

Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab

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Abstract

A wider variety of world-leading muon beams and experiments can be developed at Fermilab, alongside and following the present $g-2$ and Mu2e experiments. The MW-scale 800 MeV PIP-II beam is ideally designed to drive a next generation of low-energy muon beams to higher intensities. The Mu2e experiment will be the world's highest-intensity low-energy muon facility, and its beam could be extended to further precision muon studies, both before and after the turn-on of PIP-II. Other experiments could include $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ searches, muonium studies, and a world-leading muSR facility.

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1 Introduction

Muon experiments offer unparalleled access to fundamental questions of physics beyond the Standard Model [1]: Do charged leptons (like their neutral partners) violate flavor symmetry? Are there new forces weaker than the Weak Force? Do antileptons experience gravity identically to leptons? To address these questions, the next generation of precision muon and muonium experiments [2], such as muon $g - 2$ and EDM measurements [3–5], $\mu \rightarrow e$ conversion searches [6], muonium spectroscopy studies [7, 8], and muonium gravity measurements [9, 10], require high-intensity muon beams at low energy with small transverse size and/or energy spread.

A high-quality positive-muon beam (called a surface muon beam) can be obtained from the decay at rest of positive pions produced in, and stopped near the surface of, a thin target. If these muons exit perpendicular to the surface, they are relatively monoenergetic and polarized — ideal for experiments in which muons are stopped in thin material samples. The surface muon beam approach works best for μ^+ , since stopped π^- and μ^- tend to be captured by atoms. (There is another family of experiments possible with muonic atoms [2].) The decay of low-energy pions that are not stopped provides a broader momentum spectrum of positive and negative “cloud” muons, which may also be useful for experiments.

In addition to their use for fundamental physics experiments, surface muons have important applications in materials science, chemistry, and biology. When polarized muons stop in a sample, their spin precession prior to decay analyzes the local magnetic field, providing key information about the sample’s microstructure. This has led to a small “industry” of muon spin rotation (μ SR) facilities and users around the world. There are no such facilities within the U.S., although creation of a muon facility at Oak Ridge has been proposed [11].

Surface muon beams are available at TRIUMF in Canada, J-PARC and MuSIC in Japan, PSI in Switzerland, and ISIS in the U.K. PSI is currently the record holder for surface-muon beam intensity. As such, it hosts, and has hosted, many of the world’s leading experiments: MEG, Mu3e, MuLAN, FAST, CREMA, and more [2]. With the coming PIP-II intensity upgrade [12], Fermilab’s low-energy muon facility will offer the opportunity to serve both the fundamental-muon-experiment and μ SR communities and make Fermilab an unrivaled center for low-energy muon science.

A different type of muon beam is used for the Mu2e experiment [6]: pions are produced from proton interactions in a target immersed within a magnetic field. Those pions are focused by a solenoidal magnetic field and their decay in flight produces a broad spectrum of muons of both signs. The Mu2e apparatus selects and transports backward pions and muons (plus some magnetically reflected forward ones) towards a stopping target, where muons captured in atomic orbits can convert to electrons ($\mu^- N \rightarrow e^- N$) or decay ($\mu \rightarrow e \nu \bar{\nu}$), and the experiment selects for neutrinoless conversion events. This approach can produce high-intensity beams (both μ^+ and μ^-) suitable for a variety of experiments. (Most of the forward-produced pions, which have a broader, higher-energy distribution, are not used by Mu2e.)

