U.S. Muon Accelerator Program
Activity Description

Advanced Concepts for Muon and Neutrino Sources

I. Introduction

This document describes a research plan put forth in response to the recommendations of the P5 subpanel and as directed by OHEP. It describes the orderly transition or termination of activities that have up to now been associated with the MAP Design & Simulation effort. Guiding principles of the proposed research are that it:

- is aligned with the P5 recommendations
- enables OHEP to get optimum value for the investment that it has already made in muon accelerator capabilities
- allows an efficient launch of muon-based accelerators in the future, if and when motivated by Physics
- meets the criteria for General Accelerator R&D projects

P5's recommendation with regard to MAP is specifically described in recommendation 25:

- *Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.*

The research proposal described here builds upon, takes advantage of, and leverages the progress made on muon-based technology for more than a decade and more recently under MAP. But it marks a significant change compared with MAP, which was specifically charged with addressing the feasibility and key design issues for neutrino factories and muon colliders. In contrast, the present proposal, integrated in the GARD program, focuses on the aspects of muon beam concepts that would be essential to providing future neutrino and muon *source* capabilities with unprecedented beam quality. Given the high priority placed by P5 on Intensity Frontier facilities at Fermilab, there seems little doubt that muons will play an increasingly important role for OHEP in the future. The concepts explored under this proposal will inform medium- and long-term planning for Intensity Frontier facilities, in accord with OHEP expectations for GARD projects.

While this effort will explore a range of advanced concepts for neutrino and muon sources, a key target is a Neutrino Factory after LBNF. This is in accord with P5's favorable comments regarding Neutrino Factories:

- *Neutrino factories based on muon storage rings could provide higher intensity and higher quality neutrino beams than conventional high power proton beams on targets. This concept would be attractive for an international long-baseline neutrino program offering more precise and complete studies of neutrino physics beyond short-term and mid-term facilities.*

This proposal is also aligned with P5's recommendation 26 related to General Accelerator R&D (GARD):

- *focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.*

Within this effort, we will explore novel approaches for reducing the cost of future muon-based accelerators. We will also explore *stageable* approaches, which are a prerequisite for affordability in large accelerator facilities. A cost-effective Neutrino Factory could therefore be the next facility beyond LBNF if the physics called for it. Also, if the LHC finds evidence of new physics in the multi-TeV range, it would provide a foundation for resuming muon collider development as one of the most promising long-term technology options for a multi-TeV Lepton Collider in terms of performance, cost and power consumption. Consequently, OHEP would be well-positioned to provide leadership in future international efforts.

In addition, there is a broad range of other scientific applications requiring high quality muon sources. An advanced muon source could significantly leverage OHEP's investment in fundamental science facilities such as a future

Mu2e upgrade, and, more generally, could benefit next-generation rare-muon-process experiments. There are also opportunities to provide improved beams for applied science and national security. Examples include muon spin rotation studies of a variety of materials (superconductors, semiconductors, chemical reactions, etc.), and muons for detection of nuclear contraband.

Key research areas (that will be described in the next sections) include:

1. High Intensity Muon Sources
2. Bright Muon Sources
3. Precision Neutrino Sources

II. Proposed Research

II.1 High Intensity Muon Sources

The main goal of this portion of the proposal is to continue to develop the key concepts required for a compact and efficient muon production and capture system based on an incoming proton beam that can provide an intense muon source. This production and capture system consists of a target within a capture solenoid, a decay channel, a chicane followed by an absorber to remove unwanted particles, and a buncher and phase rotation system to manipulate the longitudinal beam phase space into a desired form.

An intense muon source based on protons remains the only identified path to the high intensity muon beams required for high energy physics applications. Since the P5 report emphasizes having Fermilab becoming the world-leading facility for neutrino beams, the importance of the proton driver interface as the Fermilab facility plan evolves cannot be overlooked. Long-range planning toward a Neutrino Factory is essential for the post-LBNF era. Thus this research area includes exploring concepts to deliver MW-class proton beams consistent with the planned evolution of the proton complex at Fermilab.

One of the most significant challenges for a muon source is energy deposition from unwanted particles in the accelerator components. Concepts have been identified that could mitigate the impact of this energy deposition (in particular a chicane and a downstream absorber). We will explore these concepts to determine the efficacy of approaches that control halos, beam loss, and energy deposition. We will deliver the specifications for and performance evaluation of a source incorporating these elements.

One promising method for achieving the highest gradients in RF cavities, in particular those that are in magnetic fields, is to fill the cavities with pressurized hydrogen gas. While vacuum RF cavities would be preferred, pressurized cavities are an important option for ensuring feasibility and possibly improving performance. The impact of this technique on the buncher and phase rotation systems of these muon sources will be studied to understand its consequences.

