MUON CIRCULATION IN THE FNAL PRECOOLER*

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ABSTRACT

The pions produced simultaneously with antiprotons are utilized to provide a circulating beam of decay muons that can serve as a source of neutrinos. The considered design indicates a primary produced flux of 1.5×10^9 decay muons per incident proton pulse.

INTRODUCTION

The Fermilab (FNAL) $\bar{p}p$ collider will require a refilling roughly every six hours. During the collection period, each 10 seconds an 80-GeV proton beam of 1.8×10^{13} ppp will strike a short tungsten target, thereby producing secondary particles. Negatively charged particles of momenta 5.357 GeV/c will be transported over a 121 m flight path to the precooler. Figure 1 shows a possible schematic of the beamline and precooler. Antiprotons will be selectively cooled and decelerated over the cycle time of several seconds. However, a substantial flux of unstable particles will be captured and circulate in the precooler for the first millisecond. We discuss the $\pi^-\mu^-$ component below.

BEAM DESIGN

The running conditions dictated the design parameters, namely to allow for achromatic injection of a beam of antiprotons with emittance 5.0π mm-mr and possessing a momentum spread $\Delta P/P$ of ±2.0%. A small source size ($r_o = 0.316$ mm) was chosen to increase the rate of collected antiprotons. The beam design assumed a 6.0 cm tungsten target. Total length was 121.5 m from target to precooler. A detailed discussion of the beam design has been presented in FNAL $\bar{p}$ Note #86.[1]

With the given source size radius (0.316 mm), a larger emittance and momentum spread beam can be passed by the transport line. Figure 2 shows the limiting envelopes for a beam with $\varepsilon = 12.64\pi$ mm-mr and $\Delta P/P = \pm 5 \times 10^{-2}$. The solid angle acceptance of the beam line can be computed as $\Delta\Omega = \pi\Theta^2$ where $\Theta = (12.64/0.316)$ mr. We have then $\Delta\Omega \sim 5$ msr for magnet apertures of 50 mm radius. The Monte-Carlo program DECAY TURTLE[2] has been utilized to evaluate the integrated $\Delta\Omega\Delta P/P$ product -- a value of 0.5873 msr was obtained. In fact, the system passes rays having even larger values of $|\Delta P/P|$ -- up to 8×10^{-2} with reduced intensity. The rms half-widths of the Θ and $\Delta P/P$ distributions for particles surviving transport to the precooler are 19 mr, and 3.9×10^{-2}, respectively.

PION AND MUON TRANSPORT TO PRECOOLER

DECAY TURTLE[2] was used to evaluate the integrated product $f_i\Delta\Omega\Delta P/P$ for both π^- and μ^- particles. Pions were started isotropically in the target with a maximum starting semicone angle $\Theta = 50$ mr and $|\Delta P/P| < 10 \times 10^{-2}$; surviving pions were allowed to decay to $\mu^-\nu_\mu$ with a characteristic length $L_o = \beta\gamma c\tau$ where $c\tau = 7.80$ m — this is 299.5 m at the central momentum of 5.3567 GeV/c. The factor f_π in the equation above is the decay survival fraction for pions ($\equiv 0.667$) or $\exp(-L/L_o)$ where $L = 121.5$ m at injection into the precooler. For muons, we have $f_\mu = (1 - f_\mu)g_\mu$ where g_μ represents the fraction of produced muons that reach the end of the channel. We found $f_\mu = 0.0755$. The actual particle yield at the precooler entrance is given by:

$$N = N_p \frac{d^2N_\pi}{d\Omega dp} R \, f_i \, \Delta\Omega \, \frac{\Delta P}{P} \, P \tag{1}$$

where N_p is the number of incident protons and $d^2N_\pi/d\Omega dp$ is evaluated from C.L. Wang's formula[3] (with $\Theta = 0$).

$$\frac{d^2N_\pi}{dpd\Omega} = 1.572 \times 80 \times X(1-X)e^{-5.73 \, X^{1.33} \, - \, 4.25 \, P_\pi \Theta} \tag{2}$$

Thus, $d^2N_\pi/dpd\Omega = 5.616$ pions/(GeV/c × sr × int. proton). The factor R is the target efficiency times the π survival fraction $R = Le^{-L/\lambda}/\lambda$ where L is the target length (6.0 cm) and λ the absorption length for tungsten (10.3 cm). Finally, the term X in Eq. (2) is the ratio of outgoing to incoming momentum ($\equiv 5.356/80$). Using Eq. (1), we find fluxes of 6.9×10^{10} π^- and 0.78×10^{10} μ^- reaching the precooler for each pulse of 1.8×10^{13} protons incident.

