Phase I-SBIR/STTR Fiscal Year 2007

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PROJECT TITLE: **Stopping Muon Beams**

TECHNICAL ABSTRACT (Limit to space provided)

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

Physics experiments often use low-energy beams of unstable particles that stop in a target in order to provide high sensitivity to rare processes while reducing backgrounds. However, the stopping rate in the target is limited by the kinematics of the production process and by multiple scattering and energy straggling in the material used to slow the particles. In practice, this means that the event rates and sensitivity are limited, because enlarging the target would compromise the performance and/or increase the cost of the detector.

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.

In this project, we will apply new six-dimensional beam cooling inventions, improved capture techniques, and our new simulation tools to develop designs for low-energy beam lines to stop many muons in small volumes.

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

We will show that beam cooling can be used to improve the design of stopping muon beams. As an example, a stopping muon beam design using a helical cooling channel (HCC) will be developed and optimized to provide improved sensitivity with reduced costs for a particular experiment to search for direct conversion of muons to electrons.

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

The use of the HCC for stopping muon beams will provide a new level of sensitivity for experimental physics searches for rare processes such as the direct conversion of muons into electrons. Progress in muon cooling may allow the development of muon colliders and neutrino factories. Many applications of intense stopping muon beams, such as spin-resonance investigations and muon-catalyzed fusion, will also benefit greatly.

Key Words: ionization cooling, stopping muon beam, muon-to-electron conversion, lepton flavor violation.

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

New beam cooling techniques are being applied to create an intense beam of low-energy muons that will stop in a small volume in order to do particle physics experiments of exquisite sensitivity. Such stopping beams will also aid the development of applications such as muon spin resonance and muon-catalyzed fusion.

PROJECT NARRATIVE

Stopping Muon Beams

Table of Contents

Table of Contents 2
Overview of Muons, Inc. Program 2
a. Identification and Significance of Problem or Opportunity, and Technical Approach 7
Significance of Opportunity 7
Technical Approach 8
The MECO Experiment 9
Momentum-dependent Helical Cooling Channel 10
b. Anticipated Public Benefit 12
c. Phase I Technical Objectives 13
d. Phase I Work Plan 14
Responsibilities 16
Phase I Performance Schedule 16
e. Related Research or R & D 17
f. Principal Investigator and other Key Personnel 17
g. Facilities/Equipment 18
h. Consultants and Subcontractors 18
Bibliography and References 19

Overview of Muons, Inc. Program

This overview of recently funded Muons, Inc. projects is provided in order to put the current proposal in context. The company's work has focused on 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. 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 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.

After 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 [1] (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 them 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 [2]. It will be possible to test this cell at 1600 PSI 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 [3] 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 meantime, tests with the existing 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 have more ionization energy loss. A paper describing the concepts and dynamics of this Helical Cooling Channel grew out of the proposal for this grant and has been published in PRSTAB [4]. 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 [5]. 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 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 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) [6] 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.

The opportunity to use many of the techniques described in this overview to create intense low energy or stopping muon beams has inspired this proposal.

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

Significance of Opportunity

In the broadest terms, the challenge facing the high energy physics (HEP) community is to find affordable ways to explore whatever physics lies beyond the Standard Model (SM). The corresponding challenge for accelerator experts is to provide the necessary facilities. In particular, a variety of approaches may be needed. 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 elucidate the physics underlying neutrino oscillations. Now that energy frontier facilities are so expensive that even the R&D supporting their design strains high energy physics budgets, it is important that there be affordable milestones along the way where the R&D successes can be used to support frontier physics. That is the role that can be played by intense stopping muon beams to support experiments studying rare processes with exquisite sensitivity.

HEP experiments have verified the predictions of the Standard Model and determined many of its parameters. But departures from the Standard Model or extensions to it will be necessary to describe the unification of all of the forces including gravity. A major search for new phenomena is being mounted at the LHC where, for example, evidence for weak scale supersymmetry may be observed. Tevatron Run II will be tightening limits in its current search for supersymmetry, and the production and decay of ~1000 top quark events (in Run II) may yet reveal new physics, perhaps even a dynamical mechanism for electroweak symmetry breaking. Complementing searches for new phenomena at the energy frontier, a host of interesting “low energy” and non-accelerator experiments also address fundamental questions, 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.

