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Antiproton Production Beam and Reverse Injection System

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I. Design Requirements

The objectives of this project are two fold: (1) To extract high energy protons from the Main Ring (MR) and target them to produce antiprotons which are subsequently captured in the existing Booster accelerator; and (2) to provide a channel for injecting either protons or antiprotons into the MR from the booster in a direction opposite to that of the normal proton acceleration as colliding beams can be created.

The present design, therefore, is in support of two separate larger projects, viz., the collisions of protons in the Tevatron (normal circulation direction) with "reverse injected" protons in the MR, and the collision of normal direction protons with reverse injected antiprotons either in the MR or in the Tevatron.

Figure 1 shows the layout of the project area. It spans the shortest distance between possible injection/ejection points in the existing accelerator structures, hence minimizing costs. The tunnel will lie underground at the level of the MR and booster.

We now formulate the principal requirements for the design of the beam elements and optics:

1) The antiproton production beam line and the reverse injection line must operate compatibly in the same tunnel and operation must be switchable from one to the other without human entry in a time measured in minutes.

2) The target area must accommodate radiation and activation levels as great as any so far produced at Fermilab.

3) "Fail-safe" features must be incorporated to insure that no serious threat results from accidents or element failures.

4) The target area should be as close to the MR as possible to allow flexibility in installing another ring to capture and cool antiprotons for future upgrading. Such placement also allows magnet services to be brought over from the MR tunnel to save costs.

5) Since elements near the production target will be strongly irradiated,these should be capable of radiation hardening. Failure of these elements should not stop the reverse injection line from working so that antiprotons already collected can be used or a switch to p-p collisions can be made if immediate repairs are inconvenient, of course, a means for making repairs in this critical area must be provided.

The following, although not taken as absolute requirements, were considered to be "desirable features" in planning:

6) The production and reverse lines should have as many elements in common as possible.

7) As far as possible, the elements used should be existing laboratory types.

8) The use of air cooling in quadrupoles over the long stretch between target and booster is desirable to save the cost of installing water cooling there.

9) The target area should be as small as possible both to cut cost and to aid in protecting the surrounding soil from activation.

The emittances of the beams to be transported by the system have been discussed in the original proposal,[1] along with many other parameters. However, we note here that the entire system must be capable of transporting $\varepsilon_x = 2\pi$ mm-mr, $\varepsilon_y = \pi$ mm-mr in the reverse direction. This is the normal booster values at 10 GeV/c injection into the MR. However, we will provide $\varepsilon_x = \varepsilon_y = 4\pi$ mm-mr emittance for the 6 GeV/c antiproton collecting beam, since this proved to be feasible without extraordinary measures. Such a beam will be captured by the booster, but only the equivalent of $\varepsilon_x = 2.6\pi$, $\varepsilon_y = 1.3$ mm-mr will survive deacceleration to the 650 MeV/c cooling momentum. It is possible that improvements can be made in the booster acceptance, and if they do appear, we would not want to be limited by the beam.

II. Description of the Beam Transport System

We now give an overall description of a beam transport system fulfilling the above requirements.

A. Production Beam

The extracted 80 GeV proton beam element layout is shown in Figure 2. Extraction takes place in the straight section at F17 (F1 service building) where a septum magnet will be placed. A kicker magnet one quarter wavelength upstream must also be provided. Extraction will be in the vertical direction because less angular deflection is required to miss the following dipole (the angle needed is 26.8 mr) than for horizontal extraction. The next MR dipole must have a special coil

so that the beam pipe can pass next to the magnet steel, under the end-loop.

The required septum, using existing technology, will fill the straight section. Hence extraction at higher energy would require considerable development work. Nevertheless, the following elements, as described below, will be capable of handling 100 GeV/c, in case such development seems necessary.

Finally, the "kicker" will have to operate reversibly for injection at 10 GeV/c as well as ejection at 80 GeV/c, for antiprotons as well as protons.

