative superconductors (Nb_3Al, HTS) and cable suitable for accelerator magnets.

g. 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 simulations and CAD work. Muons, Inc. also has office space in the ARC building at Jefferson Lab in Newport News, VA.

The work of this proposal is to be performed in collaboration with Fermilab. The design of the magnet system will rely in part on the personnel and facilities of the Fermilab Technical Division.

h. Consultants and Subcontractors

The Research Institution is **Fermi National Accelerator Laboratory**.

The certifying official is **Dr. Bruce Chrisman**, Associate Director, who has provided a letter committing to the research described above at the level of 30% or $30,000 if the grant is funded at $100,000 starting in July 2007 for a period of 9 months. His address is:

Dr. Bruce Chrisman
Fermi National Accelerator Laboratory
P. O. Box 500, MS 200
Batavia, IL 60510
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We have no plans to use other consultants or subcontractors.

Appendix: Overview of Muons, Inc. 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. The proposal described here is to develop the fundamental theory of one of the enabling technologies for these projects. Namely, high gradient RF cavities provide the fast acceleration required in these applications and the efficient energy replenishment for ionization cooling that are demanded by the short muon lifetime. 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 possible only 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 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, viscosity, and heat capacity. These facts make it our material of choice.

As discussed below in project 6, 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 cooling channel designs, which imply fewer losses 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. 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. Recent simulations of cooling channels using a Helical Cooling Channel (HCC) of superimposed helical dipole, helical quadrupole, and solenoidal fields show a 6D emittance reduction factor of 50,000 in a channel only 150 meters long. That cooling factor is very much larger than that of other cooling channels of comparable length.

Once the beam has been cooled in the HCC other cooling techniques become 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 Lepton Collider (ILC).

One possibility that was explored at the Low Emittance Muon Collider (LEMC) Workshop [7] (held at Fermilab 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. Namely, it would 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 SC Linac and the neutrino factory cost would be incremental.

The next step, first proposed in the Phase I Reverse Emittance Exchange Proposal with the Thomas Jefferson National Accelerator Facility (JLab), and explored at the LEMC workshop, 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, say 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 and makes the neutrino factory an intermediate step to a collider. Second, the large single bunch intensities that a high luminosity muon collider requires are avoided 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 the bunches to a hundred GeV/c or so for a Higgs factory or to 2 to 3 TeV/c for an energy frontier muon collider.

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]. This test cell is capable of 1600 PSI operation in the 5 Tesla LBL Solenoid 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. In the mean time, tests with the existing test cell with and without magnetic field are continuing.

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 January 2007. 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 [1]. 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 [2]. 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 (the subject of Project 7 described below).

4) **Ionization Cooling using Parametric Resonances (PIC)** 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.

5) **Reverse Emittance Exchange for Muon Beam Cooling,** with Jefferson Lab (Dr. Yaroslav Derbenev, Subgrant PI) begun in July 2005 and funded until July 2008 is a project to develop techniques 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. In addition, a new concept developed in Phase I to coalesce muon bunches will be included in the optimization of the longitudinal phase space to enhance collider luminosity.

6) Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities, with Fermilab (Dr. David Neuffer, Subgrant PI) was started in July 2005 and funded until July 2008 with complementary computational and experimental goals. The use of gas filled RF cavities close to the pion production target for phase rotation, bunching, 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. Measurements taken in Phase I have shown that pressurized cavities are not affected by external magnetic fields, making them much better for muon cooling applications than evacuated cavities, which are strongly affected by such fields.

Projects Granted in 2006 now being developed for Phase II proposals:

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) [10] 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.
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. has enthusiastic

collaborators from IIT, Jefferson Lab, Fermilab, and now Lawrence Berkeley National Lab, Argonne National Lab, and Brookhaven National Lab who are part of this effort. The grants described above support six young accelerator scientists. We hope that recent simulation results showing 6D cooling factors of 50,000 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.

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