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DESIGN CONCEPTS FOR MUON-BASED ACCELERATORS

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Abstract

Muon-based accelerators have the potential to enable facilities at both the Intensity and the Energy Frontiers. Muon storage rings can serve as high precision neutrino sources, and a muon collider is an ideal technology for a TeV or multi-TeV collider. Progress in muon accelerator designs has advanced steadily in recent years. In regard to 6D muon cooling, detailed and realistic designs now exist that provide more than 5 order-of-magnitude emittance reduction. Furthermore, detector performance studies indicate that with suitable pixelation and timing resolution, backgrounds in the collider detectors can be significantly reduced thus enabling high quality physics results. Thanks to these and other advances in design & simulation of muon systems, technology development, and systems demonstrations, muon storage-ring-based neutrino sources and a muon collider appear more feasible than ever before. A muon collider is now arguably among the most compelling approaches to a multi-TeV lepton collider. This paper summarizes the current status of design concepts for muon-based accelerators for neutrino factories and a muon collider.

INTRODUCTION

It has been more than 3 decades since muon colliders and muon storage rings were proposed [1-3]. Interest in muon colliders increased significantly following the observation that ionization cooling could be used to rapidly cool muon beams. Several workshops were held in the 1980s and 1990s, and in 1997 the Muon Collider Collaboration was formed, which later became the Neutrino Factory and Muon Collider Collaboration (NFMCC). By the late 1990's muon collider and neutrino factory design efforts were well-established worldwide. In 2007 the International Design Study for a Neutrino Factory (IDS-NF) was initiated. In 2011, muon R&D in the United States was consolidated into a single entity, the Muon Accelerator Program (MAP) [4].

The purpose of MAP is to perform R&D in muon accelerator technologies and to perform design & simulation to demonstrate the *feasibility* of concepts for neutrino factories and muon colliders. In the short time that MAP has existed there have been many accomplishments that have significantly changed our understanding of technology limits and design concepts for muon accelerators.

Particularly noteworthy is the situation regarding RF breakdown in magnetic fields, as is needed in ionization cooling systems. At the time MAP was initiated there was significant concern that RF cavities could not operate at sufficiently high magnetic fields while maintaining high gradients. Under MAP this phenomena has been understood and several solutions demonstrated. Careful cavity design has been shown to limit gradient loss with increasing magnetic field. Beryllium has been shown to have almost no damage due to breakdown compared with copper. Experiments at the Fermilab MuCool Test Area (MTA) have demonstrated that using cavities filled with high-pressure gas can prevent this breakdown, and that this is a viable technology for muon cooling systems [5].

Under MAP design studies have been carried out hand-in-hand with technology R&D, because for the designs to be credible they need to take account of technology limits. Though MAP has not involved detailed engineering studies, the designs studies have been performed with an awareness of gradient limits, space requirements for hardware, etc.

At this conference, more than 60 papers have been submitted on muon accelerator designs and technologies. Very many of these were submitted by MAP researchers. The following highlights some key accomplishments under MAP in design concepts for muon-based accelerators for neutrino factories and muon colliders.

DESIGN OVERVIEW

The MAP design & simulation effort included neutrino factories (short baseline and long baseline) and muon colliders. The Muon Accelerator Staging Study (MASS) developed a staged approach that bridged the Intensity Frontier and the Energy Frontier [6,7]. An important aspect is that each stage is both a facility for doing physics and an R&D facility for the next stage.

The staging begins with nuSTORM [8], a short-baseline neutrino facility that could be built with existing technology. Experiments done at nuSTORM could settle the sterile neutrino debate, and could provide precise neutrino cross-section measurements needed for long-baseline experiments like DUNE. In nuSTORM, pions would be injected into a decay ring with long straights where they would decay into muons that would be stored, and whose decays would produce a precision neutrino beam. The remaining non-decayed pion beam would be directed at a beam dump that would provide beam to an R&D platform on muon cooling.

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The next facility in the staging plan is a neutrino factory. A design concept based at Fermilab is called NuMAX, a 5 GeV ring optimized for the baseline from Fermilab to SURF. Initially NuMAX would involve a limited proton beam power on target and no cooling; 6D cooling would then be added to improve its perfomance; lastly the beam power of the proton driver would be upgraded, resulting in performance similar to IDS-NF. Also, NuMAX would serve as an R&D platform for testing ionization cooling at significant muon beam intensity.

The following elements of the staged approach are muon colliders. It begins with the Higgs Factory, which requires accelerating each muon beam to 63 GeV. The collider ring would have a circumference of about 300 m, a fact that exemplifies the strong attraction of muon accelerators as compact facilities able to explore high energy physics. The Higgs Factory would be followed by a multi-TeV collider. Under MAP, collider ring designs were developed for center-of-mass energies of 1.5 TeV, 3,TeV, and 6 TeV.