PRECOOLER CIRCULATION

We are interested in producing a circulating beam of μ^-, thus, we want to track the π^- around the ring and monitor the flux and phase space of surviving muons. In fact, the precooler accepts a smaller momentum bite than the upstream transport line. Stable particles were tracked one time around the ring using DECAY TURTLE. The integrated acceptance $\Delta\Omega\Delta P/P = 0.2937$ msr was obtained. This number is one-half that of the transport line. The rms half-widths of the Θ and $\Delta P/P$ distributions for surviving particles were 19.5 mr and 1.8×10^{-2}, respectively. Next, pions were run through the entire path of 595.6 m (transport + 1 revolution of precooler). We obtained $f_\pi = 0.137$; the corresponding value for decay muons was $f_\mu = 0.0406$. Using Eq. (1), we calculate the fluxes after one revolution.

$$N_\pi = 1.8 \times 10^{13} \times 5.616 \times 0.325 \times 0.137 \times 0.2937 \times 10^{-3} \times 5.357 \tag{3}$$

or $N_\pi = 0.71 \times 10^{10}$ and similarly $N_\mu = 0.21 \times 10^{10}$.

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One notes that the muon flux has dropped significantly. The loss was due mainly to removal of low momentum muons. We expect a roughly constant circulating muon beam flux of about 0.15×10^{10} over the first few revolutions. These muons would cluster at the machine momentum of 5.357 GeV/c and possess a momentum spread $\Delta P/P = \pm 3 \times 10^{-2}$. In addition, the μ beam emittance is about 40π mm-mr in both planes.

A discussion of neutrino fluxes obtained from the muon decays is given by D. Neuffer.[4]

REFERENCES

1. E. Colton, *Antiproton Transport to Precooler*, FNAL $\bar{p}$ Note #86 (September 5, 1980).
2. K.Brown, D.Carey, and Ch.Iselin, *DECAY TURTLE*, CERN 74-2 (1974).
3. C.L. Wang, Phys. Rev. D10, 3876 (1974).
4. D. Neuffer, *A Muon Storage Ring for Neutrino Oscillation Experiments*, this conference.

FIGURE CAPTIONS

Figure 1. Planned overall layout of target, transport, and FNAL precooler.

Figure 2. Beam envelopes through system for $\epsilon = 12.64\pi$ mm-mr and $\Delta P/P = 5 \times 10^{-2}$.