The first experimental indication of physics beyond the Standard Model (SM) is the observation of neutrino oscillations, establishing that neutrinos have mass. Neutrino mass terms require either the existence of right-handed neutrinos (Dirac mass terms) or a violation of lepton number conservation (Majorana mass terms). So, the Standard Model is incomplete, but how to complete it is unknown. The fact that neutrino masses and mass splittings are tiny compared to the masses of any of the other fundamental fermions may suggest new physics originating at the grand unified theory or Planck scale or may indicate the existence of new spatial dimensions. Whatever the origin of the observed neutrino masses and mixings, a profound extension to the current picture of the physical world is implied.

Since lepton flavor violation (LFV) in the neutrino sector is now established, it is interesting to ask whether there is observable LFV in the charged lepton sector. An intense stopping muon beam would allow sensitive searches for such phenomena. In Phase I of the proposed research, we will use the muon cooling design tools and innovations developed by Muons Inc., in the context of proposed improvements to the beam facilities available at Fermilab, to design a stopping muon beam to enhance the feasibility and improve the sensitivity of a $\mu^- \to e^-$ conversion experiment, a sensitive probe of LFV in the charged lepton sector which may run at Fermilab in parallel with the future neutrino program.

There is a real chance that this experiment can make a discovery of profound importance for the basic model of the physical universe. This physics cannot be addressed by experiments at the high energy frontier. LFV decays of light particles are a more sensitive probe than any conceivable collider experiment at a high energy machine.

Technical Approach

In this project, we will apply new six-dimensional beam cooling inventions [7], improved capture techniques [8], and simulation tools [9] to develop plans for low-energy beam lines to stop many muons in small volumes. In Phase I, as an example, a design using a helical cooling channel will be developed and optimized to improve the sensitivity and reduce the cost of a particular experiment to search for direct conversion of muons to electrons. We anticipate that the primary goal of the Phase II work will be a consistent design of a workable stopping muon beam. This design will identify major parameters and provide a sensible performance estimate. In addition, preliminary engineering design of critical hardware components will permit the planning of hardware prototypes that will be needed to continue this work in the future. We will also apply similar concepts to stopping muon beams for other applications.

A muon-to-electron conversion experiment called MECO [10] was proposed at Brookhaven as part of the RSVP (rare symmetry-violating processes) project. Many review panels concluded that the physics case for the experiment was compelling, but ultimately high costs led the National Science Foundation to terminate the RSVP project. The MECO experiment included a bent solenoidal magnet encompassing the production target, the decay path, the muon stopping target, and the detector system. The magnet system alone, at an estimated cost of about $56M, represented more than half the direct cost of the experiment. In addition, the operation of the AGS complex for the experiment represented a potentially large indirect cost. The indirect costs can be reduced by doing it at Fermilab synergistically with the future neutrino program. 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.

Physicists at Fermilab have shown that the existing Fermilab facilities can be used for an experiment like MECO in parallel with its future neutrino program [11]. After the Tevatron Collider era is over, Fermilab can use the antiproton source facilities to increase the proton intensity in the Main Injector for the neutrino program (in the SNUMI2 project). A straightforward way has been found to provide a proton beam with the necessary characteristics for an experiment like MECO synergistically with SNUMI2. Briefly, protons from the Booster would be momentum-stacked at 8 GeV in the Accumulator ring, transferred to the Debuncher ring, rebunched, and then slowly extracted from the Debuncher while the Main Injector accelerates protons for the neutrino program. The resulting bunch structure would be ideal for a muon to electron conversion experiment. Material presented at a recent meeting to discuss a so-called mu2e experiment can be found at [12].

Muon cooling may reduce the cost and enhance the capabilities of such an experiment in a number of ways. First, reducing the transverse and longitudinal emittances of the muon beam would increase the number of muons that can be stopped in a target of a given configuration.

Secondly, the presence of the absorber in the beam transport can be used to shift the most intense part of the muon momentum spectrum into the acceptance of the stopping system instead of using the low-energy tail of the spectrum. (Without longitudinal cooling, the shift of the momentum spectrum using an energy absorber would lead to an increase of momentum spread as the beam slowed due to the large negative slope of the dE/dx versus energy curve at low energy.)