Figure 1 shows a block diagram of the Neutrino Factory and Muon Collider systems. Note that portions of the Proton Driver, Target, Front End, and linac, are common to both facilities.

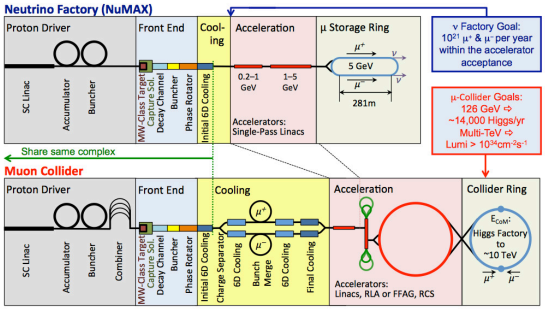

Figure 1: Block diagram of neutrino factory and muon collider facilities studies under MAP.

PROGRESS IN MUON ACCELERATOR DESIGN UNDER MAP

Though MAP has existed for only 3 years, there has been tremendous progress in regard to design concepts. Some highlights include:

Proton Driver: Under MAP, designs were developed for the accumulator and compressor rings of the Proton Driver, based on the expected parameters of the Project-X linac [9]. Potential instabilities were analysed and found to be not a problem. Initial studies were performed of injection stripping and of a beam delivery system for focus on target as needed in a muon collider design.

Target & Front End: MAP has explored several target designs, most importantly a design based on a solid carbon target and a high power design based on a liquid Mercury target [10]. The target parameters have been optimized [11], and preliminary work has explored energy deposition control using a chicane and downstream absorber [12]. Front End designs have been developed that use a buncher and phase rotator to form the beam into a train of bunches that can be captured, cooled, and accelerated by downstream systems [13,14].

Cooling: Muon cooling designs have matured greatly under MAP. Figure 2 shows how the horizontal and vertical emittances evolve as the muons travel through the cooling subsystems. When MAP began there was not an accepted approach to how the various subsystems should be organized. Thanks to progress under MAP, start-to-end simulations have now been performed of the vacuum [15] and gas-filled [16] cooling systems to reach the bottom of Figure 2. These start with a FOFO snake cooling section that can cool both mu+ and mu- simultaneously [17,18]. This is followed by a 6D cooling system, a bunch merge [19,20], and a post-merge 6D cooling system. Tapering has been shown in simulations to significantly improve the performance of 6D cooling systems [21]. In a vacuum channel, space-charge effects were explored using the WARP code [22]. An important development in muon cooling system design under MAP, initially recognized by Balbekov, is that the cooling of a Guggenheim-style lattice could also be achieved using a rectilinear channel with slightly tilted solenoids [23]. This is an important advance because the Guggenheim would have had very challenging engineering issues in the late stages of the channel. Under MAP there have been major advances in the design & simulation of a gas-filled Helical Cooling Channel (HCC) [16,24-26]. The HCC is attractive because it is compact (it uses dielectric-loaded cavities) and mitigates potential issues associated with high gradient RF in magnetic fields due to its use of gas-filled cavities.) The attractive features of these designs have motivated a new look at a hybrid channel that combines the best of both [27-29]. The final cooling stage needed for a muon collider needs further R&D, although promising concepts exists [30-32].

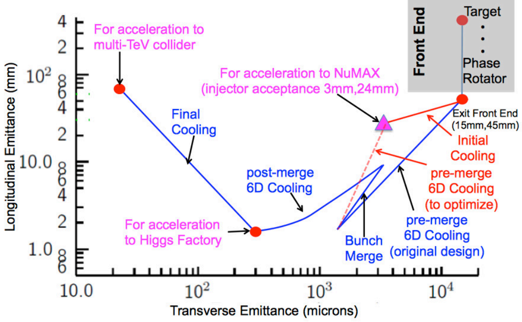

Figure 2: Transverse and longitudinal emittance evolution in a muon cooling system.

Acceleration: Under MAP, it was shown that, for low energies (up to about 5 GeV) a dual-use linac accelerating both the proton and the muons beams is a viable and cost effective system for a facility such as NuMAX [33]. By reusing existing infrastructure, it could potentially reduce the time and cost to develop a facility. Multi-pass recirculating linear accelerators (RLAs) are an efficient means of acceleration up to a few 10's of GeV, as needed for a Higgs Factory [34]. For higher energies, FFAGs were explored but found to be not economically advantageous. Instead, hybrid rapid-cycling synchrotrons containing ramped normal conducting cavities and fixed SC cavities, were found to be the method of choice for acceleration to 100's of GeV and the TeV range [35].

