Development of Muon Accelerators for Neutrino Experiments

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Abstract. High-brilliance muon beams offer a unique potential for precision neutrino studies by providing intense neutrino beams with well-defined flavor content and energy spectrum. They also offer a path to improved precision searches for charged lepton flavor violation, and provide a basis for a next generation lepton-antilepton collider. The R&D for these muon facilities involves several technologies of which cooling the muon beam is a critical component. This talk will review progress on the development of the key technologies and their demonstration experiments.

1. Introduction
Muon-based accelerators provide a unique opportunity to address several of the outstanding questions in particle physics by enabling facilities at both the Intensity and the Energy Frontiers. Muon storage rings can serve as sources of intense neutrino beams (the Neutrino Factory concept), and can also enable a muon collider providing a precision leptonic probe at the multi-TeV scale. In addition, intense muon beams can enrich searches for charged lepton flavor violation.

In the neutrino sector, the discovery of neutrino oscillations has provided irrefutable evidence of physics beyond the Standard Model. As described elsewhere in these proceedings, there is a wide range of experiments underway and on the horizon aimed at measuring the neutrino mixing parameters. Beyond these experiments, the need for precision measurements will continue to drive future experiments. The Neutrino Factory (NF) remains the ultimate tool for precision neutrino studies by providing intense, extremely well-characterized beams of neutrinos and antineutrinos whose flavor content, energy spectrum, and flux can be known to better than 1%. In addition, since neutrino beams from muon decays contain equal fractions of $\nu_e$ and $\nu_\mu$, their cross sections can be directly measured thus minimizing uncertainties. These advantages along with the flexibility in neutrino energy make the NF the only facility that would allow precision measurements of the mixing parameters with sensitivities comparable with those achieved in the quark sector.

At the energy frontier, the fact that the muon is a point particle means that the full beam energy is available for particle production. Further, since the mass of the muon mass is much greater than that of the electron, there is almost no synchrotron radiation. This results in a narrower energy spread at the interaction point as compared with an $e^-e^+$ collider, and allows for a circular muon collider with a small footprint.
Muon storage rings and muon colliders (MC) were proposed a long time ago [1, 2]. The realization that high intensities and luminosities could be enabled by ionization cooling of muon beams [18] renewed interest in MC and NF [3] leading to the initiation of the International Design Study for a Neutrino Factory (IDS-NF) [5]. In the U.S, diverse R&D efforts towards a muon accelerator were brought under the umbrella of the Muon Accelerator Program (MAP) [4].

Figure 1 shows the IDS-NF’s baseline design layout of a NF, and Figure 2 shows the MAP scheme which includes designs for both a NF and a MC. The IDS-NF and MAP designs for a NF are similar and have comparable physics reach [17] and differ mainly in the final muon energy. In either case, a high-power MW-scale proton beam impacts a capable target and the produced pions decay into intense muon beams after which they are bunched and their energy spread reduced to prepare them for cooling. After cooling, the muon beams are accelerated to the desired energy and injected for circulation in a storage ring.

In the MAP design (Figure 2), it can be seen that both the NF and MC facilities share the same front-end up until initial cooling. This synergy in technology allows for a shared R&D effort and a staged implementation. The Muon Accelerator Staging Study (MASS) under MAP has developed a staging scenario [11] specifically in the context of the U.S high energy program. The key feature of the plan is that it builds up in complexity and provides valuable physics reach at each stage while at the same time enabling the R&D demonstrations for the succeeding, more complex, stages. The plan starts with:

(i) nuSTORM [12, 13]: a NF-like storage ring providing a definitive search for light sterile neutrinos, as well as neutrino-nucleon cross section measurements needed for long baseline experiments such as DUNE, and at the same time serving as a test bed for 6D muon cooling R&D, followed by:

(ii) NuMAX [14]: an “entry-level” low-intensity NF optimized for the long baseline from Fermilab to the Sanford Underground Research Facility, and enabling $\delta\text{CP}$ measurement with sensitivities already rivaling several long baseline neutrino experiments;

(iii) NuMAX+: a full intensity NF, upgraded from NuMAX, with an order of magnitude increase in intensity and physics reach similar to that of the IDS-NF baseline, enabling the CP measurements with sensitivities surpassing superbeam experiments;

(iv) Higgs factory: a $\mu^+\mu^-$ collider with a small footprint and superb energy resolution: the synergies between NF and MC technologies means that several components from the NF can be used in building the collider;

(v) A multi-TeV MC if, or when, the physics from the LHC warrants such a facility.

Figure 1. Schematic layout of the IDS-NF neutrino factory.

Figure 2. Figure caption for first of two sided figures.
2. Challenges
The challenges for muon accelerator facilities stem from two characteristics of the muon:

(i) they result from tertiary production: \( p \rightarrow \pi \rightarrow \mu \); and
(ii) they have a short lifetime of 2.2 \( \mu s \).

