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Antiproton Production Beam and
Reverse Injection System

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1. Introduction

Colliding beam experiments at Fermilab have been considered in many guises, and were discussed in the 1968 Summer Study.¹ The POPAE² program was an early and very large scale proposal. The early decisions relating to the main ring tunnel size, access, etc, were influenced by the anticipation of the Tevatron and colliding beams experiments. The approach of using only one tunnel and two accelerators drastically reduces the cost of providing for colliding beams. Among the requirements to collide the beam in the main ring with that in the Tevatron is a means of injecting beam in the reverse direction and reversing the field in the main ring magnets.

During the early design stages of the reverse proton injection project, electron cooling of beams was successfully demonstrated at Novosibirsk.³ This technique makes possible the collection and storing of antiprotons until sufficient intensities are reached to make $\bar{p}p$ collisions with usable luminosities. Since protons and antiprotons have opposite charges they may be accelerated and stored in the same ring and made to collide to produce up to 2 TeV in the center-of-mass system - the highest energy by far that can be achieved anywhere in the foreseeable future.

Electron cooling, the subject of another design report,⁴ requires low energy particles to realize short cooling times for high emittance beams, while antiproton production yields peak at much higher energies. The needed flux can be obtained by capturing antiprotons in the existing booster accelerator and decelerating them before injection into the cooling ring where they can be accumulated and finally returned to the booster.⁵

Both antiproton production and reverse injection functions can be accommodated in a single channel, as this report will show. The area of major construction is shown in Fig. 1, which shows the two-way passage for particles from the booster to main ring tunnels and the enclosures for the antiproton production area, as well as the connection between booster and cooling rings. The detector area is not shown - it will be the subject of a later report.

Before launching into details of design in the next sections, a brief discussion of the physics interest in colliding beams is in order.

II. Physics with Proton-Proton and Proton-Antiproton Storage Rings

Present experimental and theoretical ideas of the structure of hadrons (strongly interacting particles) lead to the expectation that a sizable fraction of $\bar{p}p$ collisions at high energy occur between point-like particle and anti-particle constituents termed quarks or partons. It is also thought that protons will contain some antiquarks in a "sea" of high energy density so that $q\bar{q}$ collisions can occur in pp interactions as well. Then hadron collisions can be compared to e^+e^- collisions except that the exchanged particles may be "gluons" (the proposed carrier of the strong binding forces between hadron constituents) as well as photons which are exclusively exchanged in e^+e^- collisions.

The interest in $\bar{q}q$ collisions stems from the fact that all types of particle-antiparticle pairs may be created there, as quantum number restrictions are removed. Thus the elusive W particles, the mediators of weak interactions, may be created as well as entirely new high mass entities.

An additional difference between $\bar{q}q$ and e^+e^- collisions is the intrinsic momentum spread of the quarks inside the nucleon which smears the CM energy of the fundamental collision. The analogous spread in e^+e^- CM energy from radiative corrections is smaller and better understood. However, this spread in the initial energy can largely be compensated for by using a high resolution detector which measures all or most of the final state products. We are then free to explore $\bar{q}q$ collisions to much higher CM energies than e^+e^- machines with present technology can achieve.

The gluons mentioned above may also participate in the interactions as individual entities. If so, their vector nature leads to the expectation that the resulting jets will be distinguishable from those of $\bar{q}q$ collisions, and these can be explored in a unique kinematic region.

The production of possible new leptons (such as the τ) in pairs, and the Higgs boson, which can test the predictive power of gauge theories, provides another interest in high-luminosity $\bar{p}p$ collisions. Higgs bosons may be made in association with W particles (in perhaps 5% of cases).

The cross section for production of W and Z (the neutral current weak particle) are shown as a function of $M_W/\sqrt{s}$ in Fig. 2, taken from a calculation by Quigg.⁶ This graph shows that W detection is possible for luminosity $\approx 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, and the points show that Fermilab will have a relative advantage over other projects if the W mass is 250 GeV. For the more usually predicted masses ≈ 100 GeV the advantage is less marked.

Finally we note that the $\bar{p}p$ cross section is expected to rise as $\ln^2 s$ from present ISR and cosmic ray data⁷ on pp collisions. Figure 2b shows an extrapolation which indicates that for 1000 x 1000 GeV collision, $\sigma_t \approx 90$ mb, twice that found in present experiments. The nature of this rise can easily be investigated.