2 Beam Design Approaches

Table 1 summarizes surface muon rates at current and future facilities. Cyclotron-based muon sources are intrinsically continuous while synchrotron-based ones are pulsed. (The μ SR technique can be employed in either mode.) Experiments such as the (as yet unnamed) future successor to MEG II, Mu3e Phase II, and the proposed MAGE [9] (among others) require at least an order-of-magnitude higher muon rate than currently available. To meet these needs, a “high-intensity muon beam” (HIMB), such as that discussed at PSI, is under study [13]. Of these experiments, those (e.g., MEG and Mu3e) detecting multi-particle final states, and thus limited by accidental coincidences, require continuous beam, while others (e.g., Mu2e and muonium studies) do not, with background suppression in Mu2e requiring a pulsed beam. It is notable that the Mu2e beam will

Table 1: Comparison of Surface Muon Facilities and Mu2e

Facility	Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	9×10^8	CW	
TRIUMF [15]	2×10^6	CW	
MuSIC at Osaka [16]	10^8	CW	
J-PARC [17]	6×10^7	pulsed	
ISIS [17]	6×10^5	pulsed	
HIMB at PSI [13]	10^{10}	CW	(design goal)
Mu2e at Fermilab	10^{11}	pulsed	Not surface muons: $p_\mu \approx 40 \text{ MeV}/c$
Mu2e with PIP-II	10^{12}	pulsed	Not surface muons: $p_\mu \approx 40 \text{ MeV}/c$

be approximately an order of magnitude more intense than that at HIMB, and the PIP-II Fermilab upgrade will increase Mu2e’s intensity by a further order of magnitude.

The intense Fermilab muon beam naturally raises the question whether other world-leading muon experiments could also be hosted there. Various approaches could be considered, including using the exit muon beam from Mu2e (which would be unpolarized) or using a beam window as a surface-muon production target. For example, the Mu2e proton beamline will have two vacuum windows [18], typically 3 mil Ti, or 2.8×10^{-4} nuclear interaction lengths thick. While $\sim 10^{20}$ 8 GeV protons will traverse them per year, the production rate of surface muons in such thin windows is many orders of magnitude too low to be competitive. Since the thickness of beamline windows is constrained primarily by beam multiple Coulomb scattering, if such a window were made of LiH it could be 90 mils thick and might produce $\sim 10^7$ surface muons/s. With some optimization it may be possible to increase this rate, and with PIP-II it will increase by an order of magnitude.

As indicated in Table 1, the muon beam exiting Mu2e will be substantially more intense than the above, but it may lack some desired features; for example, having passed through the Mu2e apparatus it will likely be less well localized and collimated. Since normal Mu2e operation requires μ^- , the polarity could be flipped to capture μ^+ only during periods when Mu2e is not operating. The Mu2e duty factor (230 ns of 8 GeV proton beam every $1.7 \mu\text{s}$ [18]) is suboptimal for applications that call for a different pulse structure or a DC beam. More time-structure flexibility will be possible with the PIP-II CW superconducting 800 MeV proton linac, which could also serve multiple $\pi \rightarrow \mu$ production targets and beamlines. The design of a target for an 800 MeV beam of 100 kW or higher power is an unsolved problem that is under investigation [19].

For muonium experiments, a novel and promising approach has been proposed: stopping slow muons in superfluid helium [20, 21]. This could yield an intense, monoenergetic, collimated, slow muonium beam in vacuum that could be used as is [9], or ionized to serve muon experiments [22].

3 R&D

To enhance progress on beam design in the interim period before a new facility can be built, an R&D platform would be extremely useful and, for some applications (e.g., muonium production in SFHe), even crucial. This could be provided by adding muon-beam capability to the “MuCool Test Area” (MTA) at Fermilab [23], or (at lower intensity) using the Fermilab Test Beam Facility (FTBF). Other options may also be available.

4 Conclusion

We propose to study the options for providing competitive surface-muon or comparable low-energy muon beams at Fermilab in the Mu2e and PIP-II “eras.” This study can inform proposals for world-leading low-energy muon experiments at Fermilab.

