MUON SOURCES FOR PARTICLE PHYSICS-ACCOMPLISHMENTS OF THE MUON ACCELERATOR PROGRAM*

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Abstract

The Muon Accelerator Program (MAP) completed a four-year study on the feasibility of muon colliders and on using stored muon beams for neutrinos. That study was broadly successful in its goals, establishing the feasibility of lepton colliders from the 125 GeV Higgs Factory to more than 10 TeV, as well as exploring using a μ storage ring (MSR) for neutrinos, and establishing that MSRs could provide factory-level intensities of ν_e ($\overline{\nu_e}$) and $\overline{\nu_\mu}$ (ν_μ) beams. The key components of the collider and neutrino factory systems were identified. Feasible designs and detailed simulations of all of these components were obtained, including some initial hardware component tests, setting the stage for future implementation where resources are available and clearly associated physics goals become apparent.

INTRODUCTION

Initial concepts for muon colliders and muon storage rings were proposed in ~1980 [1-4], and research toward these concepts intensified in the 1990's in the search for feasible high-energy accelerator projects. In 2011, muon accelerator R&D in the United States was consolidated into the Muon Accelerator Program (MAP) The purpose of MAP was to perform R&D in heavy electron particle accelerator (HEPA) technologies and to perform design studies to demonstrate the *feasibility* of concepts for neutrino factories and muon colliders [5, 6, 7]. MAP established that feasibility. The design studies have been accompanied by technology R&D, establishing the feasibility of key components, including high gradient rf in magnetic fields and mercury jet targets. The following highlights some key accomplishments under MAP in R&D for muon-based accelerators for neutrino factories and muon colliders.

DESIGN OVERVIEW

The key components of collider and neutrino factory systems are displayed in block diagram form in Figure 1. For a collider, these are a high-intensity proton source, a multi-MW target and transport system for π capture, a front end system for bunching, energy compression and initial cooling of μ's from π decay, muon cooling systems to obtain intense μ^+ and μ^- bunches, acceleration up to multiTeV energies, and a collider ring with detectors for high luminosity collisions. For a neutrino factory the same system could be used but with a racetrack storage ring for decay ν production and without the cooling needed for high luminosity collisions.

The proton driver and front end can also be adapted to provide a dramatically improved source for μ, π and K experiments.

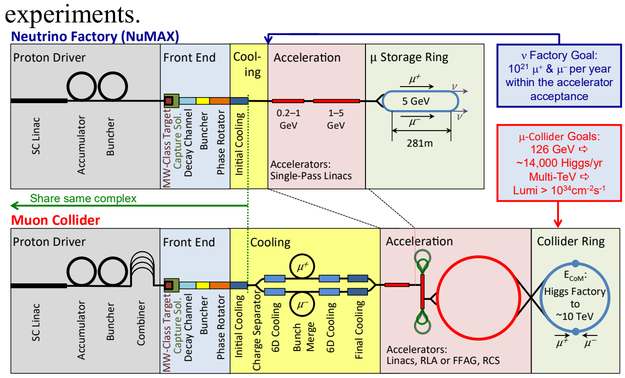

Figure 1: Block diagram of neutrino factory and muon collider facilities, as studied under MAP.

PROGRESS IN MUON SOURCES AND FACILITY DESIGN UNDER MAP

The MAP program provided key improvements in muon facility 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 parameters of the Project-X linac [8]. Potential instabilities were analyzed and mitigated. Initial studies were performed of a beam delivery system for focus on target as needed in a muon collider design. Meanwhile, JPARC has directly demonstrated that a proton source can operate at MAP-required parameters. A proton driver based on a JPARC-style linac + rapid-cycling synchrotron could be used [9].

Target & Front End: MAP explored several target designs, including a design based on a solid carbon target and a high power design based on a liquid Mercury target [10, 11]. The Front End designs use a novel rf buncher and phase-energy rotator to form the beam into a train of μ^+ and μ^- bunches that can be cooled, and accelerated by downstream systems [12, 13]. An energy deposition control system using a chicane and downstream absorber was also invented [14, 15].