Both of these factors should substantially improve the ratio of stopping muons to incident protons, which was estimated to be 0.0025 in the beam configuration described in the MECO proposal. Increasing that ratio will have enormous positive impact because it can be used to improve the sensitivity of the experiment, to reduce hadronic backgrounds, and to reduce the need for protons, thereby making the experiment easier to implement, less demanding on valuable resources, and more transparent to the Fermilab neutrino program.

Muons, Inc. has developed a helical cooling channel [**Error! Bookmark not defined.**] concept that is directly applicable to this stopping muon beam. Subsequently, Muons, Inc. and Fermilab have developed an elegant design for the proposed helical solenoidal magnet [13].

The MECO Experiment

The MECO concept is shown in figure 1 and includes three large superconducting magnets: the muon production, transport, and detector solenoids. Protons incident on the production target produce negative pions which decay to muons. The muons are captured in the production solenoid and transported by the bent solenoid to the stopping target. 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. This is a striking kinematic signature; ordinary muon decays at rest produce electron energies less than 53 MeV. 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.

The clear bores of the magnets are connected, forming a single cavity under vacuum. The magnetic field along the axis of the cavity has regions of uniform field connected by regions of monotonically decreasing strength. In the 4 m long production solenoid, the axial magnetic field intensity B is graded from 3.6 T to 2.3 T. The field in the straight section of the 12 m S-shaped transport solenoid falls from 2.3 T to 2.0 T. In the 10.5 m detector solenoid, the field is graded from 2.0 T at the entrance to 1.0 T between the stopping target and tracking detector, and constant thereafter.

A recent presentation at Fermilab to the Laboratory directorate by J. Miller of Boston U. showed different values for the magnetic fields, although the basic concept is the same as the description above by Popp in 2000. Both the trigger and tracker are high-rate detectors with their active regions located far from the solenoid axis to intercept conversion electron helices and avoid beam particle interactions and lower-energy decay products. The primary proton beam for MECO was to be provided by the Alternating Gradient Synchrotron (AGS), with ~ 1 sec machine cycle for 40 x 10^{12} protons. The choice of beam energy, 7-8 GeV, optimizes π and minimizes $\bar{p}$ (a potential background source) production. The beam (not shown) enters the

production solenoid on the right at 10 degrees to the axis and exits to the left. A tungsten target is bombarded to produce $\pi^{\pm}$ which subsequently decay to $\mu^{\pm}$, following helical trajectories along the magnet axis. The graded field reflects left-moving charged particles with momenta outside the 30° (half angle) loss cone, toward the transport entrance. Since particle energy and $p_{\perp}^{2}/B$ are constant, as charges move to regions of lower B the angle between the momentum and solenoid axis decreases. Pions with transverse momenta $p_{\perp} < 180 MeV/c$ travel within the 30 cm inner radius of the magnet. Most π decays occur in the production region.

