NOVEL MUON BEAM FACILITIES FOR PROJECT X AT FERMILAB

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Abstract

Innovative muon beam concepts for intensity-frontier experiments such as muon-to-electron conversion are described. Elaborating upon a previous single-beam idea, we have developed a design concept for a system to generate four high quality, low-energy muon beams (two of each sign) from a single beam of protons. As a first step, the production of pions by 1 and 3 GeV protons from the proposed Project X linac at Fermilab is being simulated and compared with the 8-GeV results from the previous study.

INTRODUCTION

We have been developing design concepts for future high-quality muon beam facilities driven by proton beams from the Fermilab Project X [1] linac. A variety of muon beams will be needed; one particular focus of our activities has been to provide a stopping negative muon beam for a muon-to-electron conversion experiment. (Muon to electron conversion is a charged-lepton flavor-changing process in which a muon converts directly to an electron in the field of an atomic nucleus without other particles being emitted. It is predicted to occur in some theories of physics beyond the standard model.)

A conversion experiment called Mu2e [2] has been approved and is currently being developed. It will use proton beam accelerated by the Fermilab Booster to generate muons stopping in an aluminum target. The proton energy is 8 GeV and the beam power is expected to be about 8 kW, corresponding to 1 μA of average proton beam current. The muon beam concept for Mu2e is similar to that of previously proposed (but not executed) experiments called MELC [3] and MECO [4].

Another conversion experiment following Mu2e will be an important experiment in the Project X era. If a significant signal is detected in Mu2e, then interest will turn to detecting conversion on one or more higher-Z nuclei such as gold. If, on the other hand, a convincing signal has not been detected, then the emphasis will be on achieving higher sensitivity. In both cases, a new initiative will be required because the design of the Mu2e beam and detector cannot readily be extrapolated to achieve much more demanding requirements. It is obviously desirable that any new initiative should be able to cover both possibilities, providing greater sensitivity as well as the ability to use higher-Z stopping targets effectively.

Project X is crucial for achieving the goals of the follow-on experiment. The baseline design for Project X includes a 3-GeV CW SRF linac followed by a pulsed linac for further acceleration to 8 GeV. Ideas for staging Project X have recently been developed; the first stage would be a 1-GeV CW linac. The design average beam current in the CW linac is 1 mA, corresponding to beam powers of 1 and 3 MW at 1 and 3 GeV, respectively. Beam power of about a megawatt can potentially provide about two orders of magnitude increase in sensitivity for a muon to electron conversion experiment compared to the Mu2e experiment at 8 kW.

The experiment requires beam bunches spaced by about a muon lifetime. The lifetime of a stopped negative muon in gold is less than 100 nsec, about 10 times shorter than that in aluminum. Project X includes a nimble chopper that will allow delivery of arbitrary bunch timing patterns, an important capability for these kinds of experiments.

CONCEPT USING DIPOLE AND WEDGE

Previously we developed a complete conceptual design for a stopping muon beam generated by an 8-GeV proton beam [5]. Figure 1 illustrates the concept. The proton beam produces pions in a target at the face of a uniform dipole field. A 180-degree bend generates a momentum-dispersed horizontal focus, where the pions encounter a wedge that renders them roughly mono-energetic. Figure 2 shows the simulated performance of the dipole and wedge monochromator. That system is followed by a decay volume matching into a helical cooling channel [6] that reduces the beam energy as it cools the muons before the stopping target.

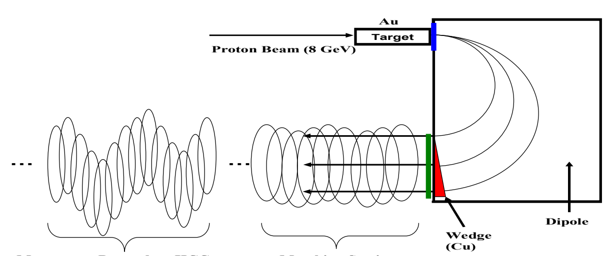

Figure 1: Layout of Dipole and Wedge (Cu), momentum dependent HCC, and the matching section. The blue line indicates where π− from the target are generated. The green line shows the location of a circular aperture immediately behind the wedge.

Subsequently we realized that RF cavities should be used for the final stage of deceleration to the stopping target in order to avoid the severe longitudinal heating that occurs in absorbers at low energy.

The same dipole-plus-wedge targeting and pion collection concept can be used for the simultaneous generation of four mono-energetic pion beams, namely positive and negative beams produced forward and

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backward from the upstream and downstream faces, respectively, of a single magnet. That concept is illustrated in Figure 3. It is important to be able to generate multiple beams from a single target station at Project X because megawatt-class target complexes are truly major investments. A fifth beam, a conventional one, could use forward pions from the downstream target.