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Cooling: Muon cooling designs 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 this could be accomplished. Under MAP, start-to-end simulations have now been performed of vacuum [16, 17] and gas-filled [18] cooling systems to reach the bottom of Figure 2. These start with a FOFO "snake" cooling section that can cool both μ^+ and μ^- simultaneously [19, 20]. This is followed by a 6D cooling system, a bunch merge [21, 22], and a post-merge 6D cooling system [23, 24]. (See Fig. 3.) An important development in muon cooling system design under MAP is that the 6-D cooling could be achieved using a rectilinear channel with slightly tilted solenoids and does not require large-aperture bending magnets [25]. Under MAP there have also been major advances in the design & simulation of a gas-filled Helical Cooling Channel (HCC) [18, 26-28]. The HCC is attractive because it is compact and mitigates potential issues associated with high gradient RF in magnetic fields due to its use of gas-filled cavities. The rectilinear channel can also use gas-filled rf [29, 30]. The final cooling stage needed for a muon collider needs further R&D. A final emittance exchange to minimal transverse emittance is needed. [31, 32].

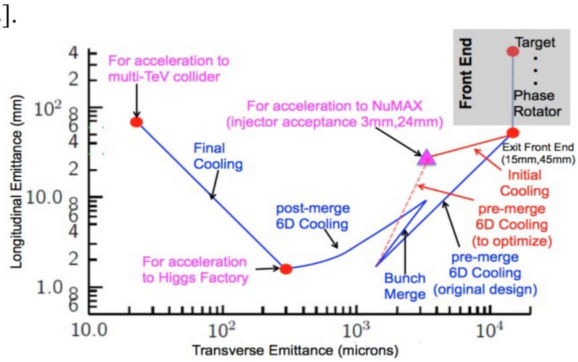

Figure 2: Transverse and longitudinal emittance evolution in a muon cooling system.

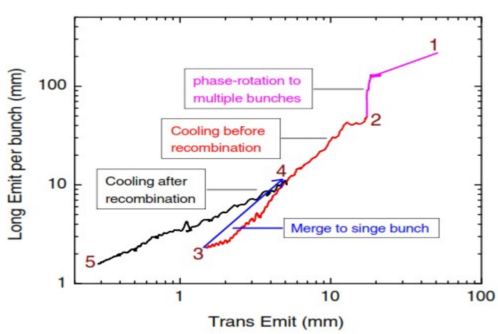

Figure 3: In a key accomplishment of the MAP program, cooling systems were designed and simulated that can provide all of the cooling needed for a collider, using feasible magnet and rf designs.

Acceleration: Under MAP, it was shown that, for low energies (up to about 5 GeV), a dual-use linac accelerating both proton and μ beams is a viable option [33]. Multi-pass recirculating linear accelerators (RLAs) are an efficient means of μ acceleration up to 10's of GeV, as needed for a Higgs Factory. and could also be used for higher energies [34]. Hybrid rapid-cycling synchrotrons, containing ramped normal conducting magnets and fixed-field SC magnets, were designed and could be more economical for acceleration from ~100 GeV to the multi-TeV range [35, 36].

Collider Rings: Under MAP, collider ring designs were developed for a Higgs Factory, and for 1.5 TeV, 3 TeV, and 6 TeV colliders [37, 38]. These took into account many factors including the design of magnets that accommodate the decay products of stored μ beams [39], the design of interaction regions, halo extraction optics, 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, component and detector shielding studies, the calculation of background in detector studies for a Higgs factory and for high energy colliders, and in design studies of machine protection systems and the mitigation of background effects [40, 41].

Muon Decay Rings: Under MAP, designs were developed for a short-baseline neutrino facility (nuSTORM) and a long-baseline neutrino Factory (NuMAX) [42-44]. The nuSTORM design used MAP concepts to develop a modest μ storage ring that could test for sterile ν's, measure ν cross sections and provide low-E μ beams for other experiments. The NuMAX design would extend the DUNE experiment with a high-intensity ν-factory for complete ν-oscillation measurements.

High-End Computing: Prior to MAP most simulations involving muon accelerators were performed with serial codes, using 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. Also, the SPACE code was developed to simulate the interaction of intense beams with plasmas in HPRF cavities [45]. Parallel scans with capabilities for design optimization were developed, including a Genetic Algorithm for magnetic horn optimization for NuSTORM [46].