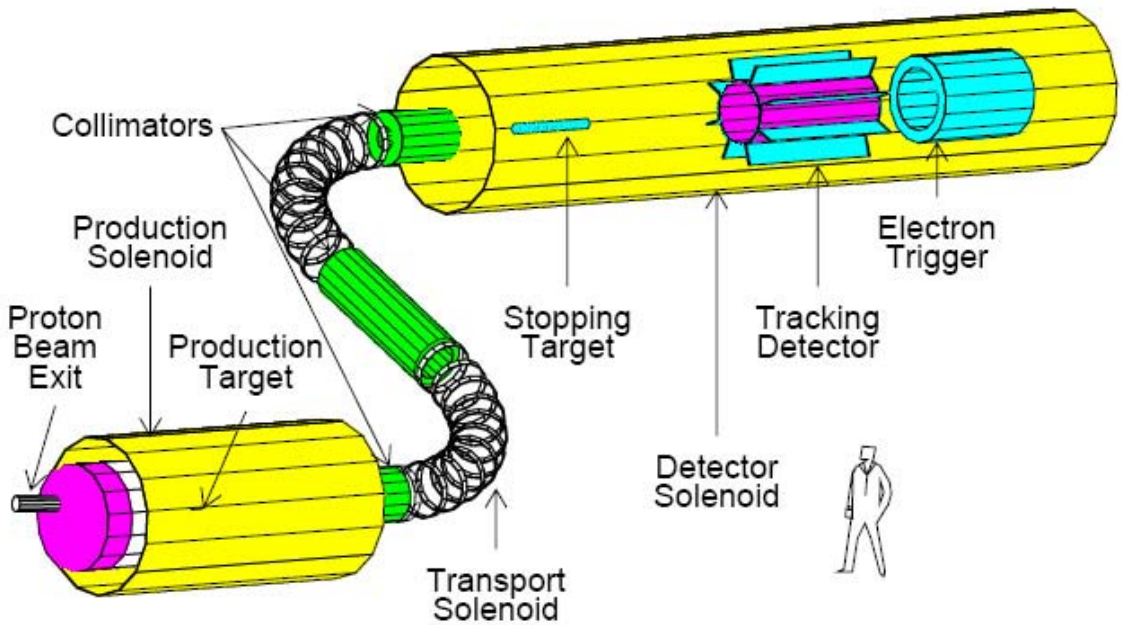

Figure 1: Conceptual picture of the MECO experiment.

Note that the proton energy for the experiment, although sited at the Brookhaven 26 GeV AGS, was chosen to be close to the 8 GeV of the Fermilab Booster. Thus the design of the beamline for the conversion experiment, the subject of Phase I of this proposal, will be done for the Fermilab beam parameters, and the improvement will be directly reflected in the ratio μ/p of stopped muons to incident protons without needing to correct for different proton beam energies.

Momentum-dependent Helical Cooling Channel

The innovation that provides the foundation for this proposal, the development of a beam line to cool muons in six-dimensional phase space, is derived from the helical cooling channel mentioned above.

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 monoenergetic 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, invented by Yaroslav Derbenev, and comprised of magnetic solenoid, helical dipole, and quadrupole magnets. This HCC-type magnet has been adapted for front end designs of a neutrino factory and muon collider, as illustrated in figure 2.

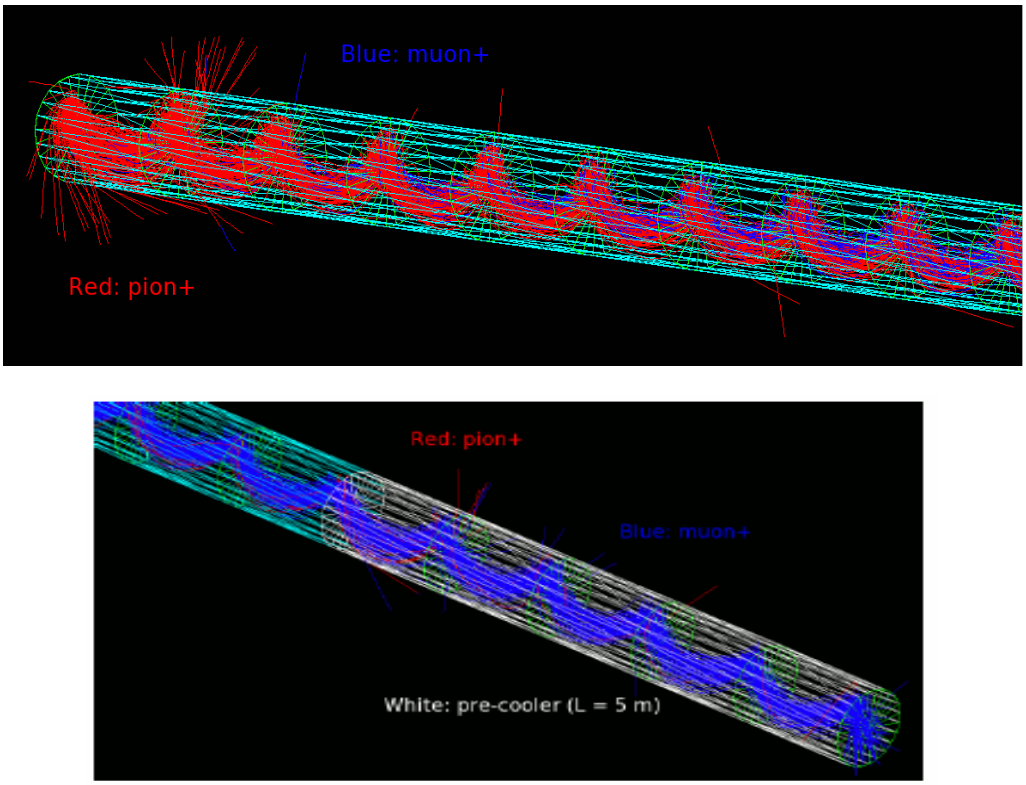

Figure 2: G4Beamline simulation of muon and pion orbits in a HCC-type magnet that is adapted as a decay channel. The decay channel ends in an absorber-filled HCC which is a precooler.