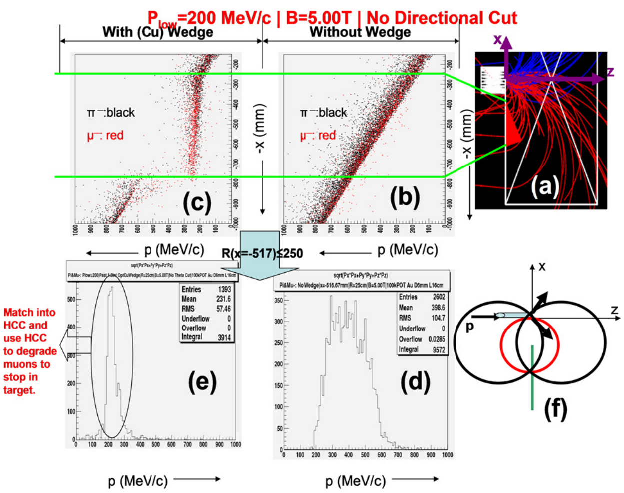

Figure 2: The Dipole/Wedge configuration to produce a 200 MeV/c pion beam in a dipole field of 5 T. (a) Top view of pions and muons in the Dipole/Wedge. Negatively (positively) charged particles are red (blue). (b) and (c) Correlation between momenta and horizontal exit position from the dipole for π^- and μ^- without and with a wedge, respectively. (d) and (e) Momentum projection from (b) and (c), respectively. Note direction reversal of momentum plot for (d) and (e). (f) Cartoon explaining momentum asymmetry in (b). Pions with a non-zero production angle must have a higher momentum in order to reach the same horizontal position at the wedge.

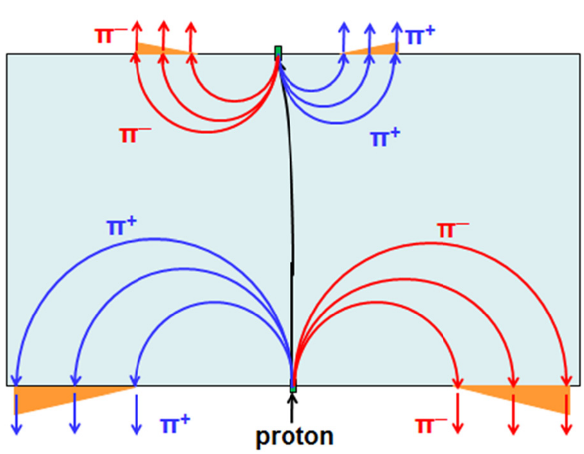

Figure 3: Layout of single dipole with two targets and four wedges to produce four monoenergetic pion beams from a single proton beam.

PION PRODUCTION SIMULATIONS

The first step in evaluating the performance of such a facility has been to simulate the production of pions by the 1-GeV and 3-GeV protons of Project X. This paper presents the results of the production studies done so far. A comparison of the results for forward vs. backward production of negative pions by 1-GeV protons is one of our goals. These pion production simulations used a rod-shaped gold target with a radius of 2.5 mm and a length of 15.24 cm, corresponding to 1.5 interaction lengths. The proton beam has Gaussian transverse profiles with projected rms beam sizes of 1 mm. G4Beamline [7] was used for these simulations.

Figure 4 shows the fluxes of negative pions produced by protons of various energies and emerging from the target as a function of cos(θ), the polar angle, and momentum. There are several features worth noting, especially for those more accustomed to higher-energy production. First, there is depletion for momenta near zero, caused mainly by the effects of ionization energy loss on low-energy pions leaving the target. That effect motivated the choice of a small target radius in these studies. It also suggested the system concept shown in Figure 3, in which the size of the upstream target can be made smaller than the proton beam size.

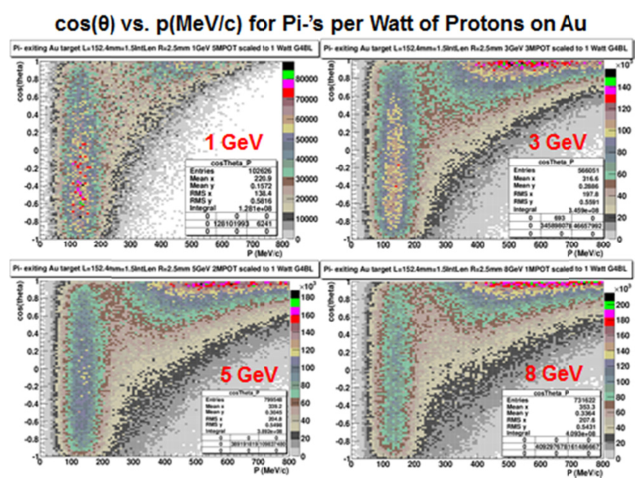

Figure 4: The fluxes of π^-'s exiting a gold target vs. Cos(θ) and P(MeV/c) for protons with kinetic energy 1 GeV (upper left), 3 GeV (upper right), 5 GeV (lower left), and 8 GeV (lower right). Entries in plots are scaled to a beam power of 1 Watt.