An additional goal of this topical area is to identify possible applications that would benefit from such an intense muon source. Indeed, muon sources could have many applications in diverse fields, including fundamental science (such as Mu2e and g-2) and areas of societal interest. For example, scientists involved in homeland security have proposed using muon sources to interrogate cargo vessels for illicit nuclear material. Many applications have an interest in having a polarized muon beam. In addition to identifying applications for which muon sources are of interest, we will examine methods for increasing the polarization of high intensity muon sources.

Primary deliverables of the envisioned 2-year effort will include:

- Updated interface specifications to the Fermilab proton complex as the long-term elements of Fermilab's Proton Improvement Plan develop;
- Design specifications for the systems required to control particle loss in the muon production and capture sections of our proton-based muon source along with the corresponding performance specifications of those systems;
- A design concept for an optimized buncher and phase rotation system utilizing gas-filled RF cavities along with its performance specifications;
- A report describing additional potential applications of a muon source of this type, which specifies the achievable performance gains;

- Design specifications for the system modifications required to provide a more highly polarized source of muons along with the corresponding performance specifications.

II.2 Bright Muon Sources

The main goals of this portion of the effort are to (1) develop 6D Cooling concepts to reduce the emittance to produce bright (i.e. high-intensity, low emittance) muon beams, and (2) work with the Muon Ionization Cooling Experiment (MICE) Step IV effort to analyze the data and incorporate results into cooling codes. We will specify and document the new generation of cooling channel lattices taking into account all recent experimental results. While a key driver is to enable an affordable Intensity Frontier facility after LBNF (i.e., a Neutrino Factory), we will also explore how these cooling concepts can be used for other applications such as a Mu2e upgrade and other facilities that would benefit from a bright muon source. We will furthermore explore these concepts with a view toward making them more affordable.

The development of 6D Cooling concepts is already in an advanced state thanks to progress under MAP on the theoretical aspects as well as experimentally at the MuCool Test Area (MTA) at Fermilab and at MICE. One area of concern has been the breakdown of RF cavities in high magnetic fields. Careful cavity design has been shown to limit gradient loss with increasing magnetic field. Beryllium has been shown to have almost no damage due to breakdown compared with copper. Experiments at MTA have demonstrated that using cavities filled with high-pressure gas can prevent this breakdown and can operate effectively at high beam intensities. An important conceptual development is the reconsideration of a hybrid cooling channel that makes use of standard (as opposed to helical) beamline components and external absorbers along with cavities that are filled with medium-pressure gas. This is a promising concept that has the potential to control rf breakdown in high magnetic fields while maintaining the relative simplicity of rectilinear channel designs. Another important development is progress in concepts that can be used in the early stages of cooling for both signs simultaneously, thereby reducing cost. These, and other concepts, will be explored and documented in this portion of the project.

By exploring muon cooling concepts (including start-to-end cooling channel simulations) that would provide a beam effectively and economically and by determining what is realistically achievable in a muon cooling channel, we will provide important information to OHEP that is needed for long-range planning (i.e. in regard to a precision, high-intensity Neutrino Factory after LBNF), as well as impact nearer term projects like a Mu2e upgrade.

Such muon cooling channels could dramatically improve cost effectiveness of the downstream accelerator complex. For example, if the muon beam could be cooled sufficiently, it could be accelerated by a dual-use linac (for H- and muons) and potentially reduce the overall facility cost, thus making a cost-effective Neutrino Factory at Fermilab a possible future option. Furthermore, a compact muon cooling channel could provide opportunities for a wide range of projects involving muons, including national security and applied science applications.

The other activity in this portion of the project will be to help analyze MICE Step IV cooling results and incorporate the resulting physics into cooling codes. MICE tracks individual particles through magnetic fields and through materials. Knowing the entrance and exit coordinates and momenta of each particle, and knowing the configuration of fields and materials in between, makes it possible to infer quantitatively the energy loss, scattering, and straggling of muons in materials, at an energy of approximately 200 MeV/c. Under this proposed project we will work with MICE experimentalists and data analysts to determine the beam-material interaction properties of muons with a number of materials, and incorporate these new results into cooling codes.

Studies of the muon cooling channels and the corresponding experimental program will produce a number of results of general interest, such as RF operation in magnetic field, general magnet requirements for future muon sources, and properties of materials of the typical absorbers (LH2 and LiH) used for cooling and for RF and safety windows (Be and Al). Simulation software will be augmented with new experimental results from MICE on energy loss in various kinds of absorbers and multiple scattering properties.

Primary deliverables of the envisioned 2-year effort will include:

- Performance specifications and lattices for 6D cooling channels, based on start-to-end simulations, suitable for use by a future Neutrino Factory;

- Incorporation of the results of interaction physics studies provided by the MICE experiment into the principal ionization cooling codes and evaluation of the performance of proposed cooling channels based on these updates.

The former will inform OHEP, FNAL, and the HEP community of the concepts and limits of techniques to obtain cooled muon beams with a range of parameters for a variety of possible fundamental science, industrial, and homeland security applications. The latter will provide the most up-to-date and reliable capability to predict the performance of cooling channels, and help reduce uncertainty and risk associated with future facilities involving muon cooling.