For complete cooling channel**s,** RF cavities superimposed on the magnetic field operate in the dense gas to replace the lost energy. For our MANX 6D proposal described as project 7 in the overview above, the RF is eliminated, and the HCC fields decrease as a function of the z position of the particle in order to accommodate the ionization loss while preserving the reference orbit helix. The intention is to measure the change in normalized emittance caused by ionization cooling and emittance exchange, eliminating the cost of RF for the demonstration experiment. The z-dependent amplitudes can be derived from the relationship between the momentum, *p*, for an equilibrium orbit at a given radius, *a*, and magnetic field parameters as described in Reference [3]:

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

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 $\kappa = ka = p_{\perp}/p_z$ is the tangent of the helix pitch angle. Equation (1) is not just a description of the requirements for a simple HCC but 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.

In addition to being a cost-effective way of demonstrating 6D cooling, the modified HCC magnet can be adapted to a stopping muon program. The HCC magnetic channel can offer a cheaper alternative to those proposed in current stopping muon proposals. The HCC channel can provide large acceptance from a production target and separation of muons from pions. The charge to mass ratio selection of the helical channel and the attenuation of strongly interacting particles by the ionization cooling energy absorber should reduce the chance that unwanted particles make it to the stopping target. A factor of 4 in cooling, particularly in the longitudinal phase space, will allow a higher stopping rate in a smaller stopping target, with concomitant advantages. The parameters of the HCC magnet can be adjusted to optimize the ratio of longitudinal to transverse cooling.

While the momentum-dependent HCC is probably the way to do the last bit of cooling in the approach that has been described here, the possible role of a HCC that incorporates RF for deep cooling will be investigated in Phase II. The advantages of stopping a muon beam that has been deeply cooled in a long, RF-filled HCC may be very attractive, with small spot sizes and high intensities.

b. Anticipated Public Benefits

The use of the HCC for stopping muon beams will provide a new level of sensitivity for experimental physics searches for rare processes. The experiment to search for the direct conversion of muons into electrons would test some of the most fundamental ideas about the laws of nature. Many applications of intense stopping muon beams, such as spin-resonance investigations and muon-catalyzed fusion, will also benefit greatly.

The ability to produce intense, bright beams of muons via ionization cooling would be a tremendous enabling technology for particle physics, opening the door to muon colliders and neutrino factories based on muon storage rings. Such facilities would enhance the ability of particle physicists to explore frontier phenomena. Accordingly, the high energy community is aggressively pursuing muon cooling concepts and technologies. Compelling basic and applied physics can also be done with stopping muon beams; muon cooling can be used to enhance the capabilities of such facilities. The ability to do important physics with an intense stopping muon beam represents an early milestone in a phased approach to the development of energy frontier facilities based on bright muon beams.

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. However, recent discoveries of neutrino mixing have opened up questions best answered not at the energy frontier but at high luminosity facilities of lower energy. In particular, a bright muon source would offer many opportunities for fundamental explorations of the underlying physics, such as the example discussed in this Phase I proposal, the study of the rare muon-to-electron conversion process.

The muon beam described here may also evolve into a muon test beam to support R&D on muon cooling. Since it is largely based on existing accelerator facilities and requires only about 10 kW of beam power on the production target, it represents an economical and technically feasible approach to a highly desirable test facility.

High intensity, high brightness, low-energy muon beams can also be used for g-2 measurements, possible energy sources from muon-catalyzed fusion, sophisticated measurements of material properties using muon spin resonance, and many other applications.

c. Phase I Technical Objectives

G4Beamline, a computer code being developed by us to simulate beam lines that pass through matter, will be adapted and applied to a particular example: the design of a stopping muon beam for a muon-to-electron conversion experiment. This will show that beam cooling can be used to improve the design of stopping muon beams.