The extracted beam is pitched flat 19 inches above normal orbit height by a special 18 foot dipole of the EPB type, i.e. made from standard laminations but with length tailored to fit between the end loops of the second MR dipole after the F17 straight. Horizontal bends begin immediately after this pitching is done, or the extracted beam will strike the tunnel wall. A total of four EPB 10 foot dipoles are required.

The beam is then kept within the MR tunnel wall, and made to follow the accelerated orbit fairly closely, as in Figure 2, by distributing horizontal bends evenly over positions F21 and F23, so that beam elements will not block the MR tunnel and impede normal maintenance activities. Finally, a counter clockwise bend near F25 brings the beam out through a penetration provided in the alcove under F2 service building. Providing a tunnel penetration at any other point would require a long slot in the tunnel wall, because of the small angles involved, and the consequent weakening of the wall is unacceptable.

The geometry around the F25 outward bend is very tight, and an EPB dipole cannot be placed in the alcove itself. This means the last bend, needing a total of 5 EPB 10' dipoles, encroaches upon tunnel space more than is desirable. This can only be avoided by using special order dipoles tailored to fit in the alcove.

The extracted proton beam then enters a length of 10" pipe, buried in the ground, which allows beam to enter the transfer hall, but serves as a permanent radiation boundary. The transfer hall, indicated in Fig's 1,2, and 3, contains the quadrupoles required to produce a highly focussed beam spot on the production target. It is accessible through a radiation maze, so that the elements there may be serviced in situ, and the actual target may also be reached by remote handling devices.

Figure 3 shows the layout of the remaining parts of the beam, from transfer hall to booster. The target vault will be a high radiation area, so that the transfer hall will be protected from residual activity and gas activation by a wall between it and the target vault.

The target vault immediately follows the transfer hall, with the target position as close as possible to the separating wall. It will be possible to extract the target through the separating wall on a railway cart and store it in a lead pig in the transfer hall. The target itself is normally in a magnetic field which bends the 80 GeV proton beam downward by 5 mr. This insures that radiation from the beam dump after the target will be directed into the ground and will not fill the following tunnel with radiation.

The target is positioned about 25 cm from the downstream end of the magnetic field, so that the produced antiprotons are bent upwards

by a total of 15 mr. The result is that they rise at 10 mr. to the gravitational level. This bend introduces negligible dispersion into the antiproton beam - the importance of this is discussed in the next section.

The antiproton beam then rises by 11 inches - this is the difference in levels between the MR and booster tunnel penetrations - and is then pitched level. The target vault ends near this point and a buried 10" pipe separates it from the final beam transport tunnel.

Antiprotons are collected by a closely spaced quadrupole triplet immediately following the target magent. The surviving protons also go through this triplet but are separating from the antiproton beam axis because of the dipole field. The protons then can be dumped as soon as they exit the triplet. The optics are described in the next section.

There now follows a section of beam after the proton dump, in which the antiproton beam is matched to the emittance of the long FODO channel and rises the 11" difference in levels between MR and booster beams. The beam is pitched level near the end of the target vault and passes through the buried beam pipes into the FODO beam transport section.

The beam transport tunnel is formed from 4 ft. diameter sewer pipe containing a FODO channel with 100 ft. quadrupole spacing. These quadrupoles can have narrow aperture and low gradient, therefore, they can beam air cooled type[2]. The relatively short spacing and the 6 GeV/c transport momentum requirement allow this. Note however, that successful beam phase space matching requires the short spacing, so that the air cooling was not a determining feature in this design.

The beam is now bent clockwise, onto a line tangent to the booster orbit at booster straight section 3, requiring a bend of 8.5°. This bend introduces the first horizontal dispersion into the Antiproton beam, and this dispersion is needed to match to the booster phase space.

The bend is followed by a phase space matching section in the sewer pipe, and the beam finally penetrates the booster tunnel wall through another buried 12" beam pipe, which provides isolation of the areas. It is finally deflected downward into the booster straight septum magnet.