II.3 Precision Neutrino Sources

The goal of this portion of the project is to develop concepts for acceleration and storage of muon beams for a post-LBNF neutrino facility. The primary objective is a Neutrino Factory as well as the initial steps (such as the nuSTORM concept) toward such a facility. The study of these concepts would directly address stageability and cost reduction. This includes exploration of dual-use (H- and muon) linac concepts or other efficient acceleration options for muons alone. This research benefits from bright muon sources developments in [2] exploring what is achievable, in terms of emittance reduction, in a 6D muon cooling channel in order to understand what beam could be captured and accelerated, and hence balance linac cost with cooling cost. It involves the design of muon storage rings, including injection and extraction systems, that would result in a precision, high intensity neutrino source.

An important issue is to explore the means to make a neutrino factory at Fermilab *affordable* in the future. Reducing the cost while maintaining performance will depend on the interplay between the cooling system, the acceptance of the acceleration system, and the acceptance of the storage rings. For example, if the beam emittance could be reduced by cooling, it would ease the requirements (and cost) of the complex and also increase the total accelerated muon flux.

Another important issue is the relationship between neutrino sources based on low-energy muon storage rings and their potential impact on LBNF systematics. There is a growing appreciation that 1% level systematics is needed in LBNF to fulfill the P5 goal. Muon storage ring concepts like nuSTORM offer precise measurement of neutrino cross sections to reach that level. Preserving expertise in muon storage ring concepts, and exploring methods to optimize their performance and reduce their cost, is important because there is a substantial risk that 1% systematic precision will be difficult or impossible to achieve without the addition of a neutrino source based on a low-energy muon storage ring.

The groundwork for this portion of the project was laid by the IDS-NF effort and by MAP. In particular, the storage rings for IDS-NF will be scaled from 10 GeV to 5 GeV, with the muon beam pointed at SURF and from three to one single train of bunches stored per cycle with potential of substantial savings. Such a system would be complementary to LBNF if the physics calls for higher precision measurements. We will also explore concepts based on a low-energy muon storage ring, particularly in regard to performance improvement and cost reduction, that would enable precise cross-section measurements that may be needed to reduce LBNF systematics.

Primary deliverables of the envisioned 2-year effort will include:

- Specifications for the acceleration system that are optimized in conjunction with the requirements of the upstream cooling system. These optimizations will aim to specify the proper balance between, cost, muon flux and machine flexibility;
- Specification for the neutrino flux and timing information from the decay ring needed for the neutrino physics experiment.

Understanding the issues in the first deliverable is key to reducing the cost of a future Neutrino Source. The second deliverable will inform the detector community about the systematic uncertainty associated with the muon beam, which is important for detector considerations and impacts the discovery potential of a future neutrino experiment based on muon decay rings.

III. Personnel and Budget

The total budget proposed for this activity in FY15 is \$2.25M, with \$1.75M being GARD-based and \$0.5M being support from the MICE-US team for integration of the MICE Step IV results into the cooling codes managed by this group. This total funding would support 10.3 costed FTEs, and approximately 2.8 additional FTEs being supported from other sources (e.g., Early Career Awards).

FY15 Breakdown of Manpower:
Activity Coordination (0.9 FTE): Robert Ryne (LBNL) and Jean-Pierre Delahaye (SLAC)
High Intensity Muon Sources (4.3 FTE): Diktys Stratakis (BNL) and Keith Gollwitzer (FNAL)
Bright Muon Sources (5.5 FTE): Pavel Snopok (FNAL/IIT)
Precision Neutrino Sources (2.4 FTE): J. Scott Berg (BNL) and Alex Bogacz (JLab)

In FY16, the proposed total effort would be expected to decrease by approximately 20% to \$1.9M with \$0.15M coming from MICE-US support. This would correspond to support for 8 costed FTEs, and another 2.6 FTEs being supported from other sources.

iv. Summary

The priority given by P5 to domestic Intensity Frontier facilities strengthens the role that muons will play in OHEP in the future. This includes the near-term (Mu2e and g-2), the mid-term (a Mu2e upgrade), and the long-term (a Neutrino Factory). Mid- and long-term planning and the supporting R&D are a natural element of the GARD program. This proposal focuses on muon and neutrino source capabilities. The emphasis is on developing affordable, stageable concepts needed for a post-LBNF neutrino factory, as well as on exploring how these advanced sources could have nearer-term and broader impact to OHEP and the Nation.

Thanks to MAP and the investments OHEP has made for many years, several key concepts that will be central to these sorts of sources in the future have been identified. Key questions are on the verge of being answered such as

- What concepts will allow us to affordably produce high intensity muon beams?
- What are the intensity limits?
- What cooling concepts can realistically be used to reduce the beam emittance?
- What are the achievable emittances?
- What are the best concepts (in terms of cost and performance) to accelerate and store the muon beams in order to produce precision neutrino sources?

If the science drivers are found to require new muon-based facilities, answering these questions is important for OHEP's long-range planning.