Our primary approach will be to increase the stopped μ / p ratio from the 0.25% accepted by the present MECO design by using the higher-energy, higher flux part of the pion/muon production spectrum. To do this we will first slow the beam by passing it 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 and stopped in the experimental target.

We understand that the MECO designers tried to improve their stopped μ / p ratio by degrading the energy, but found that the strong negative slope of the dE/dx versus momentum curve at low energy caused an unacceptable increase in momentum spread. So they settled for using the low-energy tail of the production spectrum. We believe that this problem can be overcome by appropriate use of longitudinal beam cooling. It is true that the low energy of the accepted pions in the MECO design allowed use of a relatively short decay channel. It is our goal to show that affordable HCC designs that make use of the peak of the production spectrum provide greater advantages.

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. We believe that we can

overcome this by reducing the density of the energy absorber. We will study modified HCC segments, decreasing the density of the absorber material as the energy decreases. Possible lower dE/dx absorber variations include sections filled with pressurized gas, taking the thin pressures windows into account, and low density inserts (e.g. Styrofoam) into the liquid hydrogen or helium absorber.

d. Phase I Work Plan

Much of the Phase I work plan is implicit in the discussion above of the technical approach. The primary effort will be the development and utilization of the G4Beamline program to explore the use of variations of the HCC in order to increase the number of stopping muons in the mu2e experimental target. Additional optimization will be done to reduce the cost of the channel. A preliminary study of backgrounds for the experiment will be started, with the idea that detailed simultaneous optimization of beam rates, costs, and background suppression can be performed in Phase II.

Our first attempt to use a simple HCC approach, where absorbers with different density are used to cool and degrade a beam produced by 8 GeV protons is shown in the following figures. Figure 3 is a G4BL display of the cooling and energy degrading HCC system. Figure 4 shows the entire momentum spectrum of produced muons and pions and the subset (hatched area) that enters the first HCC segment at the left of Figure 3, which is at Z=0.

