INTENSE 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. Work is currently underway to use muon cooling design tools, and an entirely new concept for reducing the energy spread of the secondary pion beam which produces the muons, to design intense stopping muon beams. Such beams can useful in applications such as muon spin resonance and muon-catalyzed fusion., and in particular, the feasibility and improved sensitivity of a muon to electron conversion experiment. These innovations can increase the muon/proton yield, provide better protection from many sources of background that could limit the sensitivity of the experiment, and provide the possibility for highly polarized stopping muon beams.

INTRODUCTION

The HCC is a new concept in muon beam cooling, which involves the use of a magnet with combined solenoid, helical dipole, and helical quadrupole fields [1]. A previous study incorporating a HCC filled with gaseous hydrogen of variable density showed promise [2] to improve the stopping muon rate for the muon to electron conversion (Mu2e) experiment by degrading the momentum down to 75 MeV/c, while maintaining a small momentum spread with the HCC cooling properties. This enables muons from the peak of the pion production process (where the rate is several times higher than at the low energy end) to be stopped in the Mu2e target. In addition, a new collection scheme for pions and muons emerging from a production target was invented using a dipole and wedge configuration. This will produce a wide, quasi-monochromatic pion beam that, in conjuction with the HCC, will minimize the muon energy spread into the detector target. This is described later.

HCC ABSORBER DESIGN

In the previous study, a gaseous hydrogen (GH2) absorber was used to simplify the simulation and to use the best material possible regarding multiple scattering and energy straggling. The calculation was simplified by assuming gas volumes of variable density separated by (imaginary) pressure vessel membranes. In the more realistic study reported here, we have used absorbers made of lithium hydride (LiH) plates, achieving density decrease by varying the spacing between plates. Furthermore, the absorber plates can be wedge-shaped to improve the effectiveness of the HCC. The goal is to degrade the muon beam momentum from 240 MeV/c, which is an optimum parameter in a new front end design described later in this paper, to below 75 MeV/c.

Figure 1 shows the average momentum of a 240 MeV/c muon as it passes through a series of close-packed identical LiH plate absorbers as a function of the absorber length. The momentum loss is non-linear, with greater loss rates at lower momenta. This results in a degradation of muon cooling and containment in the channel. The non-linearity can be compensated for by varying the spacing of the LiH plates. The required spacing is calculated by a simple relation:

$$\Delta l = \left[\frac{dp/ds}{[dp/ds]_{ref}} - 1 \right] \Delta d \qquad (1)$$

where Δl is the required spacing, *dp/ds* is the momentum reduction per unit length as a function of momentum, calculated from the Bethe-Bloch formula, $[dp/ds]_{ref}$ is the designed momentum degradation, and Δd is the thickness of the absorber plate, respectively.

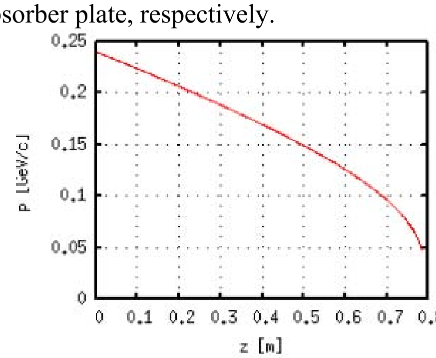

Figure 1: Muon momentum vs absorber length for a continuous LiH absorber.

Figure 2a shows the compensation achieved by applying Eq. 1.1. The momentum loss is seen to be linear. The absorber consists of a series of 560 discrete 1 mm thick LiH plates spaced as shown in Figure 2b, designed for a uniform momentum loss rate ($[dp/ds]_{ref}$) of 0.02375 GeV/c/m. The plates are spaced over an 8 m long region that corresponds to their installation in a helical cooling channel. In the helical trajectories in the channel, particles traverse the plates at a 45 degree angle, so that the effective path length in the absorber is 1.4 times longer than the absorber thickness: the number of plates required is 560, equivalent to 800 plates at normal incidence.

WEDGE-SHAPED ABSORBERS

A further refinement of the absorber design is illustrated in Figure 3a. The particle trajectories are off-center in the HCC, with higher momentum particles at larger radii. Wedge-shaped absorbers, with thickness varying in the

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radial dimension compensate for the radial momentum dispersion. For this study, the linear density change with respect to the absorber radius is approximated by five discrete rings of different thicknesses.

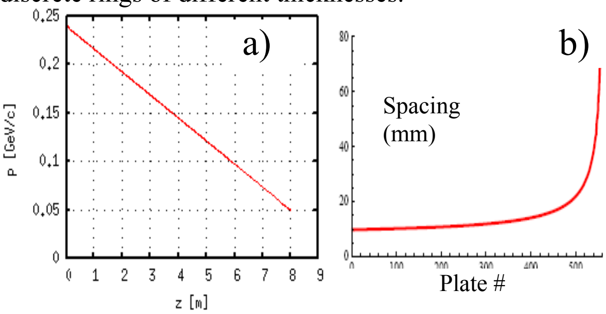

Figure 2: a) Muon momentum calculated for a set of 560 discrete 1 mm LiH plates spaced according to Eq (1.1), and b) Spacings of those LiH absorbers to maintain a linear momentum loss rate shown in a). The horizontal axis is the sequence number of the plates.