Collider Rings: Under MAP, collider ring designs were developed for a Higgs Factory, and for 1.5 TeV, 3 TeV, and 6 TeV colliders [36-38]. These took into account many factors including the design of magnets able to survive in the environment of a stored muon beam [39], the design of final focus systems, halo extraction schemes, longitudinal dynamics including wakefield effects, chromaticity correction, and beam-beam effects.

Machine-Detector Interface (MDI): During the course of MAP many improvements were made to MARS15. MARS was used for many purposes across the full range of MAP designs, including production studies in the target [11], component and detector shielding studies [39], the production of backgrounds needed for detector studies in the Higgs Factory design and high energy colliders, and in studies of using carefully designed protection systems and timing to mitigate background effects [38,40,41].

Muon Decay Rings: Under MAP, designs were developed for a short-baseline neutrino facility (nuSTORM) and a long-baseline neutrino Factory (NuMAX). In regard to nuSTORM, two approaches were studied, one involving a FODO ring [42] and one involving an RFFAG [43]. The RFFAG system has the potential to allow for larger energy acceptance, although the cost differential between the two designs needs further study. The NuMAX design is based on a scaling of the IDS-NF decay ring from 10 GeV to 5 GeV. Two approaches were studied using FODO and FDDF injection straight sections and shortened cells to accommodate an improved injection scenario.

High-End Computing: Prior to MAP most simulations involving muon accelerators were performed with serial codes. Particle simulations typically used at most 100,000 particles, often less, and in some cases required many hours to run. The main codes used for design & simulation have been G4Beamline, ICOOL, and MARS. Under MAP, ICOOL and G4Beamline were parallelized. All three codes were installed at NERSC. In addition, the electromagnetic package ACE3P has been critical to RF cavity design and multi-physics structure simulation [44]. Also, the SPACE code was developed to simulate the interaction of intense beams with plasmas in HPRF cavities [45]. In addition to complete codes, many supporting capabilities have been developed. This includes scripts for parallel scans, capabilities for parallel design optimization, and capabilities that combine measurements with simulations for computer model calibration, inference, and uncertainty quantification.

CONCLUSION

The design & simulation work and technology R&D done under MAP have made significant advances in demonstrating the feasibility of muon accelerators. Under MAP, key technological obstacles have been overcome (e.g., high gradient RF in magnetic fields). MAP designers have demonstrated via simulation the performance of realistic system designs for a neutrino factory and nearly all sub-systems required for a muon collider.

Nevertheless, the recent P5 recommendations have resulted in the termination of the MAP effort, and funding for muon R&D is evaporating. This places increased importance on international collaboration, such as the UK-based MICE effort, which is the only remaining funded activity. Despite the current shift in US priorities, muon accelerator expertise should be preserved for several reasons:

1. Appreciation is growing that the nuSTORM concept can provide the cross-section measurements necessary to overcome the systematics limitations of long baseline oscillation experiments as well as the ability to unequivocally settle the sterile neutrino question.
2. Although the P5 report maintains support for international design efforts like ILC and very high-energy p-p colliders, the viability and cost-scale of these projects will be clarified in the near future. If they cannot proceed, advanced concepts, such as muon accelerators, will offer the only route to a cost-effective discovery machine for the Energy Frontier.
3. With the successful operation of the MICE Ionization Cooling Demonstration in 2017, the foundation for long baseline neutrino factory capabilities will be in place, thus providing the precision neutrino source required for detailed study of the neutrino sector.
4. If the LHC finds evidence for new physics at the multi-TeV scale, muon colliders, with their small footprint (hence cost) and favorable luminosity performance at these energies, will deserve renewed attention.

A muon accelerator facility holds significant promise for precision capabilities spanning the Intensity and Energy Frontiers. We note that the designs described here were studied with supercomputers. From this perspective, it is interesting to compare the current state of high-end computers and high-energy colliders:

Both fields have undergone exponential growth for decades, as embodied by Moore's Law and the Livingston Curve, respectively. In both cases new technologies were needed to stay on, or close to, these growth curves. In supercomputing, this involved embracing massive parallelism in the 1990's. In recent years, it has involved the realization that power consumption is a key design constraint for future high-end systems. With this in mind the US government is strongly supporting R&D to reach the exascale. In the case of high-energy accelerators, priorities continue to focus on massive proposed concepts like ILC and FCC, while closing out muon accelerator R&D -- the most favorable collider technology in terms of luminosity per watt -- which could dramatically reduce the size and cost of a future facility. At this time it can be argued that such massive concepts are still worth exploring. But if R&D efforts are unable to make them affordable, then advanced concepts, including muon accelerators, will be the only remaining concepts with the potential to realize the colliders of the future.

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