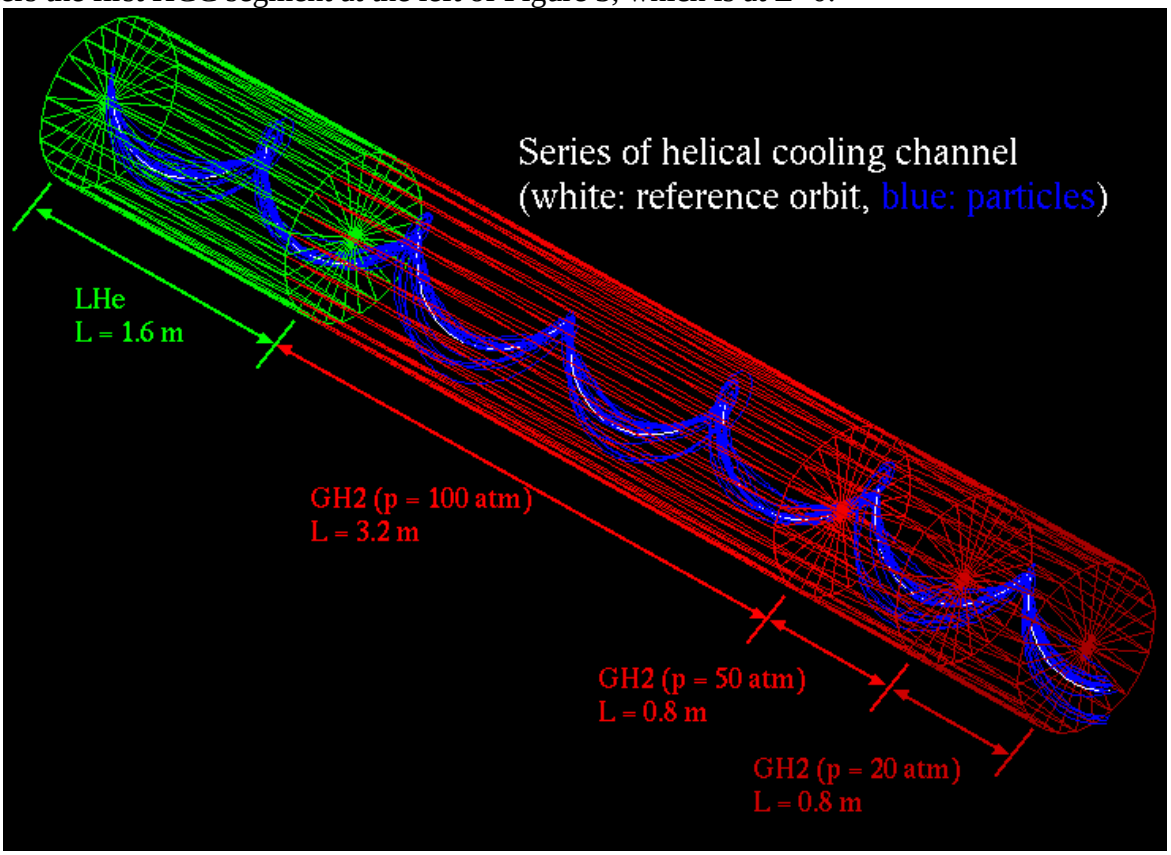

Figure 3: HCC with decreasing density used for first simulations.

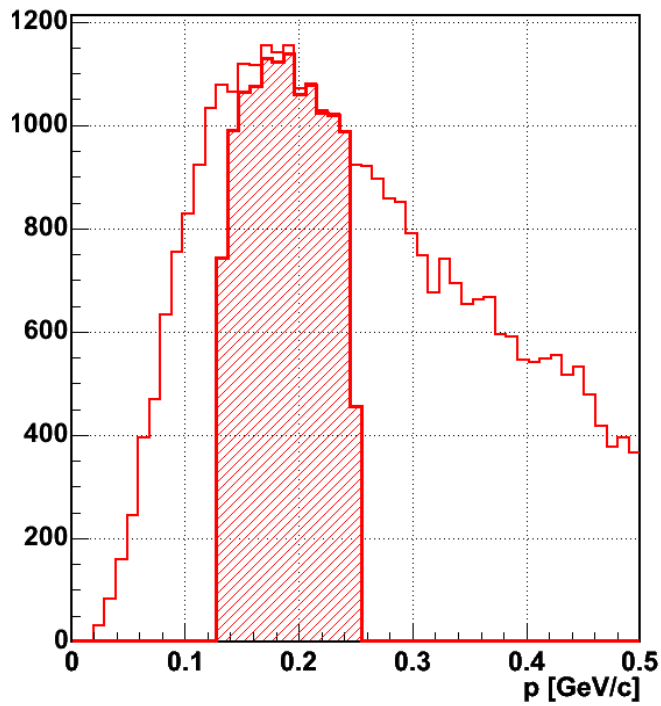

Figure 4: A plot of the π / μ flux from the target produced by an 8 GeV proton beam and the subset (hatched area) that enters the first HCC segment. The pi/mu production target is a 30 cm iron rod. The capture section has a 20-to-2 Tesla 10 meter long tapered solenoid.

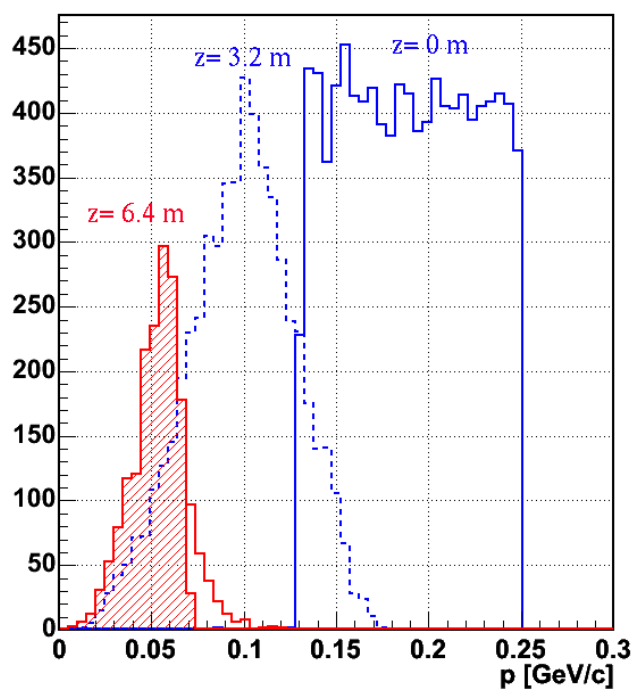

Figure 5: A plot of the evolution of the muon momentum spread as the beam passes from the start of the cooling channel (z=0) through a series of HCC segments with reduced hydrogen absorber density to just before the stopping target (z=6.4 m).

