AN OVERVIEW OF THE US MUON ACCELERATOR PROGRAM*

M.A. Palmer#
FNAL, Batavia, IL 60510, USA
for the MAP Collaboration

Abstract

The Muon Accelerator Program (MAP) is the U.S. organization tasked with carrying out the R&D necessary to evaluate the feasibility of future facilities based on muon accelerators. This includes research that could lead to the construction of a neutrino factory, Higgs factory and/or multi-TeV muon collider. Activities include design work for all stages of a muon accelerator complex, from the proton driver and target through the collider and/or muon decay rings, development of the critical technologies needed for such a facility, and support for experiments demonstrating key principles such as muon cooling (eg, the Muon Ionization Cooling Experiment). MAP coordinates a collaboration that includes participants from 18 U.S. institutions, which span the national laboratory system, universities and industry. The major research thrusts and goals as well as the structure of the research program are summarized.

INTRODUCTION

In 2008, the U.S. Particle Physics Project Prioritization Panel (P5) defined 3 frontiers that encompassed the major thrusts of the U.S. high-energy physics program [1,2]: the Energy, Intensity and Cosmic Frontiers. Together, research across these three frontiers explores the nature of the origin of the universe and the fundamental forces with which it operates. A principal motivation for a research program to develop a Muon Accelerator capability is the fact that such machines can support a cutting edge research program that spans both the Intensity and Energy Frontiers. On the Intensity Frontier, a Neutrino Factory (NF) would provide the most precise and intense source of electron and muon neutrinos that has ever been conceived. Such a facility could provide a beam containing 5×10^{20} ν_e and ν_μ, each, to a far detector. Such capability would enable measurements of CP violation in the neutrino sector with comparable precision to measurements that have been made with the B-factories in the quark sector. At the boundary between the Intensity and Energy Frontiers, Muon Accelerators also offer a route to a Muon Collider designed for very small energy spread at a center-of-mass energy corresponding to the Higgs mass. By utilizing s-channel production of the Higgs, current machine designs are projected to provide roughly 40,000 Higgs decays per year [3,4]. The very small energy spread of such a machine, $\delta E/E$~$3\text{-}4\times10^{-5}$, would enable a direct measurement of the Higgs width. Finally, such a facility would provide a route to an Energy Frontier Muon Collider (MC) in the 1-10 TeV center-of-mass energy range, which would be able to exploit any TeV-scale discoveries by the Large Hadron Collider (LHC).

THE U.S. MUON ACCELERATOR PROGRAM

The U.S. Muon Accelerator Program (MAP) was approved in early 2011 to assess the feasibility of the technologies required for the construction of a high intensity Neutrino Factory (NF) and a Muon Collider (MC). The MAP effort grew out of the merger of two previous efforts: the Neutrino Factory Muon Collider Collaboration (NFMCC) and Fermilab's Muon Collider Task Force (MCTF). The program is taking an approach where the feasibility assessment is sub-divided into 3-year phases, with clear deliverables and intermediate assessments specified for each phase. In anticipation of a successful conclusion of the feasibility assessment, the goal of MAP is to prepare a proposal, by the end of this decade, for a follow-on effort to develop the detailed technical design for a Muon Accelerator Facility, which can support both NF and MC capabilities.

Figure 1 shows the major accelerator sub-systems required to support a NF and MC. Many of the major systems could be shared for the two applications. The major components of these facilities include:

- [NF+MC] A high intensity, multi-MW class ***Proton Driver*** that is able to provide a suitable bunch structure to a high power target. At Fermilab, the proton driver would be based on Project X [5]. An initial implementation, with 1 MW of incident proton power based on Stage II of Project X, could support operation of the first long baseline NF.
- [NF+MC] A ***Target*** and high-field (~20 T) ***Capture Solenoid***, which ultimately must be capable of operation at 4 MW of incident proton power. The MERIT experiment has demonstrated the ability of a liquid Hg jet target to operate at up to 8 MW of incident beam power [6].
- [NF+MC] A ***Front End*** where the muon beam is bunched and phase rotated to provide a bunch train containing both species. For the NF application, an initial stage of 4D ionization cooling channel is the last accelerator system of the front end. For an MC, a full 6D cooling channel begins at this point. It should be noted that, in a dual-use facility, incorporation of the 6D cooling channel could also benefit NF performance.