A. Reverse Injected Beam

Under reverse injection settings, the booster contains either protons or antiprotons rotating counter clockwise. Extraction is then channelled through the same septum and beam transport line,as for injection (using a charge independent kicker), except that the line is tuned for 10 GeV/c, the MR injection momentum, instead of the 6 GeV/c produced antiproton momentum. This beam then is transported to the target vault and the vertical pitching magnet (see Fig. 3) deflects it downward. However, in this case the reverse beam is pitched down only 8.42 mr instead of the 10 mr that would carry it along the antiproton beam axis. This reduced bend insures that the reverse beam misses the production target and falls to the level of the MR extracted beam some four meters "upstream" of the target, where it is levelled by a separate dipole. Note that for the reverse beam condition, the target dipole, collecting triplet, and the beam matching elements along the antiproton axis before the pitch to level, are all turned off, while separate interleaved elements aligned along the new axis are turned on.

Hence, the target need not be moved, and the "fail-safe" features mentioned earlier are present.

Once the reverse beam has been levelled, and matched at the MR penetration point, it follows the 80 GeV/c extracted beam orbit exactly, with those elements tuned to 10 GeV/c rather than 80 GeV/c.

At this point we note that, if the beam optics allow phase spaces to be matched at the MR, booster and target, all the design requirements of Section I have been met.

III Description of the Beam Optics

A. Main Ring to Target Area

At the point of extraction at F17, the circulating MR beam has substantial horizontal dispersion, and extraction introduces a small vertical component as well. The optical problem then is to remove both horizontal and vertical dispersions at the target so a very small spot may be achieved, meanwhile insuring that the beam size (β value) stays small enough so that the reverse injection beam (with much greater emittance than the 80 GeV/c beam) will not be wiped out in the relatively small vertical aperture of the bending magnets.

These requirements are met by the optics shown in Fig. 5. A FODO channel of four elements (Q1,Q4,Q5,Q6) nested among the horizontal bends, with gradients set for $\approx 30^{\circ}$ phase advance per cell, keeps the beam envelope from growing too large and brings the horizontal dispersion, η_x, to zero at the last bend, where η_x' is also brought to zero. A doublet, Q2 and Q3 is also placed about the point where η_x first passes through zero, and this is used to change the phase of β_y so that it is satisfactorily small at the horizontal bend positions. Final tuning required Q5 to move slightly off the equal spacing first assumed for the FODO.

After η_x is taken care of, another doublet, Q7 and Q8, is used to advance the phase of η_y. Note the Q7 polarity is opposite to that expected for a continuation of the FODO pattern, but Q8 is close enough so that β_x does not get out of hand. Even so, β_x will be too large for the aperture of MR quadrupoles, used up to this point, and a 4 inch bore quadrupole is needed. However, the beam path at this point is clear of the MR and there should be sufficient space in the F2 alcove for it to be mounted. As can be seen from Fig. 5, the beam envelope at the target position will be sufficiently small that it can by-pass the production target within the beam pipe under reverse injection conditions.

Figure 6a shows the optics used to produce a small spot in the production target. Q9,Q10,Q11,Q12 are four 10' EPB quadrupoles in the transfer hall set to produce the small target spot. The solution shown produces β_x = 5 cm, β_y = 10 cm, so that the expected 80 GeV/c emittance will allow a spot size of the order 0.1 - 0.2 mm.

For reverse beam operation, the quartet is turned off and a doublet is powered. This doublet is used to adjust vertical dispersion nearly to zero at the target position, so final matching to the antiproton channel can be done.

Up to Q6, optics for production and for reverse injection are identical - gradients are simply scaled to the momentum used. However, Q7 to Q12 lengths are tuned slightly differently in the two cases to make the appropriate matches.

B. Antiproton Collection Beam

The antiproton collection beam can be considered in four parts:

(1) A triplet front end and a beam dump for the incident protons;

(2) A matching section between the triplet and the long FODO channel,

with 540° phase advance (45° per cell) to transport large emittance and match η_y at the bend point near the booster; and (4) A horizontal bend and final matching section to create horizontal dispersion and match all parameters at the booster injection/ejection point.

The optics to be used in (3) and (4) are again identical (momentum scaled) for production and reverse injection. However, for reverse beam, (1) is turned off and separate elements in (2) are used for the required matching.

