Fundamental Aspects of Muon Beams

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I. Introduction

I.1 Overview

This white paper describes activities whose primary goal is to perform beam dynamics studies to explore the limits of concepts through advanced simulations and theory for the generation and manipulation of muon beams. Previously, muon accelerator activities were carried out under the auspices of Muon Accelerator Program (MAP) and predecessor organizations. The 2014 Particle Physics Project Prioritization Panel's (P5) 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.*

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 the DOE Office of High Energy Physics (DOE-OHEP) in the future. The R&D described here leverages the progress made on muon beam dynamics for more than a decade, most recently under MAP. It will inform medium- and long-term planning, and will address a number of important questions such as:

- What are the intensity limits of muon beam generation?
- What are the emittance limits of muon beam cooling?
- What are the fundamental limits for rapid acceleration of muons?
- What are the fundamental limits of precision neutrino beams generated from stored muons?

If new experimental discoveries are found to require new muon-based facilities in the far-term, having answered these questions will be important for charting the best path forward.

I.2 Impact

The main objective of this R&D is to perform beam dynamics studies to explore the limits of present concepts for the generation and manipulation of muon beams. The impact will be to inform the physics community and DOE-OHEP about what is possible regarding a range of future muon-based facilities beyond the near-and mid-term facilities that were identified by P5. Such future facilities could include a neutrino factory as the obvious facility to follow LBNF if there is a physics case for it. The front end for such a facility could also provide muon beams that could be cooled for use in next-generation rare-muon-process experiments (e.g., upgrades to Mu2e and g-2). All these facilities would provide infrastructure for a cost-effective, staged scenario leading to a far-term muon collider.

There may also be a mid-term impact: There is a growing appreciation that muon storage ring concepts like nuSTORM might be needed to reduce systematics so that LBNF can achieve its goals[1]. If so, wherever such a facility is built in the world, US expertise in muon accelerators would be highly valuable.

The focus of the US accelerator-based high energy physics program on neutrinos means that muons are likely to play an increasingly important role for OHEP in the future. Establishing an effort on muon beam dynamics concepts in the GARD portfolio would help ensure that OHEP would be well-positioned to provide key roles and leadership in future international efforts involving muons.

While the main impact of this R&D would be for high energy physics applications, it is worth mentioning that there are other scientific applications requiring high quality muon beams. There are opportunities to provide improved beams for applied science and national security. Examples include muon spin rotation studies of a variety of materials and phenomena (superconductors, semiconductors, chemical reactions, etc.), and muons for detection of nuclear contraband.

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[1] P. Huber, *et al.*, "The Case for Muon-based Neutrino Beams," a white paper submitted to the HEPAP Accelerator R&D Sub-panel (2014).

I.3 Muon R&D alignment with P5 and GARD

A number of statements have been made -- in the P5 report and at OHEP meetings -- that are supportive of muon accelerator R&D especially 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.*

While the R&D proposed here does not involve the design of a neutrino factory, it does target the basic aspects of muon generation and manipulation that are relevant to a range of possible applications including a neutrino factory.

In addition, the final report of the DOE Review of the Muon Ionization Cooling Experiment (MICE) and MAP held in August 2014 confirms that:

> *Aspects of MAP beneficial to future neutrino sources should be transferred into GARD, directly competitive with other GARD objectives.*

If a lepton collider at the energy frontier is warranted by physics, and if key technological challenges can be overcome, a muon collider is arguably the most promising *advanced concept* option for a multi-TeV lepton collider in terms of performance, cost, and power consumption. This is well aligned with P5's recommendation regarding R&D, that it:

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

In view of the P5 report, our proposed GARD activities represent a significant change with respect to the MAP activities that are closing out in 2015. First, our GARD effort focuses on *fundamental aspects* of muon beams rather than on designing facilities. Second, it represents a significant reduction in scope, eliminating collider-specific aspects like background mitigation and neutrino radiation mitigation. Under GARD we will focus on these key R&D activities:

1. Fundamental limits to muon beam intensity
2. Fundamental limits to muon beam brightness
3. Fundamental limits to muon beam acceleration and storage

II. R&D Topics

II.1 Fundamental limits to muon beam intensity

The main goal of this portion of R&D effort is to explore the intensity limits of high intensity muon beams generated by a beam of protons striking a target. These sources consist 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.