*Work supported by US DOE under contract DE-AC02-07CH11359.
#mapalmer@fnal.gov

ISBN 978-3-95450-140-3

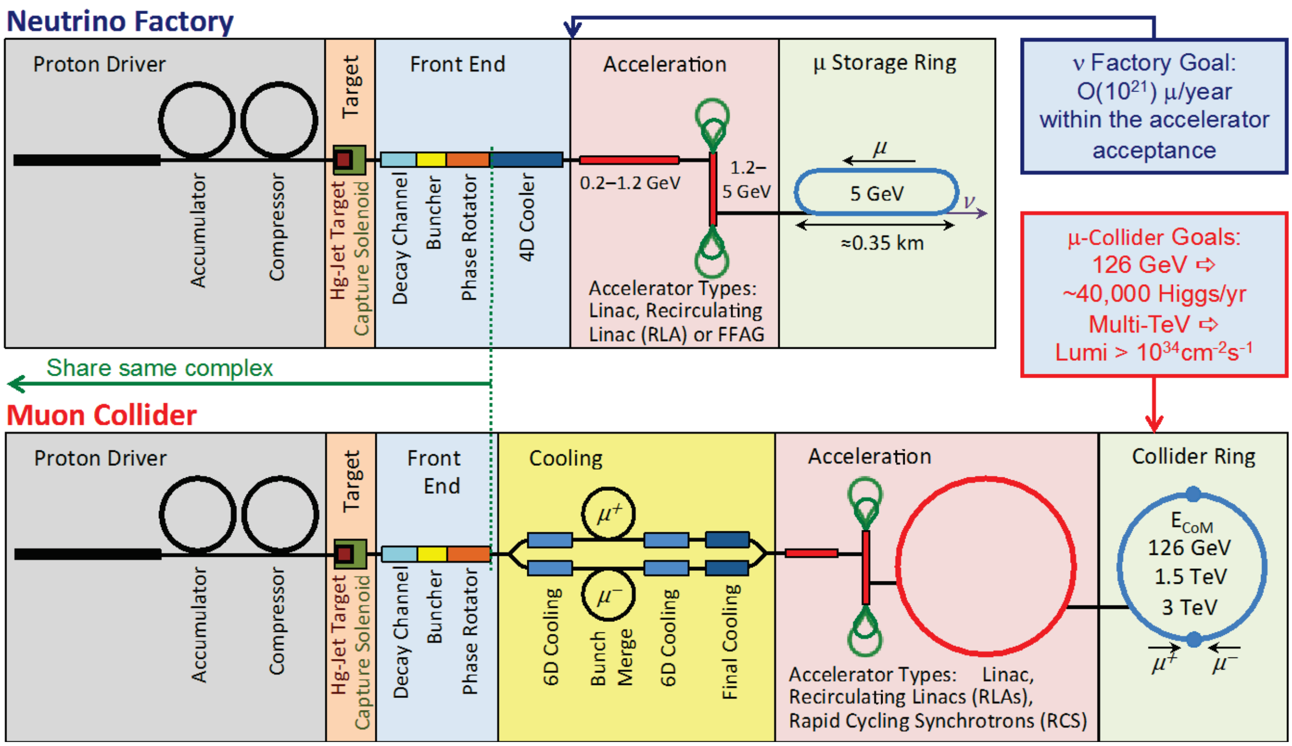

Figure 1: Block diagrams showing the principal elements of a Neutrino Factory (NF) and a Muon Collider (MC). In a dual-purpose facility, it is envisioned that the NF and MC will operate with a shared proton driver, target and front end.

