

Fundamental Aspects of Muon Beams (J.P.Delahaye/SLAC and R.D.Ryne/LBNL)

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 goals¹. 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.

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).

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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.

Key R&D activities identified in MAP, as described in Ref. 2, that will be discussed in the following sections include:

1. Target and Front End studies for high intensity muon beams
2. Muon cooling studies for producing bright (i.e. high-intensity, low emittance) muon beams
3. Fast acceleration of muons
4. Muon storage rings (to produce precision neutrino sources) and muon collider rings

II. R&D Topics on fundamental beam issues

II.1 High intensity muon sources

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

² MAP Note: "Muon Accelerator R&D Issues," a white paper requested from the Muon Accelerator Program by the Advanced Acceleration Concepts sub-group of the HEPAP Accelerator R&D Sub-panel (2014).

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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 High brightness muon sources

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 fields³. 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 Fast Muon Acceleration

The goal of this portion of the R&D effort is to explore the performance limits of the rapid acceleration of muons. The study of these concepts would also address stageability and cost reduction. This includes exploration of dual-use (H- and muon) linac concepts or other efficient acceleration options for muons alone like Recirculating Linacs and Rapid Cycling Synchrotrons (RCS). Recirculating Linacs, possibly equipped with large acceptance multi-pass arcs (similar to the optics developed for Fixed Field Alternating Gradient machines) offer the potential for significant cost savings and will be investigated. Simulations will be performed on muon beam dynamics in 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.

³ 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).

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This research effort will be coupled to the work on bright muon sources developments described in sections II.1 and II.2, 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.

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 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 overall complex and increase the total accelerated muon flux.

II.4 Muon Storage and Collider Rings

The main goal of this portion of the R&D effort is to analyze and optimize the performance of muon storage rings that would serve as precision neutrino sources.

An 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.

The focus of this portion of the effort will be to investigate techniques to deliver and store muon beams in an affordable, stageable way to bridge mid-term (nuSTORM-like) and far-term (neutrino factory) needs. The groundwork for the mid-term was laid by the nuSTORM design effort while the far-term was laid by the IDS-NF and NuMAX design efforts, all directly supported by MAP.

In regard to collider rings, there was major progress under MAP in ring design, component protection, and mitigation of detector backgrounds. This progress brought us significantly closer to validating the feasibility of a muon collider at Higgs Factory energy, at 1.5 TeV, and at 3 TeV, if muons can be cooled to produce the required emittances. Given the P5 priority on Intensity Frontier facilities, and the reduced funding (compared with MAP) that might be available in GARD, the collider portion of this part of the R&D effort would be a modest activity focused on beam dynamics and instabilities in a future collider.

III. Resources

The R&D effort proposed here under GARD would involve about 7.5 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 activities²:

1. High intensity muon sources (2 FTE): Simulation studies to evaluate solid target damage from short proton pulses; to characterize the beam control, transmission and losses in a muon accelerator front end system and to specify the performance limitations imposed by energy deposition issues; to understand and optimize the performance of a front end utilizing gas-filled RF cavities; to understand the performance trade-offs between polarization and intensity in a proton-based muon source.
2. High brightness muon sources (2.5 FTE): Evaluation of the expected performance of a 6D Initial Cooling channel which could support neutrino factory and other physics applications (e.g., CLFV experiments). Simulation studies to evaluate the beam physics effects that would impact the performance of an ionization cooling channel (including beam-plasma interactions in a gas-filled channel); to evaluate the performance of a Final Cooling channel as required to provide low transverse emittance beams for a high luminosity TeV-scale muon collider.
3. Fast Muon Acceleration (1 FTE): Simulations to evaluate beam stability and emittance diluting effects in muon linacs and RLAs; to evaluate beam stability, emittance diluting effects, transmission performance and fast-ramping magnet requirements in RCS accelerator systems.
4. Muon Storage and Collider Rings (1.5 FTE): Studies aimed at lower cost low energy muon storage ring options to strengthen the long baseline neutrino physics program. Simulations to characterize the performance of a long baseline neutrino factory based on updated performance specifications of the front end, cooling and acceleration

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systems. Tracking studies to characterize the performance of proposed colliders and their sensitivity to collective effects.

The above resources represent a significant reduction compared with MAP Design & Simulation activities. This reduction is due to greatly reducing the scope (dropping nearly all 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 addressing bottlenecks (e.g., limits to intensity and emittances), affordability and performance. In addition, 0.5 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 \$1.75M in support annually.

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.