

MODULAR TRANSPORT DESIGN FOR FNAL ANTIPROTON SOURCE TO PRECOOLER*

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Summary

An efficient beam collector and transport design is presented which transfers and matches a 4.5 GeV antiproton beam with momentum spread of $\pm 2\%$ into the precooler admittance of 5.0π mm-mr. The limits of the transport are a solid angle acceptance of 5.0 msr and momentum pass band of $\pm 5\%$. A short focal length pulsed lithium lens serves as the collector. The following beam transport line is composed of: (1) vertical translation section; (2) horizontal translation section; (3) matcher; and (4) injector. Monte-Carlo techniques are utilized to evaluate effects of aberrations and multiple scattering upon the computed particle yields. Estimates are presented of the pion and muon fluxes injected into the precooler.

1. Introduction

The Tevatron I upgrade includes the creation of an antiproton (\bar{p}) source for the purpose of providing for $\bar{p}p$ collisions at a c.m. energy of 2 TeV with a luminosity of greater than $10^{30}/(\text{cm}^2 \text{ s})$.¹ The source will consist of one or more rings which cool and accumulate significant fluxes of circulating antiprotons; 80 GeV extracted protons will be used to produce 4.5 GeV \bar{p} in a short, dense target. The collector and following transport should inject a maximum number of these particles into the acceptance of the following cooling ring. Therefore, one must minimize effective beam emittance growth due to chromatic aberrations and scattering. For this scenario, the full precooler admittance ellipses possess an area of 5.0π mm-mr in both transverse planes, and the $\Delta P/P$ passband is $\pm 2\%$ full width.

The collector was chosen to be a pulsed lithium rod through which the \bar{p} beam passes. The azimuthal magnetic field setup within the conductor is linearly proportional to the pulse current and to the beam radius.² The device functions as a cylindrically symmetric focusing thick lens. The beam can be kept uniformly small ($r < 1$ cm), thus reducing chromatic aberrations significantly, as compared to a quadrupole collection system. This consideration outweighs the effect of multiple scattering when transport of large values of $\Delta P/P$ are contemplated.³ The transport line consists of modules of telescopes or half-wave transformers. These systems consist of four quadrupoles and possibly bending magnets; they possess point-to-point and waist-to-waist optics and exhibit advantageous chromatic characteristics.⁴ The minimum system consists of the collector, matcher, and injector (just two modules). We include two translation systems between the collector and matcher, which serve to select the proper charge and momentum and provide for isolation from the proton beam. Each of these translation systems consist of two modules that possess a net unity transform. In Sec. 2, we discuss the optical design; the Monte-Carlo techniques utilized to calculate the performance of the system are discussed in Sec. 3. The \bar{p} , π^- , and μ^- yields are calculated in Sec. 4. Improvements and conclusions are communicated in Sec. 5.

2. Beam Design

The specified match conditions at the precooler injection were $\beta_x = 13.59$ m, $\beta_y = 9.25$ m, and $\alpha_x = \alpha_y = \eta_x = \eta_x' = \eta_y = \eta_y' = 0$. The injection takes place via a 3.0 mr fast kicker preceded by a combination of pulsed and dc septum magnets. The β and α functions are matched at the bend point of the pulsed septum magnets, and η , η' on the machine side.

The transport includes four achromatic sections: (1) vertical translation ($\Delta y = + 2.93$ m); (2) horizontal bend; (3) matcher; and (4) injector. The six telescopes are specified in Table 1. M_x and M_y refer to the optical magnifications of each telescope. One notes that telescopes 1 and 2 are mirror symmetric, as are 3 and 4. The systems were designed using TRANSPORT.⁵ A listing of the chosen beam line is given in a design note.⁶ The physical layout of the beam transport in the xz plane is shown in Fig. 1; the focusing thin lenses represent horizontally focusing quadrupoles. Horizontal bends are depicted by prisms. The general layout of the overall system is exhibited in Fig. 2.