Figure 5 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 3 with smaller and smaller density. We believe that much of the reduction in flux as the beam passes down the channel is due to the reduced acceptance caused by the required dispersion. This will be improved by means of theoretical analysis and numerical simulation studies during the course of the Phase I project. Nevertheless, even though nothing has been optimized, the μ / p 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 albeit very preliminary, since we have not looked at transverse distributions or backgrounds, nor have we fully understood the ramifications of using a stronger capture solenoid than was used in the MECO simulations.

Responsibilities

The work described above is to be performed by Rolland Johnson, Thomas Roberts, Mary Anne Cummings and a new postdoc of Muons, Inc. and Charles Ankenbrandt and Katsuya Yonehara of Fermilab. This will be organized as a team effort, as usual in modern physics experiments, where everyone will participate in all aspects of the project. The work is primarily simulations and associated computational effort that can be done anywhere there is a computer and an internet connection.

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

Fermi National Accelerator Laboratory: Dr. Charles Ankenbrandt will be responsible for the Fermilab subgrant.

Phase I Performance Schedule (Tasks and Milestones)

3 months after start of funding:

1) Stopping beam with HCC segments simulated in G4BL
2) Low density HCC examined theoretically

6 months after start of funding:

1) Cost-performance optimization examined
2) Background studies and mitigation strategies outlined
3) Studies of variations of the low-density HCC

9 months after start of funding:

1) Critical issues identified for Phase II
2) Phase II proposal ready

e. Related Research or R & D

The MECO experiment proposal is well documented, and the proponents of that proposal have participated in the discussions of the mu2e experiment that may be proposed to be done at Fermilab. We understand that the probability of the mu2e experiment being approved may depend on its cost and its compatibility with other experiments at Fermilab. We are fairly certain that we can provide more muons for less money than was estimated for the MECO experiment. We are eager to demonstrate that the new cooling, capture, and simulation techniques that were developed for a muon collider will be very effective for stopping muon beams.

Much of this work is clearly related to projects that are described in the overview. However this stopping muon beam project is an independent extension of those projects in an entirely new direction. There is no overlapping effort.

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 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 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. Dr. Johnson has considerable 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 considerable 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 Physicist: **Dr. Charles M. Ankenbrandt**, a senior accelerator physicist at Fermilab, has contributed for three decades to the design, operation, and improvement of Fermilab facilities. He has led the Booster Synchrotron Group, the Main Ring Group, and the Accelerator Theory Department. He invented "slip stacking" and co-invented "barrier buckets", techniques used heavily at Fermilab. He is currently a member of the Proton Source Department and the Neutrino Factory and Muon Collider Collaboration.

Muons, Inc. Physicist**: Dr. Thomas J. Roberts** was a member of the technical staff at AT&T Bell Laboratories for over 20 years where he had a highly-varied career, including: telecommunications systems engineering and architecture; speech recognition algorithm development and implementation; computational hardware design and interfacing; Operating Systems architecture, design, and implementation; software architecture, design, and implementation. Bell Labs is the original source of UNIX, C, and C++, and Dr. Roberts is a recognized expert on all of them within Bell Labs. Originally trained in High Energy Physics (U. of Illinois, Urbana, IL; Ph.D. in Physics, 1975. Purdue Univ., W. Lafayette, IN; B.S. in Physics, 1971), he worked as a post-doc and research scientist at the U. of Michigan from 1975 to 1982 before joining Bell Labs. Since the beginning of 2002 he has started working again in high-energy physics, learning accelerator physics and contributing first at IIT and then with Muons, Inc. to muon cooling projects. He has played a major role in the design of MICE and the implementation of the RAL muon beam line. Dr. Roberts left Bell Labs in 2006 and now works full time at Muons, Inc.

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.

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
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chrisman@fnal.gov

We have no plans to use other consultants or subcontractors.

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