Secondly, the flux is depleted for momenta in the vicinity of 285 MeV/c due to pion interactions in the target at the peak of the Δ resonance in pion-nucleon interactions. Third, there is an enhancement around 120 Mev/c, especially for negative pions produced in the backward hemisphere; it is most pronounced for low-energy incident protons. However, Mokhov [8] has recently pointed out that the backward enhancement predicted by modelling tends to be larger than what is observed experimentally.

Figure 5 shows results like those of Figure 4, this time for positive and negative pions at 1 and 3 GeV. Note the copious production of high-energy pions in the forward direction for all cases except that of negative pions produced by 1-GeV protons.

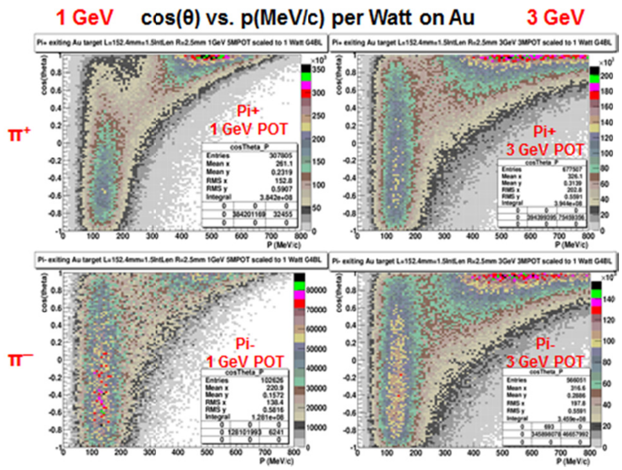

Figure 5: The fluxes of π^+'s (upper) and π^-'s (lower) exiting a gold target vs. Cos(θ) and P(MeV/c) for protons of 1 GeV (left plots) and 3 GeV (right plots).

APPLICATION TO DIPOLE AND WEDGE

The dipole and wedge system works well for polar angles within about 300 mr of the forward or backward directions. Accordingly, Figure 6 shows momentum spectra of pions emerging within that angle for the various cases of interest. It should be noted that the production studies so far were done without a magnetic field. A magnetic field should help low-energy pions escape the target. That will be simulated in the future.

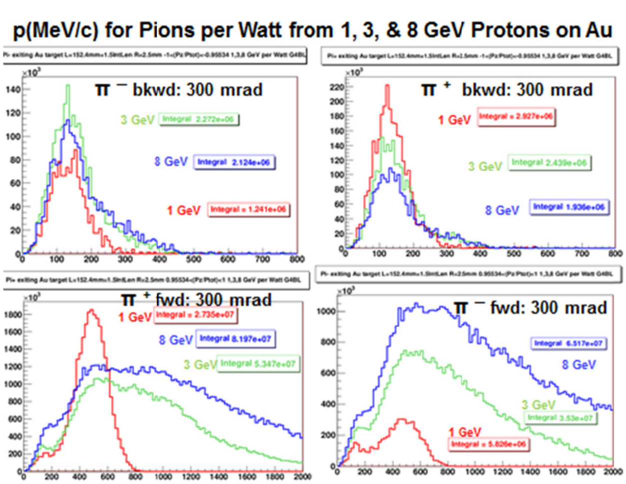

Figure 6: Momentum spectra (MeV/c) of π^+'s and π^-'s traveling forward (within 300 mrad) or backward (<300 mrad), produced by 1, 3, and 8 GeV protons. The plots are normalized to 1 Watt of beam power. The placement of the plots (right/left & upper/lower) matches the location of the beams in Figure 3.

A few conclusions are immediately obvious. After a wedge, the backward beams would have momenta around 100 MeV/c or lower, too low for ionization cooling to be effective. So they should just be decelerated to the stopping target. (V. Lebedev [9] of Fermilab has recently proposed another concept using backwardly produced negative pions for a conversion experiment.) On the other hand, the forward beams could be effectively "wedged" to about 250 MeV/c or higher, ideal momenta for ionization cooling using a variable-energy helical cooling channel without embedded RF cavities.

Table 1 compares pion yields to be expected under the various conditions. The momentum bite of 200 MeV/c corresponds to a reasonable width for a wedge.

Table 1: Particle yields per Watt in 200 MeV/c momentum windows in Figure 3.

PID	Dir	KE(p) (GeV)	ΔP (MeV/c)	$N_{particle}$ per Watt
π^-	bkwd	1	50-250	1.167×10^6
π^-	bkwd	3	50-250	1.949×10^6
π^-	bkwd	8	50-250	1.683×10^6
π^+	bkwd	1	50-250	2.75×10^6
π^+	bkwd	3	50-250	2.117×10^6
π^+	bkwd	8	50-250	1.606×10^6
π^+	fwd	1	400-600	1.639×10^7
π^+	fwd	3	500-700	1.022×10^7
π^+	fwd	8	500-700	1.176×10^7
π^-	fwd	1	400-600	2.726×10^6
π^-	fwd	3	450-650	7.214×10^6
π^-	fwd	8	500-700	1.016×10^7

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