Tertiary production implies that high beam power is required to produce muons in sufficient quantities, which in turn means that the production target must be capable of withstanding the power. Further, the kinematics of the production process results in the muons having a large transverse emittance, and a wide energy spread. This implies that the beams have to be focused both longitudinally and transversely, and that the beam has to be reduced for efficient acceleration and transport. The short lifetime of the muon implies that the cooling and acceleration must be performed rapidly thus necessitating the need for rapid cooling techniques and the operation of high-gradient rf cavities in strong fields.

3. R&D and system demonstrations
Significant progress has been made in addressing the technical challenges and several system demonstration experiments have been either carried out or underway. These include the Mercury Intense Target (MERIT) experiment at CERN [7], the Muon Ionization Cooling Experiment (MICE) [8] at RAL, and the non-scaling fixed-field alternating gradient (FFAG) experiment EMMA (“Electron Model of Muon Acceleration”) [9] at Daresbury Laboratory. In addition, the MuCool Test Area (MTA) [10] at FNAL is a dedicated test facility for testing components for a muon cooling channel.

3.1. Muon production and front-end
Achieving the NF goal of \( 10^{21} \) neutrinos/year (or luminosities > \( 10^{34} \text{cm}^{-2}\cdot\text{s}^{-1} \) for a MC) requires a multi-MW proton beam. In order to maximize the production of pions, the proton beam energy must be in the multi-GeV range, and in addition, the beam must be bunched into a suitable structure by the addition of accumulator and compressor rings. The IDS-NF baseline calls for a pulsed proton beam with average beam power of 4 MW and energy between 5 and 15 GeV (in this range, the beam power is only weakly dependent on the energy). Several solutions have been proposed and site-specific solutions including a FFAG at a green-field site have been detailed in [6]. The MAP design which is site-specific to the U.S is based on Fermilab's Proton Improvement Plan (PIP) [16, 15] at Fermilab, and starts with a 200 kW linac at 0.8 GeV enabling nuSTORM, followed by a 1 MW facility at 5 GeV, further followed by a facility delivering between 2 MW and 4 MW (NuMAX+).

With proton beam powers in the multi-MW range, the target system poses several engineering challenges. Not only must it copiously produce pions and efficiently capture them, but it must also dissipate the high beam power. Further, in order to optimize the capture of pions with large transverse momenta, the target must operate in a high solenoidal field. Extensive studies have been performed to optimize the choice of target, pion-capture and decay channels and designs have been developed for the capture system and shielding. The baseline is a solid or liquid-metal target immersed in a high-field solenoid magnet to capture both \( \pi^+ \) and \( \pi^- \). Figure 3 shows a recent designs for solid target (graphite or carbon-composite) and high power liquid-Hg targets. For beam power up to a MW (e.g. at NuMAX), conventional solid targets would remain feasible and for the several-MW range, a proof-of-principle of a liquid-mercury jet target was successfully demonstrated by the MERIT experiment at CERN. In MERIT, which completed in 2007, 24 GeV/c proton beam pulses with intensities up to \( 30 \times 10^{12} \) protons per pulse were intercepted by a Hg jet within a solenoid whose field was varied from 10 to 15 T. The jets were typically injected with velocities of 15-20 m/s. For proton beams impacting a jet in a 15 T field, it
was found that the jet breakup was confined to less than 20 cm [7] which is consistent with a repetition rate of 70 Hz and a total beam power of 8 MW.

The beam that emerges from the target capture solenoid passes through a decay channel and then a series of rf cavities where the beam is bunched into a train and phase-energy-rotated (whereby the energy spread is reduced by accelerating slower low-energy bunches, and decelerating faster high-energy bunches) in preparation for cooling.

### 3.2. Muon cooling

As mentioned earlier, the fact that muons come from tertiary production $p \rightarrow \pi \rightarrow \mu$, gives rise to a beam with large transverse emittance and a wide spread in energy. This beam has to be cooled before it can be efficiently accelerated and injected into a storage ring. While muon cooling is not essential for a NF, it enables high intensities and luminosities and is a cost-efficient way of increasing the yield of muons without increasing the proton beam power or increasing the acceptance of the detector. Conventional beam-cooling methods – radiative, electron, stochastic, laser – are too slow (of the order of minutes to hours) on the timescale of the muon lifetime. Ionization cooling which relies on energy loss in an absorber medium is the only technique fast enough to cool muons [18]. An ionization-cooling channel comprises absorbers and rf accelerating cavities placed within a suitable focusing magnetic lattice. As muons traverse the absorber, they lose momentum both longitudinally and transversely. The rf cavities restore the lost longitudinal momentum, thus reducing the transverse phase space of the muon beam.

\[
\frac{d\varepsilon_N}{ds} \approx -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \varepsilon_N + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0},
\]

where $\varepsilon_N$ is the normalized transverse emittance, $\beta$ the velocity in units of $c$, $E_\mu$ the energy in GeV, $\beta_\perp$ the transverse betatron function, $m_\mu$ the muon mass in GeV/$c^2$, and $X_0$ the radiation length in the absorber. The first term on the right describes reduction of emittance per unit length (“cooling”) while the second term describes the effect of multiple scattering (“heating”). Equilibrium emittance is reached when the terms are equal and beyond this point cooling is not possible. In order to minimize heating effects from multiple scattering in the absorber, a low-Z material is optimal, and to maximize the cooling term strong focusing is required at the absorber. Whereas energy loss and cooling occur in the absorber, the operating rf gradient determines the
length of the cooling channel and how much cooling can be achieved. In the initial stages as the beam enters the channel, transverse sizes are large and the rf frequency required is relatively low. However, as the beam is cooled and the emittance is reduced, rf gradients and frequency can be increased.