Low-energy Muon Applications: Prior to MAP, the neutrino factory and muon collider collaboration made critical contributions initiating the mu2e and g-2 experiments at Fermilab. These contributions have continued as these projects have initiated construction. Further R&D based on MAP can provide the basis for higher-intensity upgrades of these experiments or other experiments exploring lepton parameters.

High-field Magnet Development: HLC performance depends directly on magnetic field. The MAP program included designs and tests of high field magnets, with Nb_3Sn and HTS conductors, as well as NbTi designs [47].

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Rf Development: 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 these phenomena has been understood and several solutions demonstrated. Careful cavity design has been shown to limit gradient loss with increasing magnetic field. Beryllium surfaces have almost no damage due to breakdown (compared with copper), and, in MuCOOL test area (MTA) experiments, can obtain high gradients within high magnetic fields [48]. Experiments at MTA have also demonstrated that rf cavities filled with high-pressure gas can avoid breakdown, and that this is a viable technology for muon cooling systems [49].

CONCLUSIONS

The MAP design & simulation work and technology R&D made significant advances in demonstrating the feasibility of muon accelerators. 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 of the sub-systems required for a muon collider.

An important prerequisite for a High Energy Heavy Lepton Collider (HLC) is a multi-MW-scale proton source, as could be developed at JPARC or ESS; however, the US HEP program does not yet have one.

Within the limited US HEP budget and project constraints, the largest initiative that the 2014 HEPAP panel could envision for the next decade is a deep underground neutrino experiment. Initiation of a high intensity proton source is included in that program. MAP research efforts were curtailed, having successfully completed the feasibility assessment goal.

Critical research important for future muon accelerators is continuing outside the MAP framework, and the 2014 HEPAP panel supported the high-field magnet R&D that is critical for future HLCs, since beam production, beam cooling, acceleration and collider performance directly depend on the magnetic field strength. Optimization of technology for secondary particle production is also a HEPAP priority, as well as rf gradient increases. The g-2 and μ2e experiments at Fermilab will provide important experience in using and optimizing μ beams, including precision spin precession measurements.

While this technology R&D is helpful, some dedicated research on HEPA will be needed to maintain its availability for future accelerators. This research should be internationally based, since any future HEP facility will require international support and the US HEP program may not have the resources for a next generation facility. This places increased importance on international collaboration, such as the UK-based MICE effort, which is the only remaining funded activity.

This research should be enlightened by the changing landscape in HEP. At present, ν experiments are focused on using π-decay ν_μ-beams to establish the parameters of the 3-ν standard model, with the next experiments to determine the mass hierarchy and to measure CP violation at the ~5σ level, if it be near maximal. If the goal after that is greater accuracy, MAP has established that a μ-accelerator based ν-beam could provide this. If the ν physics is more complex, with more ν's or unexpected interactions, then it is probable that μ-based beams could be needed.

A high-brightness muon facility also holds significant promise for enabling capabilities for Intensity Frontier experiments, such as precision symmetry experiments (following μ2e, g-2, …).

LHC, with its extensions to higher luminosity and energy, is the current HEP discovery machine. So far, its discoveries are the Higgs at 125 GeV and the absence of new HE particles beyond that. A primary purpose of a lepton collider is detailed exploration of established or expected resonance states (J/ψ, ϒ, Z_0, …); future identification of any at higher energy by LHC or theoretical physics could require the construction of a HLC.

If more precise measurements of the Higgs are needed, in particular measurements of its mass, width, and its coupling to μ, then a 125 GeV μ^+-μ^- collider would provide the highest precision. Since μ beam energies can be measured by spin precession (frequency), rather than by calorimetry or bending radius, they can be measured much more accurately. Masses and widths of the nearby Z_0 and tt* resonances could also be measured, completing a precision scan of the standard model at highest possible accuracy.

The absence of new HE particles may indicate the need for a higher energy machine. A ~10 TeV HLC could have the discovery reach of a 100+ TeV pp collider, and could be considered if the cost and scale of a hadron collider becomes unacceptable.

Since the optimum μ accelerator needed for further exploration after 2030 may differ substantially from the present concepts, a renewed design and optimization effort is essential to a healthy HEP program. An international μ-based accelerator program will be needed to provide the best solutions.

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