- [NF] An ***Acceleration*** system including a linac followed by either a Recirculating Linear Accelerator (RLA) or Fixed-Field Alternating Gradient (FFAG) ring to accelerate the muon beam to the final NF energy, ~5 GeV for a NF located at Fermilab.
- [NF] A ***Muon Storage Ring*** with straights pointed at a suitable detector. For an implementation at Fermilab, this would be a ~5 GeV racetrack with straights pointed to an underground detector located at the Sanford Underground Research Facility (SURF), a baseline of ~1300 km. The initial implementation of this facility has been designated NuMAX (**Neu**trinos from **M**uon **A**ccelerators at Project **X**).
- [MC] A ***6D Cooling*** system capable of reducing the 6D beam emittance by several orders of magnitude. Figure 2 shows the evolution of the emittance down the length of such a channel. Depending on the collider application, the stopping point in the emittance plane may vary. For the Higgs Factory application, which requires the smallest possible beam energy spread to characterize the Higgs width, the stopping point would be the red point at the bottom of the plot. In order to obtain sufficient luminosity for TeV-scale colliders, reaching the upper left point is required. Some applications, e.g. operating near the ttbar threshold, could be optimized by cooling to an emittance value somewhere on the line joining these two points, thus trading off energy resolution versus luminosity.
- [MC] An ***Acceleration*** system to bring the beam energy to the specified beam energy of the collider ring. The first stages of acceleration could re-use the acceleration stages of the NF. For a Higgs Factory operating with a ~63 GeV beam energy, further acceleration could be provided by either an RLA or a Rapid Cycling Synchrotron (RCS). In order to reach TeV-scale beam energies, an RCS is likely the only effective choice.
- [MC] ***Collider Rings*** which could support operation as a Higgs Factory at a CM energy of ~126 GeV up to multi-TeV energy scales. It should be noted that the nominal circumference of a Higgs Factory would be ~300 m while TeV-scale rings would be a few to several kilometers in circumference, where dipoles with 10T fields have been assumed. Each of these possibilities would readily fit on the Fermilab site.

MAP R&D PRIORITIES

A key deliverable for the MAP Feasibility Assessment is a detailed design concept for each of the major elements in the accelerator complex as described in the previous section. Thus an immediate priority is the formal selection of an initial baseline design for each system. The process of developing and evaluating designs with the necessary level of detail is underway. It is expected that the initial baseline will be in place on the 2015 timescale. These designs will then be used to guide further technology R&D and to evaluate the anticipated performance of the final complex.

ISBN 978-3-95450-140-3

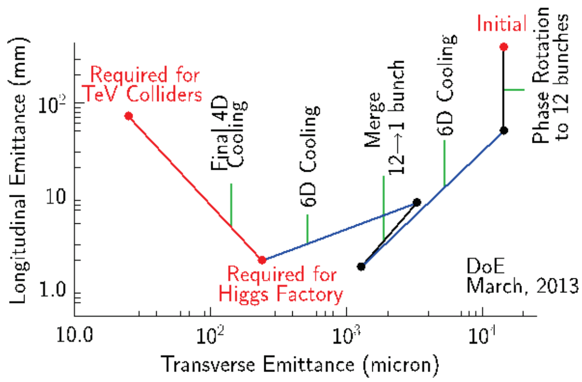

Figure 2: Emittance evolution along a 6D ionization cooling channel for a Muon Collider (MC). The entrance to the channel is the point at the upper right of the plot. The very small energy spread required for a Higgs Factory could be obtained by stopping at the bottom red point. Smaller transverse emittances, and hence higher luminosities for TeV-scale colliders, would require letting the cooling continue to the upper left red point.