References

- [1] A. De Gouvêa, P. Vogel, Prog. Part. Nucl. Phys. **71**, 75 (2013); arXiv:1303.4097 [hep-ph].
- [2] T. Gorringer and D. Hertzog, Prog. Part. Nucl. Phys. **84**, 73 (2015).
- [3] H. Iinuma, J. Phys. Conf. Ser. **295**, 012032 (2011).
- [4] A. Adelmann, K. Kirch, C. J. G. Onderwater, and T. Schietinger, J. Phys. G Nucl. Part. Phys. **37**, 085001 (2010).
- [5] A. Crivellin, M. Hoferichter, and P. Schmidt-Wellenburg, Phys. Rev. D **98**, 113002 (2018).
- [6] R. H. Bernstein, P. S. Cooper, Phys. Rep. **532**, 27 (2013); <https://doi.org/10.1016/j.physrep.2013.07.002>.
- [7] K. Jungmann, “Muonium - Physics of a most Fundamental Atom,” Nucl. Phys. B (Proc. Suppl.) **155** (2006) 355.
- [8] P. Crivelli, Hyperfine Interact. **239**, 49 (2018).
- [9] A. Antognini et al., Atoms **6**, 17 (2018); doi:10.3390/atoms6020017.
- [10] K. Kirch and K. S. Khaw, Int. J. Mod. Phys. Conf. Ser. **30**, 1460258 (2014), Proc. 2nd Int. Workshop Antimatter and Gravity (WAG2013); arXiv:1509.02918.
- [11] See <https://www.ornl.gov/event/opportunities-seems-facility> and <https://traviswilliams.ornl.gov/seems/> (accessed 5/13/2020).
- [12] V. Shiltsev, “Fermilab Proton Accelerator Complex Status and Improvement Plans,” Mod. Phys. Lett. A **32** (2017) 1730012; FERMILAB-PUB-017-129-APC (2017).
- [13] K. Kirch et al. (eds.), Particle Physics and Related Topics at the Paul Scherrer Institute: Input to the European Strategy process, <https://indico.cern.ch/event/765096/contributions/>, No. 121.
- [14] T. Prokscha *et al.*, “The new μ E4 beam at PSI: A hybrid-type large acceptance channel for the generation of a high intensity surface-muon beam,” Nucl. Instrum. Meth. A **595** (2008) 317, <https://doi.org/10.1016/j.nima.2008.07.081>.
- [15] “Muon Beamlines at TRIUMF,” web page, <http://cmms.triumf.ca/equip/mubeamlines/node1.html#tabbeamlines> (accessed 4/21/2020).
- [16] Y. Hino *et al.*, “A Highly intense DC muon source, MuSIC and muon CLFV search,” Nucl. Phys. B Proc. Suppl. **253–255** (2014) 206, XII Int. Workshop on Tau-Lepton Phys. (TAU2012). ; <https://doi.org/10.1016/j.nuclphysbps.2014.09.051>.
- [17] N. Kawamura, “Muon beamlines and Target Technologies at J-PARC,” presented at Compact muon sources workshop, Univ. of Huddersfield, 12–13 Jan. 2015, https://indico.cern.ch/event/356972/contributions/1766762/attachments/710282/975044/FutureMuonSources_20150112.pptx (accessed 4/21/2020).
- [18] Mu2e Document 4299-v15: Mu2e Technical Design Report (TDR), Ch. 4 Accelerators, available from <https://mu2e-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4299> (accessed 4/28/2020).

- [19] V. S. Pronsikh *et al.*, “Target Station Design for the Mu2e Experiment,” Proc. IPAC2014, paper THPRI085 (2014).
- [20] D. Taqqu, “Ultraslow Muonium for a Muon beam of ultra high quality,” Phys. Procedia **17** (2011) 216.
- [21] D. Taqqu, “Compression and Extraction of Stopped Muons,” Phys. Rev. Lett. **97** (2006) 194801.
- [22] S. Kanda, “Muonium production target for the muon $g - 2$ /EDM experiment at J-PARC,” Nucl. Phys. B Proc. Supp. **253** 212 (2014), XII Int. Workshop on Tau-Lepton Phys. (TAU2012); <https://doi.org/10.1016/j.nuclphysbps.2014.09.054>.
- [23] A more ambitious scheme for a muon beam in the MTA is discussed in J. A. Johnstone, C. Johnstone, “Prospects for a Muon Spin Resonance Facility in the Fermilab Mucool Test Area,” Proc. IPAC2018, paper MOPML032 (2018).