MUON ACCELERATORS FOR THE NEXT GENERATION OF HIGH ENERGY PHYSICS EXPERIMENTS *

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Abstract

Muon accelerator technology offers a unique and very promising avenue to a facility capable of producing high intensity muon beams for neutrino factory and multi-TeV lepton collider applications. The goal of the US Muon Accelerator Program is to provide an assessment, within the next ~6 years, of the physics potential and technical feasibility of such a facility. This paper will describe the physics opportunities that are envisioned, along with the R&D efforts that are being undertaken to address key accelerator physics and technology questions.

INTRODUCTION

Muon Accelerators offer unique potential for the U.S. High Energy Physics (HEP) community. In 2008, and subsequently in 2010, the U.S. Particle Physics Project Prioritization Panel (P5) [1,2] recommended that a world-class program of Intensity Frontier science be pursued at Fermilab as the Energy Frontier program based on the Tevatron reached its conclusion. Accordingly, Fermilab has embarked on the development of a next generation neutrino detector with LBNE and a next generation proton source with Project X. Looking towards the fruition of these efforts, however, we must also consider how to provide the next generation of capabilities that would enable the continuation of a preeminent Intensity Frontier research program. Building on the foundation of Project X, Muon Accelerators can provide that next step with a high intensity, precision source of neutrinos to support a world-leading research program in neutrino physics. Furthermore, the infrastructure developed to support such an Intensity Frontier research program can also enable the return of the U.S. HEP program to the Energy Frontier. This capability would be provided in a subsequent stage of the facility that would support one or more muon colliders, which could operate at center-of-mass energies from the Higgs resonance at ~125 GeV up to the multi-TeV scale. Thus Muon Accelerators offer the unique potential, among the accelerator concepts currently being discussed, to provide world-leading experimental capabilities for physics at both the Intensity and Energy Frontiers.

THE MAP FEASIBILITY ASSESSMENT

The U.S. Muon Accelerator Program (MAP) has the task of assessing the feasibility of Muon Accelerators for Neutrino Factory (NF) and Muon Collider (MC) applications. Critical path R&D items, which are important for the performance of these facilities, include:

- Development of a high power target station capable of handling ≥4 MW of power. Liquid metal jet technology has been shown to be capable of handling this amount of power [3]. However, a complete engineering design of a multi-MW target station with a high field capture solenoid (nominal 20 T hybrid normal and superconducting magnet with ~3 GJ stored energy) requires considerable further work. The possibility to pursue a staging scenario, starting with a 1 MW class target, removes considerable technical risk and will benefit from developments at other facilities (e.g., spallation sources) that are presently exploring multi-MW class target stations.
- Muon cooling, which is required in order to achieve the beam parameters for a high performance NF and for all MC designs under consideration. An ionization cooling channel requires the operation of RF cavities in tesla-scale magnetic fields. Promising recent results from the MuCool Test Area (MTA) at Fermilab point towards solutions to the breakdown problems of RF cavities operating in this environment [4-6].
- Evaluation of collective effects for high intensity and low energy beams (in the ~200 MeV/c and lower range for muon ionization cooling). Assessing the likely impact of these effects on the muon beams required for NF and MC applications is an important deliverable of the MAP feasibility assessment.
- For the MC, a new class of backgrounds from muon decays impacts both the magnet/shielding design for the collider itself and the backgrounds in the detector. It has been found that the detector backgrounds can be managed by means of pixelated detectors with

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good time resolution [7,8]. Thus, this issue appears to present no impediment to moving forward with full detector studies and machine design efforts.

Results in each of these areas will inform a community decision on Muon Accelerator facilities.

THE MUON ACCELERATOR STAGING STUDY

A dedicated working group within MAP has been charged with evaluating potential staging options for a Muon Accelerator Facility. As part of this effort, baseline parameter specifications have been developed for a series of facilities, each capable of providing cutting edge physics output. In addition, each stage is configured to allow evaluation of the performance of systems required for the next stage. The plan thus provides clear decision points before embarking upon each subsequent stage. The staging plan under consideration builds on, and takes advantage of, existing or proposed facilities, specifically:

- Project X at Fermilab as the MW class proton driver for muon generation;
- Homestake as developed for the LBNE detector, which could then house the detector for a long baseline Neutrino Factory (NF).