There are a number of unique technology R&D challenges that must be successfully addressed to enable a Muon Accelerator Facility. Four of the most challenging issues are listed here:

- Development of a high power target station capable of handling ≥4 MW of power. While the MERIT experiment has demonstrated the potential of liquid metal jet technology, the complete engineering design of a multi-MW target station with a high field capture solenoid (the nominal design includes a 20 T hybrid magnet with ~3 GJ stored energy) remains challenging. Pursuing a staging scenario, which starts with a 1 MW class target, removes considerable technical risk initially and will allow the higher power design to benefit from developments at other facilities (e.g., spallation sources) with similar needs.
- Muon cooling, which is required in order to achieve the beam parameters for a high performance NF and for all MC designs under consideration. MAP is a participant in the Muon Ionization Cooling Experiment (MICE), which will demonstrate the principals of 4D cooling required for a NF [7]. MAP is pursuing two principal technology paths for the 6D ionization cooling channel, the Helical Cooling Channel, based on high pressure RF cavity technology [8], and a second concept based on vacuum RF technology with discrete absorbers [9]. 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 [10-12].
- Evaluation of collective effects for high intensity muon beams which must be manipulated at very low energies (eg, ~200 MeV/c in the cooling channel). 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 good time resolution [13,14]. 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 AND MAP TIMELINE

A dedicated working group within MAP has been charged with evaluating potential staging options for a Muon Accelerator Facility [15]. In this scenario, each stage should be capable of providing cutting edge physics output, while also enabling the evaluation of the systems required for operation of the subsequent stage. Thus, clear decision points are provided throughout the process for moving forward with the facility. The staging plan assumes:

- Project X at Fermilab as the MW class proton driver for muon generation;
- The Sanford Underground Research Facility (SURF) as the location housing the detector for a long baseline NF.

The performance characteristics of each stage provide unique physics reach:

- νSTORM: an initial short baseline NF which can provide a definitive search for sterile neutrinos as well as neutrino cross-section measurements that will ultimately be required in support of high precision measurements at any long baseline experiment [16].
- νMAX: an initial long baseline NF, optimized for a detector at SURF, which will provide a neutrino source that exceeds the capabilities of conventional superbeam technology.
- Super νMAX: a full intensity NF, 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 [3,4].
- 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 SURF are provided in Table 1. MC parameters for two stages of a Higgs Factory as well as 1.5 TeV and 3.0 TeV colliders are provided in Table 2. Each of these machines would fit readily within the footprint of the Fermilab site.

