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ADAPTATION OF THE FERMILAB PROTON SOURCE TO SUPPORT NEW MUON FACILITIES[*]

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Abstract

The PIP-II proton accelerator will provide the intensity sufficient to power a new generation of high energy facilities at Fermilab. Extension of that linac to higher energy with following acceleration and bunching rings could provide the intensity needed to feed a muon production target for a high-energy $\mu^+ - \mu^-$ collider. Scenarios using a rapid-cycling synchrotron or an ~8 GeV Linac are presented and discussed. Some near-term opportunities at Fermilab for muon collider R&D are introduced.

INTRODUCTION

Future colliders are an essential component of a global strategic vision for particle physics. The P5 report [1], and the 2020 European Strategy for Particle Physics Update, recommended long-range development of a ≈10 TeV parton mass Collider. A ≈ 10 TeV Muon Collider situated at Fermilab was cited as an intriguing possibility and the report recommended that Fermilab proton source development accommodate that possibility. [2] See Fig. 1.

In 2014 the MAP program was developing an initial design for a multi-TeV muon collider. The initial concept for its proton source was a 4 MW 8 GeV SRF linac followed by an accumulator and a compressor ring to generate intense proton pulses for pion and muon production. [3] An updated proton source design, based on currently developing muon collider requirements and technology, and adapted to Fermilab proton source expansion, is needed.

RECENT PLANNING FOR FERMILAB PROTON COMPLEX UPGRADES

The Fermilab proton complex delivers intense high-energy protons to produce a variety of secondary and tertiary beams for fundamental physics experiments. The Deep Underground Neutrino Experiment (DUNE) is a large liquid argon detector that will be constructed in Lead, South Dakota and the Long-Baseline Neutrino Facility (LBNF) is a new beamline constructed at Fermilab to deliver 120 GeV protons for the production of horn-focused neurino beams [4]. Together DUNE/LBNF will serve as the flagship particle physics experiment at Fermilab.

Simultaneously, Fermilab is in the process of the Proton Improvement Plan II (PIP-II) upgrade [5], which is projected to increase the 120 GeV beam power to at least 1.2 MW. PIP-II includes a new 2 mA CW-capable SRF linac to deliver 0.8 GeV H^- ions to the Booster, an upgrade of the Booster ramp rate from 15 Hz to 20 Hz, and number of smaller scale improvements for the reliability and performance of the machines.

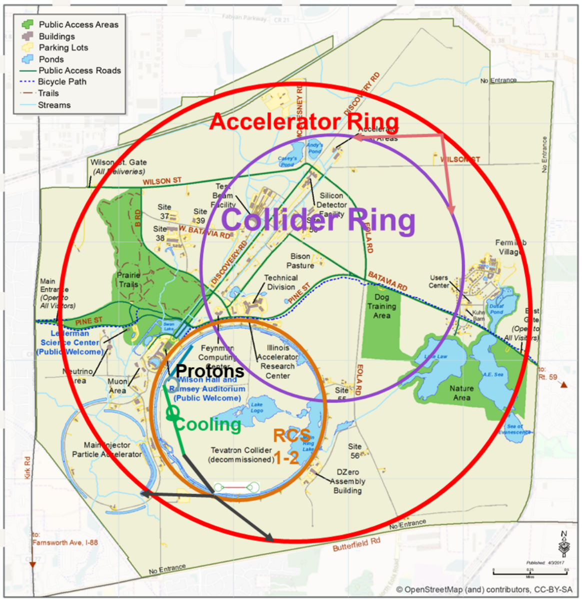

Figure 1: Diagram of how a muon collider facility could be built on the Fermilab site. The facility is designed for 10 TeV collisions (5 TeV μ^+ and μ^-).

The P5 report [1] affirmed support for the PIP-II and DUNE/LBNF projects in Recommendation 1b, and in Recommendation 2 also supports a newly proposed Fermilab upgrade known as Accelerator Complex Evolution Main Injector Ramp & Targetry (ACE-MIRT). The goal of ACE-MIRT is to achieve 2+ MW at 120 GeV for the DUNE/LNF program. Firstly, by reducing the Main Injector cycle time from 1.167 s to ~0.65 s, allocating greater portion of Booster cycles to the long-baseline neutrino program and fewer to the 8 GeV program. Secondly, by improving machine reliability and modernizing accelerator infrastructure. Next, by accelerating the pace of development for high-power low-Z neutrino targets. Lastly, with a new irradiated materials R&D program to anticipate the impact of the higher beam power on other targetry materials (used in horns, windows, baffles, girders, cooling manifolds etc.) Ideally, the ACE-MIRT upgrades would be in place coinciding with the projected completion of the mu2e experimental program (~ 2033) [6].

Table 1 displays the present, PIP-II era, and ACE-MIRT era capabilities of the Fermilab proton complex.

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Table 1: Parameters for Fermilab proton complex. *8-GeV beam power given for what is available simultaneous with 120-GeV program.