The performance characteristics of each stage provide unique physics reach:

- νSTORM: a short baseline Neutrino Factory enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long baseline experiment [9].
- L3NF: an initial long baseline NF, optimized for a detector at Homestake, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology.
- NF: a full intensity NF, upgraded from L3NF, as the ultimate source to enable precision CP violation measurements in the neutrino sector.
- Higgs Factory: a collider whose baseline configurations are capable of providing between 5,000 and 40,000 Higgs events per year with exquisite energy resolution [10,11].
- Multi-TeV Collider: if warranted by LHC results, a multi-TeV MC may offer the best performance and least cost for any lepton collider operating in the 1-10 TeV energy regime.

Nominal parameters for a short baseline NF (νSTORM) and two stages of a long baseline NF optimized for a detector located at Homestake are provided in Table I. MC parameters for two stages of a Higgs Factory as well as 1.5 TeV and 3.0 TeV colliders are provided in Table II. Each of these machines would fit readily within the footprint of the Fermilab site. The ability to deploy these facilities in a staged fashion offers major benefits:

1. The strong synergies among the critical elements of the accelerator complex maximize the size of the experimental community that can be supported by the overall facility;
2. The staging plan reduces the investment required for each stage to levels that will hopefully fit within the future budget profile of the U.S. High Energy Physics Program.

Table I: Neutrino Factory Staging Parameters

Parameter	Unit	νSTORM	L3NF	NF
Stored μ^+ or μ^-/yr	Per species	8×10^{17}	2×10^{20}	1.2×10^{21}
ν_e or ν_μ to detector/yr		3×10^{17}	8×10^{19}	5×10^{20}
Far Detector	Type	SuperBIND*	Mag. Liq Ar	Mag Liq Ar
Det. Baseline	km	1.5	1300	1300
Ring Mom.	GeV/c	3.8	5	5
p-Driver P	MW	0.2	1	3
p-Driver E	GeV	60	3	3
p/yr	10^{21}	0.2	41	125
Rep. Freq.	Hz	1.25	70	70

* A Magnetized Liquid Argon Detector also possible.

Table II: Muon Collider Baseline Parameters

Parameter	Unit	Higgs Factory		Multi-TeV	
E_{CM}	TeV	0.126	0.126	1.5	3.0
Avg. Lumi.	10^{34} cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
δE_{beam}	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. IPs		1	1	2	2
Rep. Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
μ/bunch	10^{12}	2	4	2	2
n_{bunch}/beam		1	1	1	1
ε_{TN}	mm-rad	0.4	0.2	0.025	0.025
ε_{LN}	mm-rad	1	1.5	70	70
σ_s	cm	5.6	6.3	1	0.5
Beam Size @IP	μm	150	75	6	3
Beam-Beam Parameter/IP		0.005	0.02	0.09	0.09
p-Driver P	MW	4#	4	4	4

Could begin operation at lower beam power (eg, PX Stage II).

THE MAP TIMELINE

νSTORM's capabilities could be deployed now. The NF options and initial Higgs Factory could be based on the 3 GeV proton source of Project X Stage II operating with 1 MW and, eventually, 3 MW proton beams. This opens the possibility of launching L3NF, which requires no muon cooling, by the next decade. Similarly, the R&D required for a decision on a collider could be completed by the middle of the next decade.

This timeline is summarized in Figure 1, which projects an informed decision point on proceeding with an NF by the end of this decade, and a similar decision point on the first MC by the middle of the next decade. An MC in the multi-TeV range would offer exceptional performance due to the absence of synchrotron radiation effects, no beamstrahlung issues at the interaction point, and anticipated wall power requirements at the 200 MW scale.