Figure 4. Schematic of the MICE experiment underway at RAL. Particle identification and tracking detectors upstream and downstream of the cooling channel allow measurement of the phase space before and after cooling.

Although the physics of muon ionization cooling is straightforward, its technological viability has not been demonstrated. Its demonstration will provide valuable knowledge about the cost and challenges of building an ionization cooling channel. The MICE experiment [8] seeks to demonstrate, for the first time, the feasibility of ionization cooling by designing, engineering and building a section of a realistic cooling channel and then exposing this channel to a muon beam and then measuring its performance under a variety of operational and beam conditions. Measurements in a variety of configurations will also validate simulation codes used in designs. The experiment uses energy loss in low-Z (lithium hydride, liquid hydrogen) absorbers with alternating-gradient focusing to reduce the divergence of the beam. MICE was designed to proceed in stages. The current phase underway at RAL will characterize the material properties of absorbers and measure the change in emittance; subsequently addition of rf cavities for re-acceleration will complete the first demonstration of muon ionization cooling. [19, 20] in these proceedings describe the current state of the experimental program and the collaboration’s plans for the future.

3.3. Acceleration system
The short lifetime of the muon means that acceleration must occur rapidly at high average gradient in order that enough muons survive. The choice of accelerator technology is dependent on the energy of the muons. At the low energies which are optimal for ionization cooling, linacs are the most efficient. Thus, in the first stage, a linac is used to accelerate the muons to sufficiently relativistic energies at which point there is enough time dilation that recirculating linacs (RLAs), FFAGs or rapid cycling synchrotrons can be used. In the IDS-NF baseline, a linac raises the muon energy to 0.9 GeV, and is followed by a series of RLAs which raise the energy to 3.6 and 12.6 GeV respectively. In the IDS-NF design, final acceleration to 25 GeV is performed in a linear non-scaling FFAG lattice consisting of triplets of focusing and defocusing combined function superconducting magnets. The advantage of the configuration is that it can handle beams with large emittances using relatively compact magnets. The proof-of-principle of muon acceleration in an FFAG has been demonstrated [23] by the EMMA experiment. The NuMAX design utilizes a dual-use linac [21] for acceleration to energies up to 5 GeV, and favors rapid cycling synchrotrons [22] for acceleration in the final stage. A dual-use linac allows the
reuse of infrastructure for the acceleration of both the proton and the muon beams and provides significant reduction in the cost, risk, and time in the development of the facility.

3.4. RF
Most ionization cooling channel designs require operating rf cavities in the presence of large multi-tesla magnetic fields which are known to affect the extent of rf breakdown [24]. The MuCool Test Area (MTA) at Fermilab has made significant progress in the characterization and understanding of rf cavities under various conditions. The 201 MHz “MICE cavity” has successfully achieved a gradient of 21 MV/m with spark rates $< 10^{-6}$ in the fringe field of the MTA solenoid. Another significant effort has been the characterization of 805 MHz prototype cavities filled with hydrogen gas. Cavities pressurized with hydrogen gas were proposed as a means of increasing the operating gradient via Paschen’s law [25] and were also found to mitigate [26] the problem of rf breakdown in strong magnetic fields. In addition the dense gas serves as an ionization cooling medium at the same time raising the potential for a hybrid cooling channel in which acceleration and cooling happen at the same time. Tests at the MTA with an 805 MHz gas-filled cavity have demonstrated gradients as high as 65 MV/m in a 3 T solenoidal magnetic field [27] and they have been shown to work in the presence of intense, ionizing beams.

4. Conclusions
Significant advancements have been made in addressing the key technological challenges to building a muon accelerator facility – feasibility of a high-power liquid-Hg target, designs for the target capture and decay systems, ionization cooling channel designs with the demonstration experiment MICE currently underway, operation of high-gradient rf cavities in strong magnetic fields, a proof-of-principle demonstration of a linear non-scaling FFAG. Under MAP, a viable staging plan – with both physics and R&D abilities at each stage – has been developed in the context of Fermilab. In fact, the first stage in this scenario – nuSTORM – is “technology-ready” and could be built now to deliver a broad range of physics from a precision search for sterile neutrinos to precise measurements of neutrino interaction cross sections which would serve future experiments. It would also serve as a test bed for proving the technology required for later stages leading up to a high intensity neutrino factory offering unprecedented precision. Because of the synergies between a neutrino factory and a muon collider, this would simultaneously refine and prove the technology needed for building a TeV-scale lepton-antilepton collider. Muon accelerators, in summary, provide the basis for world-leading physics programs at both the intensity and energy frontiers of high energy physics.

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