We now Describe Each Section Briefly:

(1) Front End of Collector Beam

The first elements of the beam (the front end) were chosen to produce a β of 2 cm in both horizontal and vertical planes at the target, and to allow capture of antiprotons of production angle within ±20 mr of the forward direction. As discussed in Section I, this will result in capture of antiprotons by a factor of 2 or more beyond that which will survive the adiabatic undamping during de-acceleration to the cooling momentum. These decisions will be further justified in Section IV.

However, we note here that if an incident beam spot size of σ=0.1 mm can be achieved, the introduction of a "spherical lens" such as the so-called HA-HA[3] lens, a Lithium current carrying cylinder, or current in a wire target[4], may increase the capture of antiprotons by producing a β of $\approx$1 cm at the target. Such a device could probably be inserted in front of the present beam without major structural alternations.

The choice of first elements is that of a close - patched triplet. The best completion-solutions of doublet and of quartet, were considered less favorable on the following grounds:

Doublet: The use of two elements with realistic fields at thier pole-tips required a beam envelope highly asymmetric in x and y. In turn this required a second element with large aperture (in both planes of course) which would require a special element such size as to require enlargement of the target vault over that of the final solution.

Quartet: An excellent solution was abtained with a auartet much like that used to obtain small β in the incident beam. Standard quadrupoles could be used with moderate gradients. However, the position of the beam dump would have to be far downstream because the quartet uses longitudinal drifts to obtain its focussing strength. This means a very substantial part of the incident beam energy would dump in the magnet coils, giving an unacceptable risk of insulation failure. (i.e., heating as well as radiation damate would be present.)

The triplet solution chosen is shown in Fig. 6. It provides a doulbe convergence, with the vertical envelope reduced so as to miss the beam dump. Spacial elements must be used here; however, the three quadrupoles may be made from laminations used for the FNAL standard 4Q120 quadrupole. The could must be wound on a special fixture and insulated using, eg, the ion arc method of baking on ceramic, which will be described elsewhere. The vacuum chamber should be the "dimpled" type to provide maximum aperture.

Figure 6 also shows how the "C" magnet around the target splits the proton and antiproton beams so that after the triplet a long beam dump may be introduced. Note that in case of failure of the C-magnet the proton beam still hits the dump quite squarely, providing a welcome fail-safe feature.

Because the antiprotons are bent upward so close to a minimum β point, negligible dispersion results. The bend introduces an effective spot size increase of <0.1 mm.

The antiproton beam roughly simulates the reverse beam as it passes over the target, at least as far as dispersion is concerned. This allows matching of the two lines to be done with quadrupoles only.

(2) Match to FODO Channel

The triplet is followed by three quadrupoles of large aperture, but needing one low field, to match the triplet into the FODO channel starting right after the vertical pitch magnet DV5. A solution was found using only two quadrupoles, but three allow some freedom is placing these elements, which must be intermingled with three quads needed to match the reverse beam (on an axis displaced by only a few cm).

(3) FODO Channel

The match shown introduces the $\bar{p}$ beam into the FODO channel at optimum aperture: i.e., the envelope repeats every 90°, or 2 elements. The vertical dispersion naturally crosses zero at the end of the FODO, so that matching to the booster will be simplified.

The properties to note in the FODO channel are: (1) all elements have equal and small field strength, (focal length = spacing/$\sqrt{2}$); (2) Maximum $\beta \approx 100$ meters, so that beams will have size $<\pm 3$ cm. This allows for later enlargement of emittance, modest good field requirements, and non-critical tuning properties.

Finally, note that only minimal dispersion η_y is introduced into the beam, as no sextupole correcting elements are required (see Sec. IV).

(4) Match to Booster

The match to the Booster from the FODO channel is accomplished by using a doublet after the bend point to match η_x, η_x' at the booster. Beam envelope and η_y, η_y' matching are done by introducing an extra quadrupole before the big horizontal bend and allowing variable strength in the last FODO element.

IV Beam Spot and Target Length: Theoretical Justification

We now try to justify the choices of solutions specified in the previous sections. So far as this author knows, the treatment is original.