COMPARISON OF HCC ABSORBERS

Figure 3b shows the final momentum distributions in a pure solenoid, the helical magnet with the wedge absorbers, and the flat plate absorbers. The average initial momentum is 240 MeV/c, the initial momentum spread is ± 50 MeV/c, the initial beam size is ± 50 mm, and the initial angular distribution (ratio between transverse and longitudinal momenta) is ± 0.2, respectively. The helical period and the helical pitch are 1.0 m and 1.0, respectively. The path length and the solenoid field strength for a reference particle are the same in all channels. The transmission efficiency for muons with final momentum below 75 MeV/c is approximately three times higher for the helical channels than for the pure solenoid. Also, the HCC with wedge-shaped absorbers yields about 20 % better transmission efficiency than the HCC with flat plate absorbers.

Finally, we compare the present helical channel with the previous design [2]. Figure 4 shows the evolution of momentum distribution in the previous gaseous absorber H2 and in the present LiH wedge-shaped absorber HCCs. The initial distribution is taken from the Study 2 channel, which is designed for a neutrino factory/muon collider. The transmission efficiency of the muons with the momentum below 75 MeV/c is 0.66 % in the present channel while that in the previous one is 1.2 %. The transmission efficiency in the GH2 is still better than that using LiH, because GH2 reduces the phase-space distortion caused by the multiple scattering and the energy straggling during the energy loss process. However, the transmission at the middle of the present channel is very high, better than that in the previous design. This suggests that the thickness and shape of the wedge absorber must be adjusted with momentum to make a finer correction for the dominant, non-linear effects.

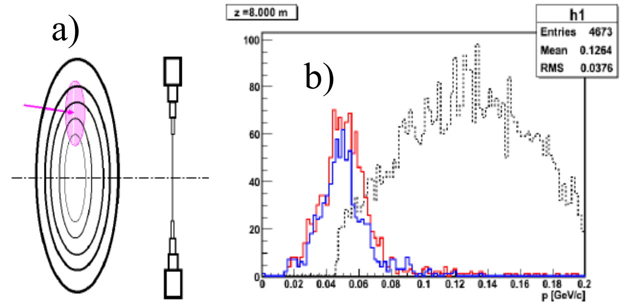

Figure 3: a) Cross sectional view of LiH wedge absorber. The magenta spot shows the beam position at the absorber. The coaxial center is the same as the helical magnet center. b) Final momentum spectra in various channels. The red curve is for a helical magnet with wedge- shaped absorbers, the blue one is for a helical magnet with flat plate absorbers, and the dotted curve is for a pure solenoid.

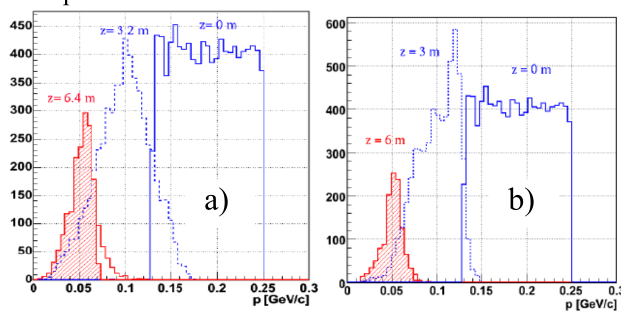

Figure 4: Muon momentum spectra at different z-positions for a) GH2 in the previous design, and b) LiH wedge-shaped absorbers, the present design. in the HCC.

DIPOLE AND WEDGE CAPTURE

A new invention coming out of Muons, Inc. is the concept of the "Dipole and Wedge Capture" (D&W) collection scheme for pions and muons emerging from a production target. A schematic of the idea is shown in Figure 5. The basic idea behind the D&W scheme is that pions produced near the forward direction (cos theta >~ 0.95) with a given momentum in a uniform dipole field will converge after a 180 degree bend to a horizontal focus. The position of these horizontal foci will be dispersed in momentum, with higher momentum pions farther from the production target. A wedge-shaped energy absorber can be placed such that each pion will be left with approximately the same momentum after it passes through the absorber. This will produce a wide, quasi-monochromatic pion beam, destined for the HCC as shown. An important consideration in this design of the muon production apparatus is to heavily suppress large backgrounds by incorporating a large bend angle. In addition to suppressing the backgrounds, this capture design can operate over the momentum region with largest flux.