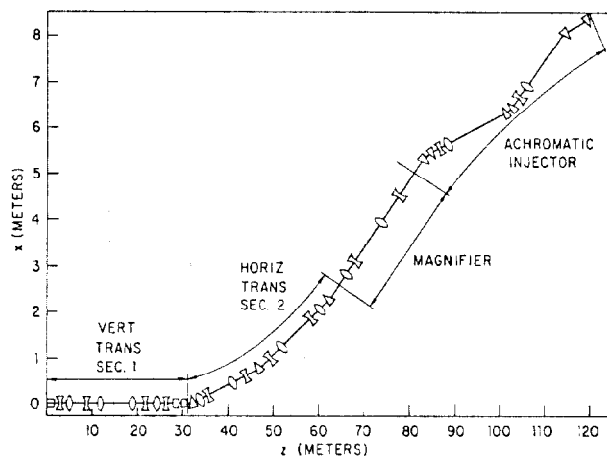


Fig. 1. Physical Layout of the Components of the Beam Line

Table 1. $\lambda/2$ Transformers

No.	M_x	M_y	Length (m)	Net Bend
1	-1.75	-2.00	14.93	5.625° up
2	-0.57	-0.50	14.93	5.625° down
3	-2.00	-1.50	17.51	4.219° left
4	-0.50	-0.67	17.51	4.219° left
5	-3.51	-2.38	16.35	---
6	-0.95	-1.16	38.51	6.454° right
Total	3.34	2.76	119.75	1.987° left

The final magnifications listed in Table 1 assume a "source" described by $\beta_x = \beta_y = 1.217$ m. This waist was obtained at a point 1.5 m downstream of a 0.1 m long lithium lens. The initial collection angle was

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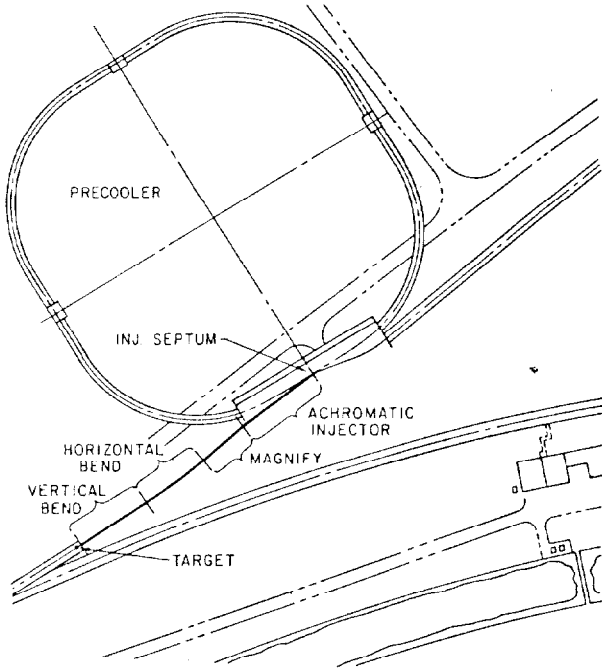
LAYOUT OF ANTI-PROTON
SOURCE AND TRANSPORT


Fig. 2. Overview of Precooler and Transport Sections

arbitrarily taken to be ± 15.8 mr (for $\epsilon_x = \epsilon_y = 5.0\pi$ mm-mr) from the primary source point 0.2m upstream of the collection lens. For 4.5 GeV \bar{p} ($P = 5.3567$ GeV/c), one needs a gradient of 840 T/m in the lithium lens. The aperture of the lithium lens represents the limiting constraint upon the beam line acceptance. A maximum semicone angle of 40 mr can be collected for the planned location of the lens. We use this source as input to the beam line and show the TRANSPORT beam envelopes in Fig. 3 for $\Delta P/P = \pm 5\%$. The entire system is nicely matched to these conditions and corresponds to a solid angle acceptance of 5.0 msr.