The production of 6 GeV/c antiproton by 80 GeV/c protons is only weak by peaked at zero degrees. Consequently we can obtain most intensity by capturing large angles and concentrating phase space with a small beam spot. Since the Courant-Snyder beam parameter β at the target is just the ratio of spatical to angular width of a beam, we require β to be as small as possible at the target.

Capturing at large angles means the effective spot size varies with positions in the target (small "depth of field") only a short length of target will be useful and that should be high density. The chromaticity will also be large, so that sextupole corrections might be useful - in which case more dispersion would be needed in the beam than in the beam already described. Finally a high density target means small absorption length for both protons (good) and antiprotons (bad).

Optimization was studied by considering the overlap of the booster acceptance ellipse, as transformed to the appropriate position in the target, with the ellipse representing the produced $\bar{p}$'s at that point. The change of beam ellipse was made a function of position and momentum

with the capture efficiency considered uniform over it, and momentum acceptance falling linearly from the central value. The production phase space was taken to be uniform in angle $\frac{d\sigma}{d\Omega}$ = const, so that at any position in the target it is an upright strip of width σ_b equal to the quadrature of geometric and multiple scattering proton beam sizes. The assumption of uniform distributions will lead to an <u>underestimate</u> of capture efficiency.

The overlap capture cross sections in the x plane is obtained from

$$d\sigma_{cx} = \frac{dx}{\sqrt{2\pi}\,\sigma_b}\, e^{-x^2/2\sigma_b^2}\; 2\sqrt{\sigma_{22}(1-\rho_{12}^2)}\;\sqrt{1-\frac{x^2}{\sigma_{11}}}\;\frac{d\sigma}{d\Omega}$$

where x is the lateral position, σ_{11}, σ_{22}, and ρ_{12} are beam matrix parameters and are function of z and ρ (longitudinal position and momentum). These parameters are illustrated in Fig. 7(a) where the overlap is shown graphically.

Transforming the overlap integral to γ,θ variables we find

$$\sigma_{cx} = \sqrt{\frac{2}{\pi}}\,\frac{d\sigma}{d\Omega}\,\frac{\varepsilon_x}{\sigma_b}\int_0^{\pi/2}\frac{1-e^{-a\cos^2\theta}}{a\cos^2\theta}\,d\theta$$

$$\text{where}\quad a = \frac{\sigma_{11}}{2\sigma_b^2} = \text{function of z and p.}$$

$$\varepsilon_x^2 = \sigma_{11}\,\sigma_{22}\,(1-\rho_{12}^2) - \text{const.}$$

We define

$$F(a) = \frac{2}{\pi}\int_0^{\pi/2}\frac{1-e^{-a\cos^2\theta}}{a\cos^2\theta}\,d\theta,$$

noting $F(0) = 1$ and $\sqrt{a}\,F(a) = G(a) \xrightarrow[a\to w]{} \frac{2}{\sqrt{\pi}}$.

These functions are shown plotted in Fig. 7 (b).

Then, for both x and y planes, at fixed z and p;

$$\sigma_c = \frac{\pi}{2} \frac{d\sigma}{d\Omega} \frac{\varepsilon_x \varepsilon_y}{\sigma_b^2} F(a_x) F(a_y).$$

We now include proton and antiproton absorption factors, choose a target length and position where the beam is "focussed" and integrate over z, and ρ.

The beam parameters were chosen to be those for the beam optics of Fig. 6, where $\beta_o = 1$ cm, an appropriate strength, short , linear lens was considered palced immediately following the target.

The first result showed the effect of chromaticity was unimportant, so that sextupole corrections would give no increased capture. Hence large dispersion is also unnecessary. Basically, the booster ellipse focusses at different position still within the target for not too different momenta, and here the match will be nearly perfect (except for the actual momentum mismatch at the booster). This is illustrated in Fig 8 (a), where the geometrical overlap is shown as a function of Z for the on-momentum ray focusses at the center of a tungsten target. The integrated yield for $\delta\ \Delta\rho/\rho = +0.2\%$ is actually slightly larger than for $\delta = 0$, as $\bar{p}$'s can more readily escape from the downstream end of the target. (We took absorption lengths $\gamma_\rho = 10$ cm, $\gamma_{\bar{\rho}} = 7.5$ cm).

