STOPPING MUON BEAMS*

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Abstract

The study of rare processes using stopping muon beams provides access to new physics that cannot be addressed at energy frontier machines. The flux of muons into a small stopping target is limited by the production process and by stochastic processes in the material used to slow the particles. Innovative muon beam cooling techniques are being applied to the design of stopping muon beams in order to increase the event rates in such experiments. Intense stopping muon beams will also aid the development of applications such as muon spin resonance and muon-catalyzed fusion.

INTRODUCTION

The high energy physics community faces the challenge of finding affordable ways to explore the physics beyond the Standard Model. Recent developments in muon cooling hold out the promise of muon colliders to extend the energy reach of the International Linear Collider and of neutrino factories based on muon storage rings to explore the underlying physics. But energy frontier facilities are very expensive, and affordable R&D programs that can give access to new physics are also important. Fortunately, there are fundamental physics issues that are best addressed by “low energy” and non-accelerator experiments. These topics are most often related to the replication of leptons and quarks in generations: the quark and lepton mass spectra, the mixing of flavors, and the CP violation induced by the mixing. These physics issues can be addressed by intense stopping muon beams to support experiments studying rare processes with exquisite sensitivity.

Since neutrino oscillations establish lepton flavor violation (LFV) in the neutrino sector, the next logical search is for observable LFV in the charged lepton sector. An intense stopping muon beam would allow sensitive searches for such phenomena. Work is currently underway to use muon cooling design tools and innovations developed by Muons, Inc. [1], in the context of proposed improvements to the beam facilities available at Fermilab [2], to design a stopping muon beam to enhance the feasibility and improve the sensitivity of a muon to electron conversion experiment, a sensitive probe of LFV in the charged lepton sector which may run at Fermilab in parallel with the future neutrino program.

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TECHNICAL APPROACH

A muon-to-electron conversion experiment called MECO was proposed at Brookhaven [2] as part of the RSVP (rare symmetry-violating processes) project. The physics case for the experiment was compelling, but high costs led the National Science Foundation to terminate the RSVP project.

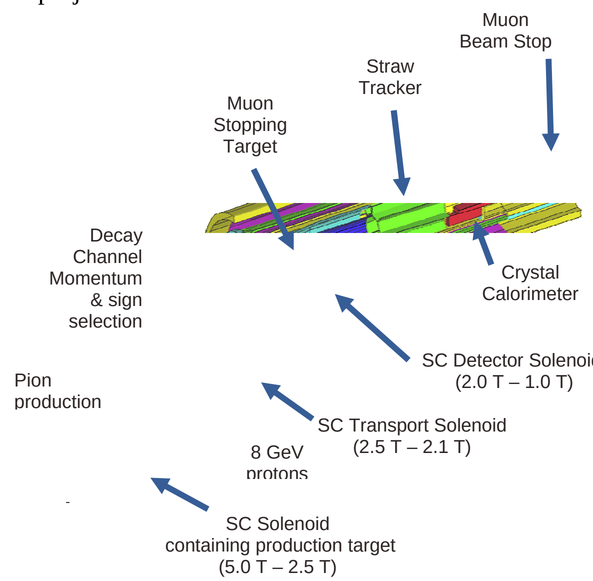

Figure 1: Conceptual picture of the MECO experiment at Brookhaven.

The MECO concept, shown in Figure 1, includes three large superconducting magnets: solenoids for muon production, transport, and analysis. Protons incident on the production target (from the right, not shown in the figure) produce negative pions. Those pions with transverse momenta < 180 MeV/c travel within the 30 cm inner radius of the magnet, and most decays to muons occur in the production region. The muons, following helical trajectories along the magnet axis, are captured in the production solenoid and transported by the bent solenoid to the stopping target. The magnetic field along the axis of the system has regions of uniform field connected by regions of monotonically decreasing strength as shown in Figure 1. Both the trigger and tracker are high-rate detectors located far from the solenoid axis to intercept conversion electron helices and avoid lower-momentum particles resulting from beam interactions or ordinary muon decays. The negative muons are captured into orbits around nuclei in the stopping target. Rarely, a muon may convert directly to an electron in the field of a nucleus. Such an electron is emitted with an energy of about 105 MeV, almost the full rest energy of the muon: a striking kinematic signature. The detector is optimized to measure the high-energy electrons, while the low-energy ones are confined to the central region of the detector solenoid.