One of the most significant challenges for a proton-based 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 perform beam simulations to determine the efficacy of approaches that control halos, beam loss, and energy deposition. We will also perform optimization studies to maximize the performance, and explore approaches that would reduce the cost of such a system.

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.

II.2 Fundamental limits to muon beam brightness

The main goals of this portion of the R&D portfolio are to (1) explore the intensity limits of 6D Cooling concepts to reduce the emittance to produce bright (i.e. high-intensity, low emittance) muon beams for a neutrino factory and other applications of bright muon beams, and (2) to simulate and optimize "final cooling" concepts that are needed to produce muon beams with ultra-low transverse emittances. Such schemes would impact several possible future projects, including a neutrino factory, a muon collider, a Mu2e upgrade, and other facilities that would benefit from a bright muon source.

The development of 6D Cooling concepts is already in an advanced state 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[2]. 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. The performance of these concepts will be analyzed and optimized using advanced simulation.

By analyzing and understanding the limits of muon cooling concepts (through large-scale beam simulations and theory), we will provide important information to DOE-OHEP that is needed for long-range planning (i.e. in regard to a precision, high-intensity neutrino factory after LBNF and in regard to a muon collider), 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 or elsewhere 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.

Lastly, it is worth mentioning the importance of advanced simulation to the design of muon cooling channels as well as to other aspects of this R&D effort. Codes such as ICOOL, G4Beamline, MARS, and Warp have been essential to MAP and will continue to be so in a future GARD effort. These codes now run at the National Energy Research Scientific Computing Center (NERSC), where they can take advantage of massively parallel computing resources. Effort will be required to port these and other codes to the next generation of hardware, due in CY2015, that will utilize many-core architectures and will require more complicated programming techniques. The simulation of muon-based systems involves multi-physics modeling with a broad range of phenomena, including strong nonlinear effects, collective effects, particle decay, halo formation, beam-material interactions, energy deposition resulting in radiation and material damage, beam-plasma interactions, and plasma chemistry, to name a few. We do not envision code development efforts (porting, adding capabilities, etc.) as being included in this R&D effort, since this is a fundamental beam physics effort, and also because the codes have applications beyond muons. Such code activities should be included in the Accelerator Physics Computation and Simulation portion of GARD.

II.3 Fundamental limits to muon beam acceleration and storage

The goal of this portion of the R&D effort is to explore the performance limits of the rapid acceleration of muons, and to analyze the performance limits of muon storage rings that would serve as precision neutrino sources. The study of these concepts would also address how pushing the limits could affect cost reduction. This includes , for example, Rapid Cycling Synchrotrons based on the hybrid option which utilizes both fixed field superconducting magnets in conjunction with normal conducting rapid cycling (>400 Hz) magnets. This research effort will be coupled to the work on bright muon sources developments described above, which will explore what is achievable, in terms of emittance reduction, in a 6D muon cooling channel. This will allow us to better understand what beam could be captured and accelerated in particular accelerator structures, and hence how to balance linac cost against cooling system cost.

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[2] D. Bowring, *et al.*, "Normal-Conducting RF Cavity R&D at the MuCool Test Area," a white paper submitted to the HEPAP Accelerator R&D Sub-panel (2014).

An important issue is to explore the means to make future muon facilities at Fermilab *affordable*. Reducing the cost while maintaining performance will depend on the detailed interplay between the cooling system, the acceptance of the acceleration system, and the acceptance of the storage rings. For example, when the beam emittance is reduced by cooling, it can significantly ease the requirements (and cost) of the upstream portion of a complex and 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-specified sensitivity goal (see Ref. 1). 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.