Figure 8(b) shows the effect of target length, coming mainly from absorption. The length integral changes surprisingly slowly. Note in both cases $\sigma_b \equiv$ geometrical beam size = 0.2 mm.

Figure 9 shows the effects of changing β_o to 1 cm and σ_b to 0.1 mm, while Fig. 10 shows the effect of target length. The central yield increases but is more peaked, resulting in a smaller increase

in yeild tha n one might predict intuitively.

Figure 11 shows the effects of folding in booster momentum acceptance and comparing length integrals. Note that for $\sigma_b = 0.2$ mm, no big gain comes out of changing β_o from 2 to 1 cm, but if σ_b can be made 0.1 mm, $\beta_o = 1$ cm will produce a factor of 2 increase in $\bar{p}$'s captured.

Finally, Figure 12 shows capture as function of target length. For strong absorption ($\lambda_p = 10$ cm, $\lambda_{\bar{p}} = 7.5$ cm) all curves indicate 5-6 in target length. For weaker absorption, we need 6-7 cm, while for $\sigma_b = 0.1$, $\beta_o = 1$ cm, length must be reduced to 4 cm to capture the extra beam available.

V Target Design

A Monte Carlo program for nucleus cascades was run by S. Mori for 80 GeV/c protons Tungsten. Energy deposition density profiles are shown in Fig. 13, for $\sigma_b = 0.5$ mm. The energy density D_E builds up to about 8 GeV cm^{-3}/proton at about 5 cm inside the target, and decreases thereafter. In a 6 cm target, 1.8 GeV total energy per proton is deposited.

At the peak in z, note that the lateral distribution is significantly broader than that of the incident beam, so that here a very small beam would still deposit its energy over a range with $\sigma \simeq 0.5$ mm. In the following we therefore assume that this is the beam size*.

The temperature distribution after heat is applied along the axis of the target is the solution of the damped wave equation

$$\frac{\partial T}{\partial t} = mV^2 T$$

where m is the diffusivity $\frac{\lambda}{\rho C}$. Here λ is The thermal of conductivity

of tungsten, $\lambda = 0.43$ cal $cm^{-1} sec^{-1} (^{o}C)^{-1}$, the density $\rho = 19.3$ gm/cm^3, and the specific heat $C = 0.032$ cal $gm^{-1} (^{o}C)^{-1}$.

Then

$$T(r,t) = \int_{o}^{\infty} \int_{o}^{2\pi} T(r',0) \frac{1}{4\pi mt} e^{-\frac{1}{4mt}(r^2+r'^2+2rr' \cos\theta')} r'dr'd\theta' .$$

For a square pulse of heat of radius σ_b

$$T(0,t) = T_o \left(1-e^{\frac{\sigma_b^2}{4mt}}\right).$$

Note that for 400 GeV protons the hadronic shower may have a much smaller radius and with the increased multiplicity, produce D_E much larger than for 80 GeV protons. In fact a CERN report concluded such targets would be destroyed by full SPS beams.

The maximum temperature rise in Tungsten on these assumptions is

$$T_o = 3.82\ 10^{-11} \frac{cal}{GeV} \frac{D_E N_p}{\rho C} = 990^{o}$$

assuming $N_p = 2\ 10^{12}$ protons/burst. The heat dissipation is governed by a relaxation time $t = \sigma_b^2/4m = 0.9$ msec, so that after 66 msec the temperature along the target axis will have fallen to 13° C. The melting point of the alloy considered is $\sim 3000\ ^{o}C\ \lambda$, and the interval between pulses is sufficient to allow cooling.

Each burst deposite 137 calories. There will be $\simeq 13$ such bursts, followed by $\simeq 2$ sec reacceleration of an 80 GeV beam, so the target must dissipate 2.5 K watts.