Beamline at FNAL

The primary proton beam for MECO was to be provided by the Alternating Gradient Synchrotron (AGS), with 40×10^{12} protons delivered at a one Hz rate. The choice of beam energy, 7 to 8 GeV, optimizes pion production and minimizes antiproton production (a potential background source). The 8 GeV energy of the Fermilab Booster proton beam is thus close to optimal. Two 8-GeV storage rings presently used for accumulating antiprotons can be reused for protons. Figure 2 shows a potential proton distribution scheme for the FNAL physics program after antiproton production ends. The idea is that 4 of the 22 Booster batches per Main Injector (MI) cycle will be available for muon production while 18 batches are used for the neutrino program. In contrast to the MECO reflecting solenoidal production channel, a forward production target is being considered, in which case the muon production system would be similar to current neutrino factory and muon collider front end designs.

Momentum-dependent Helical Cooling Channel

We propose to explore ways to improve the capabilities and reduce the direct costs of a muon-to-electron conversion experiment by using muon beam cooling techniques to enhance the sensitivity of the experiment and to reduce the cost of the magnet system. Ionization cooling ordinarily shrinks only transverse emittances, so emittance exchange is necessary for longitudinal cooling. In earlier concepts, emittance exchange was accomplished by using a dipole magnet to create an energy-position correlation of the beam in a wedge-shaped absorber. Higher energy particles pass through the thicker part of the wedge and suffer greater ionization energy loss, thus producing a more mono-energetic beam. The conceptual innovation developed by Muons, Inc. is to fill the bending magnet with a continuous, homogenous absorber such as dense hydrogen gas. Higher-momentum particles lose more energy because they have longer path lengths in the gaseous absorber, thereby reducing the beam energy spread and hence the longitudinal emittance. This concept of a continuous absorbing medium was refined by the development of the Helical Cooling Channel (HCC) [4], having superposed solenoid, helical dipole, and helical quadrupole magnetic components.

An innovative HCC magnet design [5] has been adapted for front end designs of a neutrino factory and muon collider where the strength of the fields diminishes as the beam loses momentum in an ionization cooling energy absorber. The first example is a decay channel and precooler illustrated in Figures 3a and 3b. One momentum-dependent HCC variation has been proposed for MANX [6], a cooling demonstration experiment employing ionization cooling and emittance exchange to achieve reduction in normalized emittance in six dimensions.

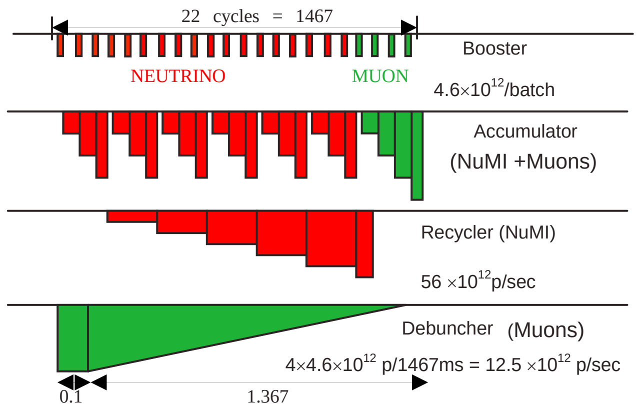

Figure 2: Potential Fermilab Proton source ring usage after the antiproton program ends.

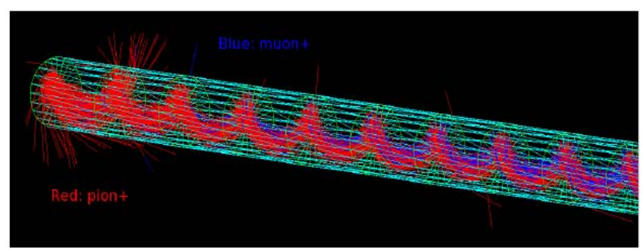

Figure 3a: G4Beamline simulation of muon (blue) and pion (red) orbits in a HCC-type magnet that is adapted as a decay channel.

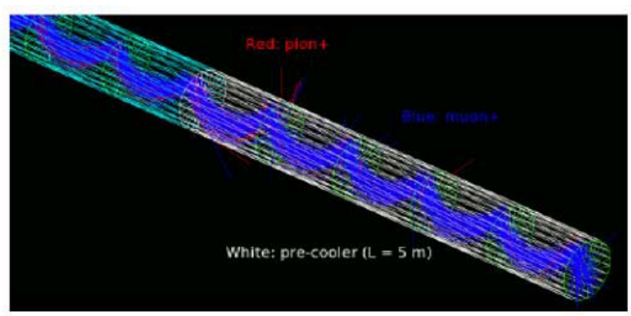

Figure 3b: The decay channel in Fig. 3a ends in an absorber-filled HCC which is a precooler.