CONCLUSION

To summarize, Muon Accelerators can enable a broad and world-leading high energy physics program, which could be based on the infrastructure of the sole remaining U.S high energy physics laboratory, Fermilab. While any decision to move forward with Muon Accelerator based technologies rests on the evolving physics requirements of the field, as well as the successful conclusion of the MAP feasibility assessment later this decade, the ability of Muon Accelerators to address crucial questions on both the Intensity and Energy Frontiers, as well as to provide a broad foundation for a vibrant U.S. HEP program, argues for a robust development program to continue. This will enable a set of informed decisions by the HEP community starting near the end of this decade.

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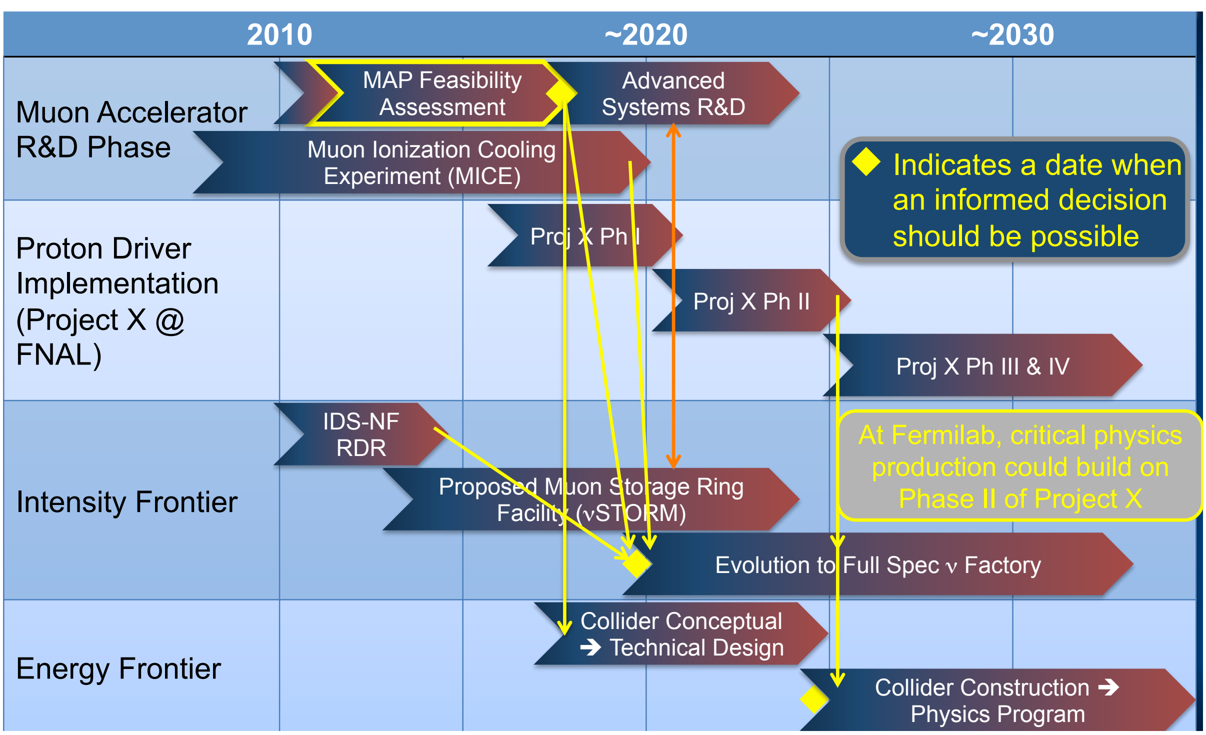

Figure 1: The MAP Timeline including the Feasibility Assessment period. It is anticipated that decision points for moving forward with a NF program supporting Intensity Frontier physics efforts could be reached by the end of this decade. A decision point for moving forward with a MC physics effort supporting a return to the Energy Frontier could be reached by the middle of the next decade. These efforts could build on Project X Stage II capabilities as soon as they are available. The development of a short baseline neutrino facility, i.e., νSTORM, would significantly enhance MAP research capabilities by supporting a program of advanced systems R&D.

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