Linac	Achieved	PIP-II	ACE-MIRT
Current	20-25 mA	2 mA	2 mA
Energy	0.4 GeV	0.8 GeV	0.8 GeV
Booster	Present	PIP-II	ACE-MIRT
Intensity	4.8e12	6.5e12	6.5e12
Energy	8 GeV	8 GeV	8 GeV
Rep. Rate	15 Hz	20 Hz	20 Hz
8-Gev Power*	25 kW	80 kW	12-24 kW
Main Injector	Present	PIP-II	ACE-MIRT
Intensity	58e12	78e12	78e12
Cycle Time	1.133s	<1.2 s	~0.65 s
120-GeV Power	0.96 MW	~1.2 MW	1.9-2.3 MW

While the precise scope of ACE-MIRT is not yet completely determined, it presents several opportunities for synergistic muon collider R&D topics. The targetry R&D program could be expanded to include materials relevant for high-Z muon production targets or capture solenoids. The 12-24 kW available for the 8 GeV program (post-mu2e) will not be competitive for statistics-dominated HEP experiments, but may be suitable for a muon cooling demonstrator facility. Other opportunities for muon collider R&D leveraging existing expertise at Fermilab include design optimization, prototyping of technical components, and proton beams with extreme space-charge.

Leading up to the Snowmass/P5 process, Fermilab presented several detailed upgrade scenarios oriented towards enhancing beam delivery to the DUNE/LBNF program to 2.4 MW, replacing the Fermilab Booster, and adding new high-power beamlines (especially at 2 GeV and 8 GeV). As an evolution of the 2003 Proton Driver [7] and 2010 Project X scenarios [8], the Central Design Group (CDG) Accelerator Working Group Report explored “8-GeV Linac + 8-GeV AR” and “2-GeV Linac + 8-GeV RCS” scenarios, including analyses of project costs and technical risks [9–12].

This design effort, also called ACE Booster Replacement (ACE-BR), featured a level of detail and a contemporary view of the technology landscape that is highly relevant for future MuC proton driver (PD) scenarios. However, these scenarios were developed with a core-focus on the Fermilab long-baseline neutrino program, and (following P5 Recommendation 12) a new strategic plan for Fermilab must be developed to also include flavor and collider physics.

The ACE-BR Rapid-Cycling Synchrotorn (RCS) upgrade scenarios are challenging to reorient towards a MuC-PD, because of the space-charge limitations encountered in accumulating ~1e13 bunches at 2 GeV. The ACE-BR RCS would only end up being competitive design choice if the optimization of the proton compression and muon production were to favor much higher proton energies (12-24 GeV) than typically considered for a MuC-PD. The ACE-BR Linac scenarios however are highly relevant to a future Fermilab MuC-PD and a preliminary analysis will be presented in the next sections of this paper. Fig. 2 below shows a siting option for an 8-GeV Linac, 8-GeV AR, and some available beamline opportunities.

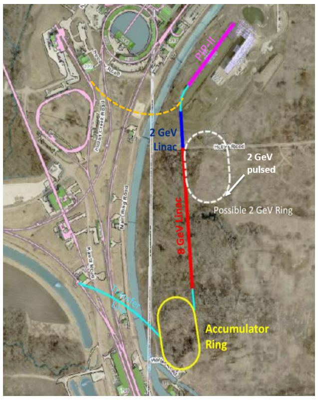

Figure 2: Possible siting of 8-GeV Linac and AR inside Tevatron footprint.

MUON COLLIDER PROTON DRIVER REQUIREMENTS

Fig. 3 shows the components of the MuC complex that consistute the proton driver. First a high-current, high-energy H^- linac. Next, an accumulator ring (AR) to the concentrate the charge into bunches. Optionally, a modest amount of acceleration may take place in the AR. Next a compressor ring (CR), usually considered a separate ring from AR, compresses each bunch into 1-3 ns long pulses with bunch rotation. Lastly, a combiner line which longitudinally superimposes and transversely juxtaposes the bunches to converge on the target as simultaneous and narrow pulse. The combiner can be avoided if the beam is accumulated in a single bunch, but generally requires larger accumulated beam emittance and superior linac performance.

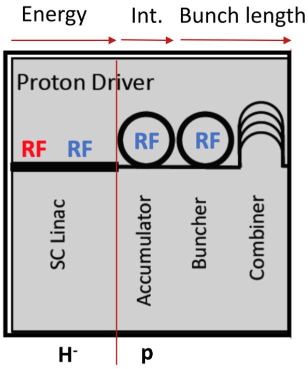

Figure 3: The MuC-PD consists a high-power H^- linac, an accumulator ring (AR), a compressor ring (CR), and then a combiner line to converge the bunches on target.

For a 10 TeV CoM muon collider, the muon decay rate at top energy is ~ 0.1s, and accordingly a 5-10 Hz repetition rate is appropriate. Muon production per kW proton beam is relatively flat over 5-10 GeV proton beam energies, decreasing slightly thereafter. During muon production, the time structure of the proton bunch is transferred to the initial muon beam, and therefore maximizing collider luminosity dictates that the bunch length should be kept to nanosecond-scale. To achieve the luminosity goal of ~20e34 $cm^{-2}s^{-1}$, the proton beam power should achieve or be upgradeable to 4 MW. Consistent with these requirements, we consider 10 Hz repetition rate, 8 GeV proton energy, 1-3 ns bunch length, and 4 MW beam power for Fermilab MuC-PD scenarios.