FNAL μ/e Conversion Experiment

The approach described here is to increase the stopped muon/proton ratio from the 0.25% accepted by the MECO design by using the higher-energy, higher flux part of the pion/muon production spectrum. The beam will be slowed by passing through a HCC segment that is much like the MANX apparatus, which could be filled with liquid helium or hydrogen. After the beam has been slowed from about 300 MeV/c to 100 MeV/c, another HCC segment with a less dense absorber will be used to slow the beam to about 50 MeV/c before it is transported to the experimental stopping target.

The use of longitudinal beam cooling overcomes the large momentum spread that results from the strong negative slope of the dE/dx versus momentum curve at low energy; this is what motivated MECO's choice of the low energy tail of the production spectrum, with its lower stopped-muon/proton yield. The idea of tapering the density of the absorber is an innovation in the theory of the HCC. In order to be effective, the magnetic dispersion, which provides the momentum or path-length dependent ionization energy loss, must increase as the beam slows and the slope of dE/dx versus E increases. However, when the magnetic dispersion is increased too far, the required magnetic fields cause the beam stability and channel acceptance to suffer. Reducing the density of the energy absorber reduces this problem. Possible lower dE/dx absorber alternatives include low density inserts (e.g. Styrofoam) into the liquid hydrogen or helium absorber, or solid low-density material such as lithium hydride in vacuum.

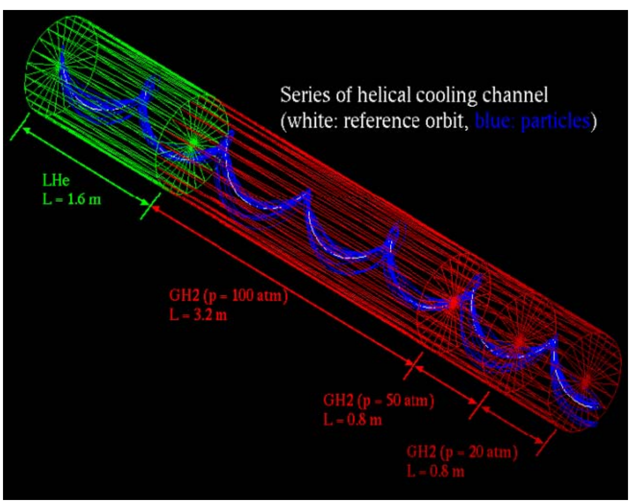

Figure 4: HCC with decreasing density used for first simulations.

Figure 4 shows a first attempt to simulate a simple, tapered-density HCC approach, where absorbers with different density are used to cool and degrade a beam produced by 8 GeV protons, using a Geant4-based program called G4Beamline [7]. Figure 5a shows the entire momentum spectrum of produced muons and pions, highlighting the subset (hatched area) that enters the first HCC segment at the left of Figure 4, at z=0. Figure 5b shows the evolution of the momentum distribution as the beam is degraded and cooled in the HCC in the series of segments with decreasing density shown in Figure 4. The reduction in flux as the beam passes down the channel is due to the reduced acceptance caused by the required dispersion. The acceptance will be improved by further theoretical analysis and numerical simulation studies. But already this first study shows the muon/proton ratio of muons stopping in a 50 mm Al target is 1.2%, almost 5 times larger than in the baseline MECO design. This is encouraging, and further study of transverse distributions, backgrounds, and the use of a stronger capture solenoid should yield additional improvements.

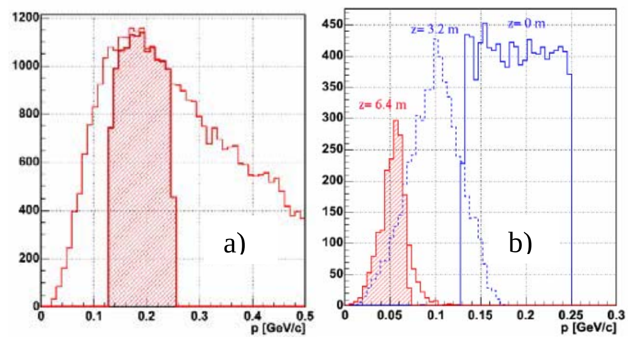

Figure 5: (a) A plot of the muon flux from the target produced by an 8 GeV proton beam and the subset (hatched area) that enters the first HCC segment. (b) A plot of the evolution of the muon momentum spread from the start of the cooling channel (z=0) through a series of HCC segments with reduced hydrogen absorber density to the stopping target at z=6.4 m.

SUMMARY

The flux of stopping muons for the study of rare processes such as muon-to-electron conversion can be improved by the use of innovative muon cooling concepts originally developed for muon colliders and neutrino factories.

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