This D&W method has several advantages for all intense

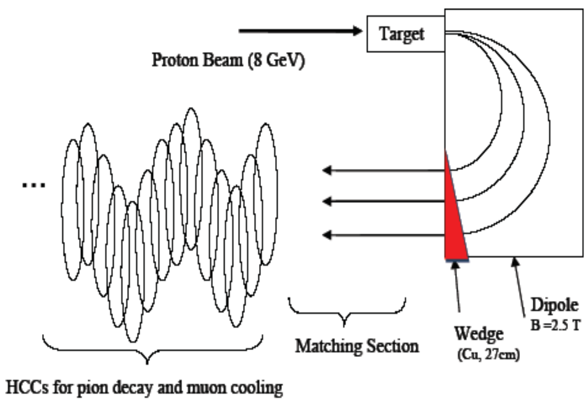

Figure 5: Conceptual diagram of the Dipole and Wedge Capture scheme to create a quasi-monoenergetic beam of pions to be injected into a Helical Pion Decay and Muon Cooling Channel. Forward pions produced off a target are turned 180 degrees where they hit an absorber that removes all but 240 MeV/c of momentum.

stopping muon beams: 1) The pion production peak is captured. 2) The pion momentum spectrum for forward produced pions can be chosen to maximize the pi/p yield. 3) The proton beam points away from the detector, reducing neutral backgrounds. 4) Wrong-sign background particles never get into the muon transport line, so an S-bend solenoid (as currently designed for mu2e) is not needed. 4) After the wedge, the quasi-monochromatic beam can be set at a momentum that optimizes HCC performance. 5) With a suitable amount of absorber material in the HCC, those muons can be selected that result from forward decays of the pions producing a polarized stopping beam. 6) With that same amount of material, pions that don't decay (and heavier particles) will range out in the HCC absorber, and not reach the stopping target, thereby greatly reducing "hadronic flash" background. Finally, there is much less spread in the transit times from production target to stopping target, essential for the use of high-Z stopping targets, where the negative muon lifetime is as low as 100 ns.

Simulations using G4beamline[3] verify the excellent relationship between the position of pions exiting the dipole (without wedge) and its momentum, as shown in Figure 6a & 6b. Protons of 8 GeV impinge on a tungsten target 19.2 cm long (~2 interaction lengths), followed by the dipole with field 2.5 T and aperture of 1 meter. The negatively charged pions are bent 180 degrees in the dipole and exit at locations that strongly correlate with momentum. A Cu wedge extends from $x = -650$ mm (reference $p = 243.75$ MeV/c) with zero thickness to $x = -1650$ mm (reference $p = 618.75$ MeV/c) with thickness of ≈27 cm. Figure 6c shows the momentum-position relation for particles after traversing the Cu wedge and demonstrates the effectiveness of the wedge in narrowing the momentum spread of the pions. Figure 6d is the momentum spectrum (without wedge) of negatively charged pions and muons that are within a circular aperture of radius 500 mm (destined for the HCC) centered on the wedge location ($x = -1150$ mm), and Figure 6e is the momentum spectrum of those particles after traversal of the wedge. Comparison of Figures 6b to 6c and 6d to 6e demonstrates the striking reduction in momentum spread that can be achieved by simple insertion of a well designed wedge.

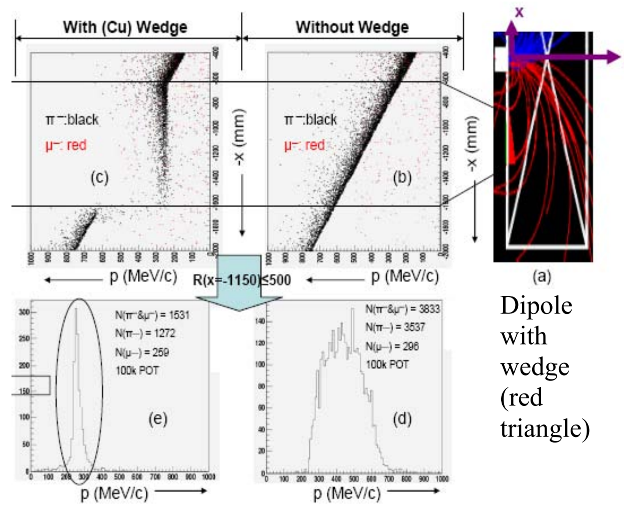

Figure 6: a) G4beamline top view of dipole and wedge. Negatively charged particles (red) are bent through dipole (2.5T; 1m aperture) with those in the momentum range 244 MeV/c ≤ p ≤ 619 MeV/c hitting the Cu wedge (red triangle). b) Projection of particle momentum vs. location of dipole exit in absence of wedge. c) Projection of particle momentum vs. location of dipole exit when Cu wedge is in place. d), e) Momentum distributions of particles in circular aperture (r = 500 mm) centered on wedge, before d) and after e) wedge traversal

CONCLUSIONS

Muons, Inc. innovations have been applied to the task of designing useful intense stopping beams. In particular, HCCs implementing LiH annular wedge absorbers to provide linear momentum losses along the channel, and recently, a new dipole & wedge pion collector for the muon source. These ideas can be implemented in developing schemes for producing polarized muon beams, and ways of lowering backgrounds for rare events searches such as the muon to election conversion experiment.

REFERENCES

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