III. Resources

The R&D effort proposed here under GARD would involve about 8 FTE made of a mixture of university and laboratory junior researchers suitably supervised by senior laboratory members. The proposed R&D effort would consist of the following activities:

1. Fundamental limits to muon beam intensity (2.4 FTE, 30% of total): Explore solutions for shielding and energy deposition control downstream from the target. Explore solutions, such as a chicane, to limit energy deposition in front end systems. Study the use of gas filled rf systems. Develop a better understanding of the front end design, including a study whether combining the buncher and phase rotation into a single system, possibly including some amount of ionization cooling, can improve system performance.
2. Fundamental limits to muon beam brightness (4 FTE, 50% of total): Understand the limits of periodic ionization cooling lattices. In beamlines designed to cool a single muon charge: explore the limits to the attainable transverse emittances; study the relationship between this limit and the rate of particle loss within various technological constraints; how magnet technology sets this limit; the relationship between dynamic aperture and equilibrium emittance; the impact of space charge and other collective effects; and the relative performance of lattices using gas-filled cavities versus those with only localized absorbers. Study these same effects in lattices which cool both muon charges in the same beamline. Study ways to attain emittances lower than those from the above periodic 6D systems. Consider ionization cooling in high field solenoids; emittance exchange in such solenoids; use of half-integer resonances (PIC/REMEX), splitting beams transversely followed by a longitudinal recombination; and any new schemes that can be generated. Study one or more of these possible solutions, including the match with the upstream cooling systems.
3. Fundamental limits to muon beam acceleration and storage (1.6 FTE, 20% of total): Study control of large longitudinal emittances in potential muon acceleration schemes. Study novel designs of hybrid pulsed synchrotrons. Explore the limits of large-acceptance muon storage rings and the impact to neutrino beam quality from such rings. Study the limits imposed by collective effects in these systems.

With regard to all the above areas, we will develop and maintain computational tools that strengthen our ability to efficiently explore the fundamental limits of the proposed schemes. In addition to the above R&D, 0.25 FTE would be allocated for managing the R&D effort and for interfacing with the GARD Program Manager. The proposed level of effort would allow significant progress over a 2-3 year period. Given the anticipated distribution of researchers involved, we estimate that this level of effort would require approximately $2M in support annually.

The above resources represent a significant reduction compared with MAP Design & Simulation activities. This reduction is due to greatly reducing the scope (dropping collider-specific activities), and changing the thrust from baseline facility design (as was emphasized under the MAP Initial Baseline Selection process) to exploratory studies that emphasize understanding fundamental limits (e.g., limits to intensity and emittances), affordability and performance.

IV. Conclusion

The 2013 Community Summer Study section on Accelerator Capabilities stated that, "*The potential for muon accelerators to address crucial questions on both the Intensity and Energy Frontiers argues for a robust development program."* It furthermore stated that, *"A vigorous, integrated U.S. research program toward demonstrating feasibility of a muon collider is highly desirable. The current funding level is inadequate to assure* *timely progress."* While budgetary realities have eliminated a robust development program at this time, it is still highly desirable to preserve and advance the core beam physics efforts in a reduced-budget GARD effort.

The priority given by P5 to domestic Intensity Frontier facilities strengthens the role that muons are likely play in the OHEP research portfolio 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 and muon collider). Mid- and long-term planning and the supporting R&D are a natural element of the GARD program. This proposal focuses on fundamental aspects of muon beams. It emphasizes exploring concepts for producing intense muon beams and bright muon beams, for rapid acceleration of muons, and for muon storage. It will provide information about the achievable intensities and emittances, and will explore methods to make muon systems more affordable and have higher performance. The introduction of this document lists a number of questions that will be answered under this R&D effort. If the science drivers are found to require new muon-based facilities, answering these questions is important for OHEP's long-range future.