ISBN 978-3-95450-140-3

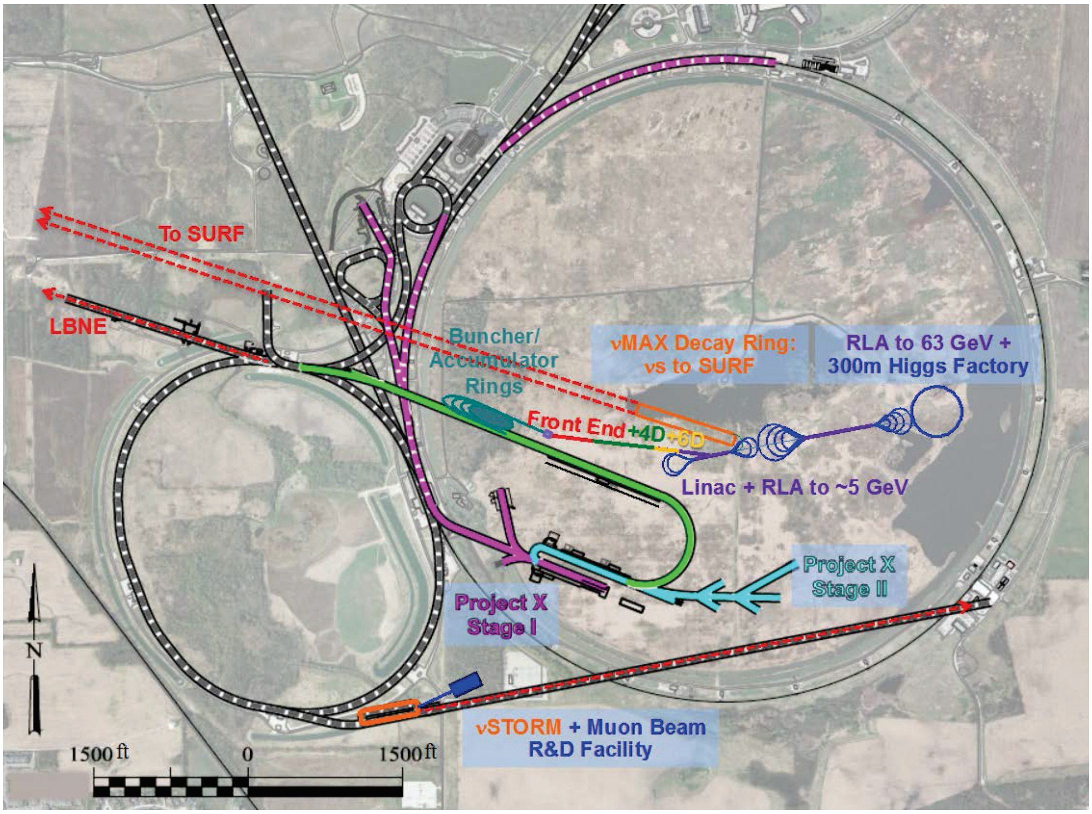

Figure 3: A staged facility, from νSTORM through the implementation of a Higgs Factory, on the Fermilab site. The second stage, implementation of the NuMAX Neutrino Factory capability, could be built on the foundation of the Project X Stage II CW Linac operating at 3 GeV proton energy.

νSTORM could be deployed now, while NuMAX and the 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. A timeline representing these stages along with the decision points that will be enabled by the MAP Feasibility Assessment are shown in Figure 4.

Table 1: Neutrino Factory Staging Parameters

Parameter	Unit	νSTORM	νMAX	Super νMAX
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 2: 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}	π mm-rad	0.4	0.2	0.025	0.025
ε_{LN}	π 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).