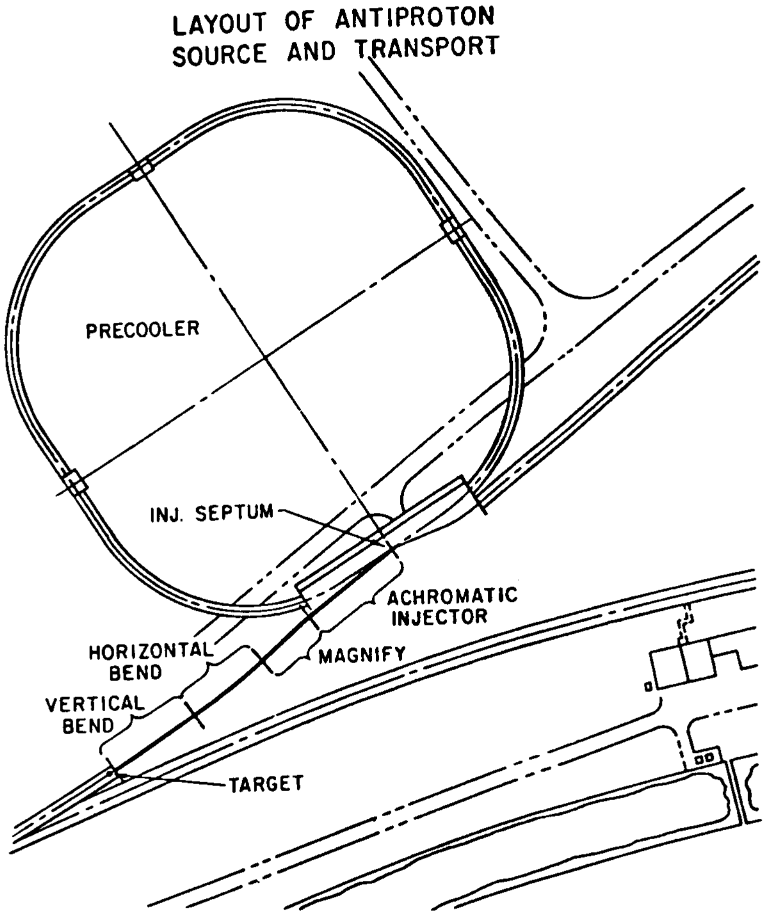

FIGURE 1

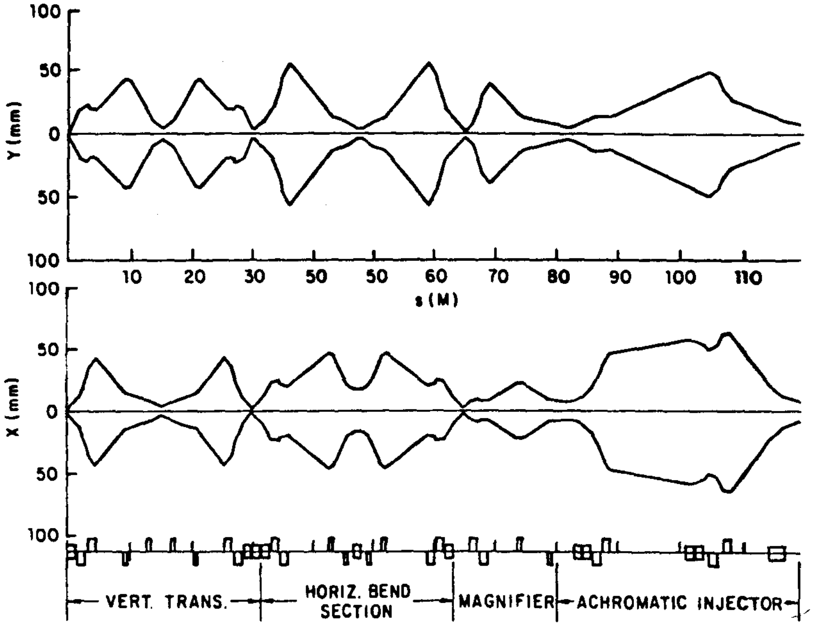

FIGURE 2

DESIGN CONSIDERATIONS FOR A MUON STORAGE RING

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ABSTRACT

It was noted earlier[1] that a muon (μ) storage ring can provide neutrino (ν) beams of precisely knowable flux and therefore suitable for ν oscillation experiments. In that paper it was suggested that parasitic use of the Fermilab $\bar{p}$ precooler could provide a useful μ storage ring. In this paper design possibilities for μ storage rings are explored. It is found that a low energy (~1 GeV) ring matched to a high intensity proton source (8 GeV Booster) is most practical and can provide ν beams suitable for accurate tests of ν oscillations.

INTRODUCTION

In an earlier paper[1] it was noted that a muon storage ring can provide electron neutrino and muon neutrino beams for the study of neutrino oscillations. In that paper the Fermilab $\bar{p}$ precooler[2] was studied as a possible μ storage ring and flux estimates for the resulting ν are obtained.

The Fermilab $\bar{p}$ precooler must perform functions of $\bar{p}$ collection at 4.5 GeV/c $\bar{p}$ cooling and deceleration to 600 MeV/c, followed by $\bar{p}$ acceleration from 600 MeV/c to 8 GeV/c. The ring is designed for the maximum momentum of 8 GeV/c and is not optimum for μ storage at 4.5 GeV/c. In this paper we explore the possibility of designing a ring specifically for μ storage, and compare the resulting neutrino fluxes to the earlier precooler estimate.

The operation of a muon storage ring to provide neutrinos has been described previously by Cline and Neuffer[1], and is illustrated in Figure 1. A proton beam is focussed with high intensity on a target of ~1-2 interaction lengths, producing large numbers of secondary pions. The pions are separated from the non-interacting protons and transported to injection in a storage ring. Pion decay within the injection transport and after injection provides muons ($\Pi\rightarrow\mu\nu_\mu$), which are stored within the ring for the muon lifetime. Muon decay in the ring straight sections ($\mu\rightarrow e_\nu\nu_\mu$) provides collimated ν_e and $\bar{\nu}_\mu$ beams. A detector is placed along a beam line at some distance L from the ring to observe ν-interactions.

In reference 1, it was estimated that ~5×10^8 - 5×10^9 ν_e and ν_μ per pulse of 2×10^{13} 80 GeV/c protons could be obtained using the $\bar{p}$ precooler as a 4.5 GeV/c μ storage ring.

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