EXAMPLE FERMILAB PROTON DRIVER PARAMETERS

One of the ACE-BR scenarios considered is a 800 kW SRF Linac delivering 8 GeV H^- ions at a rate of 5 mA average over 2 ms every 10 Hz. This scenario uses ILC-style 1.3 GHz cavities, LCLS-II-style cryomodules, and E-XFEL-style klystron RF power sources [9, 10]. An upgrade of this linac scenario to 6-25 mA would correspond to 1-4 MW at 10 Hz suitable to MuC-PD parameters.

Next, the H^- particles will need to be strip-injected into 8 GeV Accumulator Ring (AR) to accumulate as protons. The traditional method of stripping H^- particles by passage through a carbon foil may lead rapid degradation of foil materials and excessive scattering losses. The emerging technology of H^- stripping assisted by laser systems, similar to those being developed at Oak Ridge Spallation Neutron Source (SNS) [13, 14] and at J-PARC [15], may allow for more reliable and lower loss H^- injection.

If the 2 ms macropulse with an average current of 25 mA is accumulated into four 20 ns pulses in a 300 m AR, then 92% of the beam must be chopped to acheive an appropriate micropulse structure and the instaneous beam current must reach 312 mA. Either pulses from multiple linac frontends will need to be interleaved into the high energy portion of the linac, or injected particles will need to be accumulated into larger than 20 ns windows.

Table 2: Example parameters for Fermilab proton driver.

Energy	8 GeV
Pulse Intensity	320 e12
Number of Bunches	4
Pulse Rate	10 Hz
Beam Power	4 MW
Bunch Length (AR)	20-40 ns
Bunch Length (CR)	1-3 ns
Ring Circumferences	300-500 m
95% Norm. Emittance	120-216 π mm mrad
Laslett Space-Charge limit	0.2-0.6

Table 2 shows a selection of possible parameters for a 4 MW Fermilab MuC-PD. Fixing the beam power, energy and pulse-rate sets the corresponding pulse intensity to 320e12 (four pulses of 80e12). For lower power scenarios, the power, intensity, and space-charge decrease proporationately. For an 8-GeV AR with conventional magnets, ~400-500 m is an appropriate ring circumference (allowing for at least 40 m H^- injection section, at least 250 m total for bending arcs, and 2-4 fold periodicity). With superconducting magnets, a 300 m circumference is achievable and would provide benefits for charge accumulation and space-charge compression.

In a separate Compressor Ring (CR) if not the same ring, each bunch must be compressed by a factor of 10-30 to achieve bunch lengths of 1-3 ns. At 3 ns and a stable Laslett space-charge tune-shift parameter of 0.2 (omitting the minus sign), the 95% normalized emittance must rise to 216 π mm mrad - a normalized emittance comparable to Oak Ridge Spallation Neutron Source (SNS), but with a required vertical aperture of only 7.5 cm.

To achieve 1 ns at full 4 MW (or to keep 3 ns but reduce the beam emittance by a factor of 3), the corresponding Laslett space-charge tune-shift parameter must rise to an extreme value of 0.6. Operational proton machines, such as the Fermilab Booster and CERN PSB have achieved similarly extreme space-charge parameters only for beams with considerable loss and undergoing rapid emittance blow-up.

Dedicated R&D on bunch compression under extreme space-charge could allow the CR design to be better optimized and to establish the ultimate performance limits of the MuC-PD. Recently, experiments for bunch compression under extreme space-charge has been proposed for the Fermilab Integrable Optics Test Accelerator (IOTA) [16] and at the Oak Ridge Spallation Neutron Source [17]. We also note a recent simulation study extrapolating bunch rotation beyond the performance of the GSI SIS-18 [18], which investigates similar research questions.

CONCLUSION

In PIP-II, LBNF, and ACE-MIRT, Fermilab has a comprehensive plan for upgrades to its proton accelerator complex that will take it through ~2033. Those upgrades will enhance proton delivery, modernize accelerator infrastructure, deploy SRF technology, advance high-power targetry, and build an international community of intensity frontier physics.

In Fermilab's near-term proton complex plans, there are many synergistic muon collider R&D opportunities including materials for high-power targetry, a muon cooling demonstrator, prototyping of technical components, and proton beam studies with extreme space-charge.

Although the DUNE/LBNF program provides a multi-decadal research program, preparation of the Fermilab accelerator complex for the post-DUNE research program should begin now, with a future muon collider program being a compelling opportunity. Here, we present an outline of a proton driver for a Fermilab muon collider facility for international feedback on key performance characteristics. It is also our hope that natural opportunities in muon collider staging can be identified for an expanded science program in neutrino, flavor, and dark-sector physics.

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