ISBN 978-3-95450-140-3

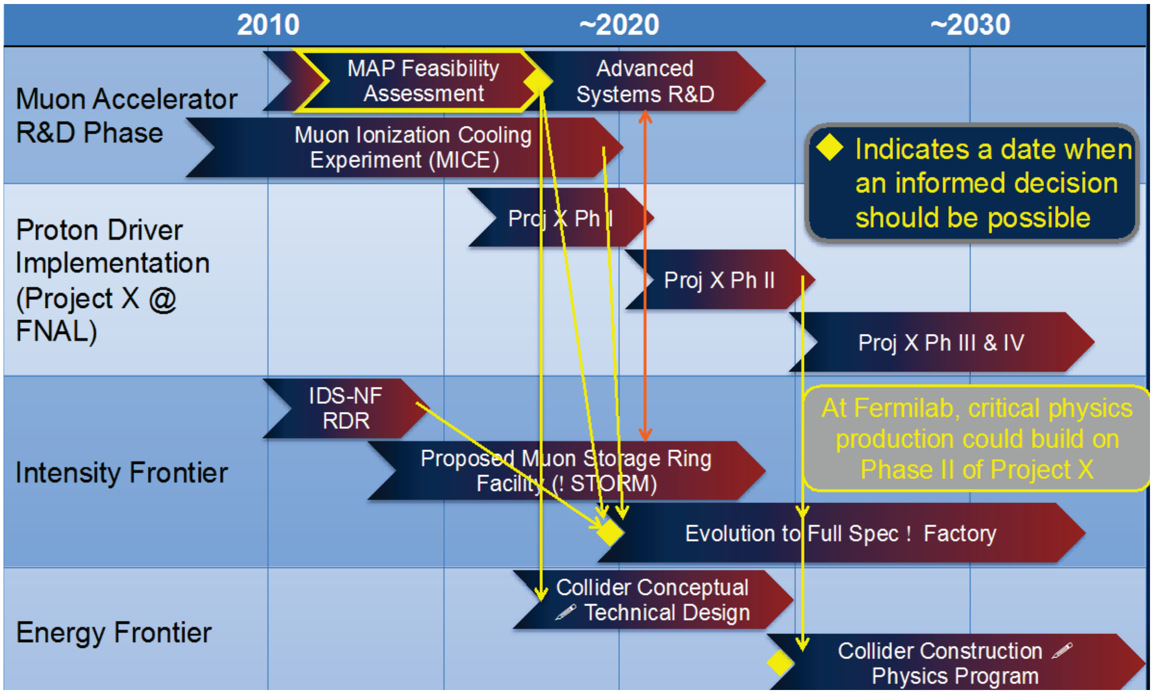

Figure 4: The MAP Timeline including the Feasibility Assessment period. It is anticipated that decision points for moving forward with a NF program supporting Intensity Frontier physics efforts could be reached by the end of this decade. A decision point for moving forward with a MC physics effort supporting 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.

CONCLUSION

In closing, there is great potential for Muon Accelerators to serve as the foundation for a world-class high energy physics program that spans both neutrino and collider physics efforts. The program is well matched to capabilities and infrastructure that are presently being developed at Fermilab. While the ultimate decision to move forward with such program depends on both the successful demonstration of the required technologies and the physics requirements of the field, the potential for such a facility to address crucial questions spanning the Intensity and Energy Frontiers argues strongly for a vibrant R&D effort to continue. We anticipate that this will allow an informed decision on proceeding with a NF by the end of this decade and another informed decision on a MC option by the middle of the next decade.

REFERENCES

[1] "U.S. Particle Physics: Scientific Opportunities, A Plan for the Next Ten Years," Report of the Particle Physics Project Prioritization Panel, May 29, 2008, http://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf.

[2] "Recommendations on the Extended Tevatron Run," Report of the Particle Physics Project Prioritization Panel, October 26, 2010, http://science.energy.gov/~/media/hep/pdf/files/pdfs/p5report2010final.pdf.

[3] D.V. Neuffer *et al.*, TUPFI056, Proc. IPAC 2013, Shanghai, China, p.1472.

[4] A. Zlobin *et al.*, TUPFI061, Proc. IPAC 2013, Shanghai, China, p.1487.

[5] "Project X Reference Design Report," The Project X Collaboration, v1.01, June 4, 2013,http://ProjectX-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=776;filename=RDR-v1.01.pdf;version=4

[6] K. McDonald, *et al.*, WEPE078, Proc. IPAC 2010, Kyoto, Japan, p. 3527.

[7] D. Kaplan, MOAM2HA01, Proc. COOL'13. Switzerland.

[8] R. Johnson, MOAM2HA03, Proc. COOL'13. Switzerland.

[9] R. Palmer, MOAM2HA04, Proc. COOL'13. Switzerland.

[10] K. Yonehara *et al.*, TUPFI059 (and references therein), Proc. IPAC 2013, Shanghai, China, p.1481.

[11] D. Bowring *et al.*, THPPC033, Proc. IPAC 2012, New Orleans, LA, USA, p. 3356.

[12] Z. Li *et al.*, THPPC040, Proc. IPAC 2012, New Orleans, LA, USA, p. 3371.

[13] A. Mazzacane, Muon Collider Detector Studies, presented at the HFMC Workshop, UCLA, March 21-23, 2013, https://hepconf.physics.ucla.edu/higgs2013/talks/mazzacane.pdf

[14] A. Conway and H. Wenzel, Higgs Measurement at a Muon Collider, April 22, 2013, http://arxiv.org/pdf/1304.5270

[15] M.A. Palmer *et al.*, TUPFI057, Proc. IPAC 2013, Shanghai, China, p.1475.

[16] P. Kyberd *et al.*, "nuSTORM: Neutrinos from STORed Muons," http://arxiv.org/abs/1206.0294

ISBN 978-3-95450-140-3