3. Beam Performance

We address two topics in this section: (1) the integrated solid-angle momentum acceptance of the system $\Delta\Omega\Delta P/P$, and (2) the matching of the transport to the precooler admittance. The program DECAY TURTLE⁷ has been utilized to obtain $\Delta\Omega\Delta P/P$. Rays were generated in a 0.316 mm radius source, randomly in $\Delta P/P$ with a spread of $\pm 10\%$, and using the standard transverse phase-space generator. They were tracked through the lithium lens and remaining transport. Particles striking an aperture (max transverse size ± 50 mm) were removed from the beam. A result of 0.5873 msr was obtained for $\Delta\Omega\Delta P/P$. For 5.0π mm-mr, the precooler accepts $\pm 2\%$ $\Delta P/P$ \bar{p} into the admittance ellipses

$$\left(\frac{x}{3.24 \text{ mm}}\right)^2 + \left(\frac{x'}{0.606 \text{ mr}}\right)^2 \leq 1.0$$

and

$$\left(\frac{y}{6.80 \text{ mm}}\right)^2 + \left(\frac{y'}{0.735 \text{ mr}}\right)^2 \leq 1.0$$

where x' and y' are the usual divergence angles. For no multiple scattering and no chromatic aberrations, all particles produced in an initial semicone angle of 15.8 mr would be collected into the above admittance ellipses. Incorporation of two identical sextupoles

placed π phase-shift apart in the horizontal bend section (see Fig. 3) reduce the vertical chromatic aberration term ($y|y'_0 \Delta P/P$).⁶ We find that 80% of the particles are collected into the admittance ellipses (1) for $|\Delta P/P| \leq 2.0\%$.

4. Particle Yields

The transmission t of the beam line, i.e., the fraction of \bar{p} that are accepted by the precooler (Eq. (1)), is found to be $t = 4.42 \times 10^{-2}$ so $t(\Delta\Omega\Delta P/P) = 2.59 \times 10^{-2}$ msr; t is reduced to 3×10^{-2} when multiple scattering in the lithium lens is included. The t is also a function of the production z within the target, which we take to be 6.0 cm tungsten. This has been modeled by running DECAY TURTLE starting the source at different z values, and following with the appropriate multiple scattering. Absorption is included in the yield calculation (below). We write the ratio of useful \bar{p} to incident protons as:

$$\frac{N_{\bar{p}}}{N_p} = \int_0^L \left(\frac{d^3 N_{\bar{p}}}{dz d\Omega dP} \right) \left(\frac{\Delta\Omega\Delta P}{P} \right) P_{\bar{p}} t(z) dz \quad (2)$$

where:

$$\frac{d^3 N_{\bar{p}}}{dz d\Omega dP} = \left(\frac{1}{\sigma} E \frac{d^3 \sigma}{dP^3} P_{\bar{p}} \right) \frac{e^{-L/\lambda}}{\lambda} \quad (3)$$

is the differential production cross section.¹ In Eq. (3), the bracketed term is $0.8 \times 5.3567/33 = 0.13$ (GeV-sr)⁻¹, L is the target length, and λ is the absorption length (assumed 10.3 cm for both 80 GeV protons and 4.5 GeV \bar{p}). We find $N_{\bar{p}}/N_p = 2.3 \times 10^{-6}$; this is somewhat less than the value of 3.2×10^{-6} quoted in the design report.¹

The π and μ injected in the precooler has also been calculated. The number of pions is given by:

$$N_{\pi} = N_p \frac{d^2 N}{d\Omega dP} \left(\frac{Le^{-L/\lambda}}{\lambda} \right) f_{\pi} \frac{\Delta\Omega\Delta P}{P} P_{\pi} \quad (4)$$

where f_{π} is the decay survival fraction (≈ 0.667) and the differential cross section is obtained from Wang's formula⁹ with $\theta = 0$. We find $d^2 N_{\pi}/dP d\Omega = 5.616$ pions/(GeV/c-sr \times int. proton). Equation (4) yields $N_{\pi}/N_p = 3.83 \times 10^{-3}$. DECAY TURTLE was run, allowing for $\pi \rightarrow \mu \nu$ in the transport line. The muon yield is calculated as in Eq. (4), but with f_{π} replaced by $f_{\mu} = (1 - f_{\pi})g_{\mu}$ where g_{μ} is the fraction of produced muons that reach the precooler; we find $f_{\mu} = 0.0755$, so $N_{\mu}/N_p = 0.43 \times 10^{-3}$. We have also calculated the π , μ fluxes remaining after one lap around the precooler. In this case, the combined aperture acceptance $\Delta\Omega\Delta P/P$ is 0.2937 msr. The 595.6 m path yields $f_{\pi} = 0.137$ and $f_{\mu} = 0.0406$. Using Eq. (4), we obtain $N_{\pi}/N_p = 0.39 \times 10^{-3}$ and $N_{\mu}/N_p = 0.116 \times 10^{-3}$. After the first few revolutions, the pions will have decayed away, leaving a roughly constant circulating muon flux equivalent to $N_{\mu}/N_p = 0.083 \times 10^{-3}$.

5. Discussion

The obtained flux $N_{\bar{p}}/N_p = 2.3 \times 10^{-6}$ impacts upon the collection time. Thus, we have investigated further options for increasing the yield, in particular to find

the maximum rate that can be obtained, irrespective of engineering and radiation safety considerations.

(a) The first option tried was to reduce the primary source to a radius of 0.1 mm; a production semi-cone angle of 50 mr can be collected. A 7.5 cm lithium lens collector was followed by a matching telescope and our previously-designed injector; no translation sections were incorporated. The best yield was obtained for a 2.0 cm tungsten target. Including multiple scattering, we find $N_{\bar{p}}/N_p = 4.75 \times 10^{-6}$. This represents a $\times 2$ gain over the conservative system.

(b) Another option involved replacing the lithium lens by pulsed quadrupole multiplets. These were less satisfactory because of severe chromatic aberrations in the plane in which the second quadrupole was focusing. The best yields were found to be $N_{\bar{p}}/N_p \leq 1.8 \times 10^{-6}$. Clearly, large $\Delta P/P$ values exacerbate the collection problem.

The antiproton transport to pre cooler will no doubt pass through several stages as the machine requirements are finalized; target and radiation safety problems have to be solved. The modular approach will prove useful in the final designs.

References

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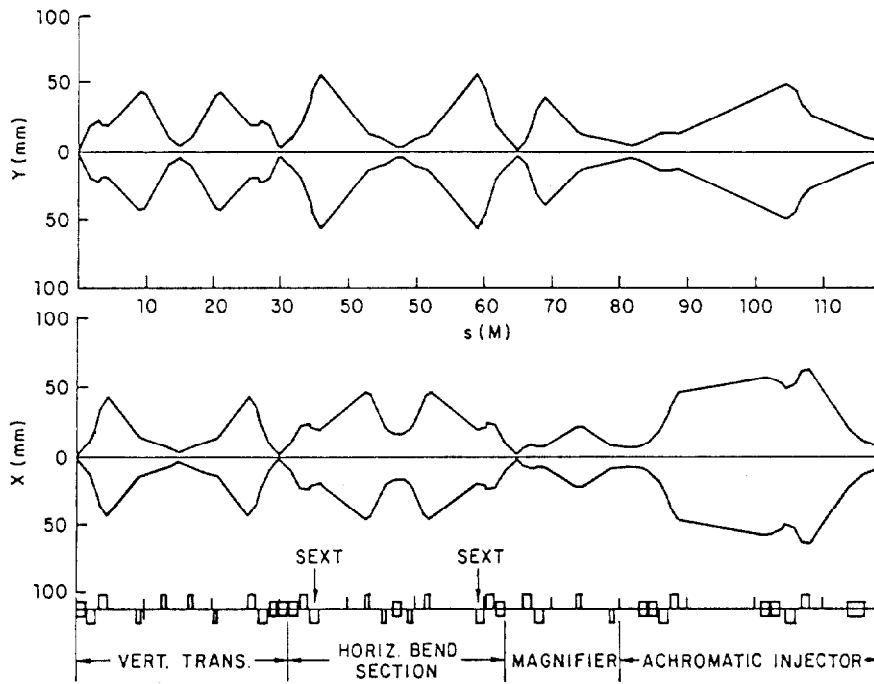


Fig. 3. Beam Envelopes through the System for $\epsilon = 12.6\pi$ mm-mr, $\Delta P/P = \pm 5\%$. Source $r_0 = 1.98$ mm Waist from Upstream Lithium Lens.