III. Production and Collection of Antiprotons

Antiprotons will be produced by 80-100 GeV/c protons from the main ring striking a Rhenium-Tungsten alloy target. The protons are extracted in booster length batches at a 15 Hz rate, which allows the booster to capture one turn of secondaries, decelerate to 200 MeV kinetic energy, transfer to the cooler, and ramp up again to receive the next batch. Only antiprotons survive the deceleration, and these are cooled and stacked in the cooling ring in the 66 msec between batches. This cycle repeats every 3 sec.

The antiproton momentum at production is set by the need to match the main ring rf time structure to that of the booster.⁵ This is done by shifting the booster harmonic number from 84 to 85 so $\beta_{\bar{p}} \approx 84/85$ and $p_{\bar{p}} = 6.05$ GeV/c. This momentum ensures a high yield, as we will show.

Data relevant to $\bar{p}$ production yields at zero degrees are shown in Fig. 3. The cross section per nucleus $d^2\sigma/dp d\Omega$ has been measured for 70 GeV/c protons on Aluminum by Antipov et al⁸ for secondary momenta above 10 GeV/c. In the same figure we show data of Dekkers et al⁹ for 23.1 GeV/c protons, and of Eichten et al¹⁰ for 24 GeV/c protons, using different target materials. Lower momentum points have been estimated using the method of Rubbia¹¹ in which symmetry about $x = 0$ (particle at rest in the pp CMS) is assumed. The lower beam energy data show that yields scale like $A^{0.8}$, which was also observed by

Cronin¹² at higher energies for small production angles. We estimate the cross section for $\bar{p}$ from Tunsten to be $\approx 100 \text{ mb sr}^{-1}(\text{GeV/c})^{-1}$. The cross section for beryllium is a factor 6-10 less.

The dependence of yield on beam energy can be inferred from Fig. 4, which shows the invariant cross sections for $pp \rightarrow \bar{p}x$ (inclusive, zero degrees). The triangular points are taken from ISR measurements¹³ at 90° extrapolated to $P_t = 0$ (there is no significant x dependence to consider, as was demonstrated by Alper et al.¹⁴). This figure suggests that a small gain in yield may be obtained by using 100 GeV/c protons instead of 80 GeV/c.

The expected angular distribution of antiprotons is shown in Fig. 5, which shows the p_t dependence found by Guettler et al.¹³ at ISR CM energy 23 GeV (equivalent to 280 GeV/c proton beam) applied to 6 GeV/c $\bar{p}$'s in the lab system. It can be taken as flat within the overall uncertainty of the cross section estimates.

We now estimate the yield of captured $\bar{p}$'s, for the beam design to be described in the following sections. Antiprotons produced at the center of a 6 cm W target within $\pm 12 \text{ mr}$ in the horizontal plane and $\pm 6 \text{ mr}$ in the vertical plane, and having $\pm 0.15\%$ momentum spread, will survive deceleration. As will be shown in Section VII, the integral over target length gives an effective length of 3.4 cm. Absorption in the target gives a reduction factor of 0.6. Then

$$\begin{aligned} \Delta p \Delta \Omega &= 6 \text{ GeV} \times .003 \times .024 \times .012 = 5.2 \cdot 10^{-6} \text{ GeV-sr} \\ \text{and } Y &= \Delta p \Delta \Omega \frac{d^2 \sigma}{dp d\Omega} \times (\text{absorption}) \times \frac{L_{\text{eff}}}{A} N \\ &= 5.2 \cdot 10^{-6} \times 10^{-25} \times 0.6 \times 3.4 \times \frac{19.3}{184} \times 6 \cdot 10^{23} \\ &= 6.7 \cdot 10^{-8} \bar{p}/\text{inc proton.} \end{aligned}$$

For $2 \cdot 10^{12}$ protons/booster batch, we have $1.3 \cdot 10^5 \bar{p}$ /batch, $1.7 \cdot 10^6 \bar{p}$ /MR cycle, $5.6 \cdot 10^5 \bar{p}$ /sec, $2 \cdot 10^{10} \bar{p}$ /hour. Note that the beam has been designed to deliver $\bar{p}$'s produced within ± 20 mr to the booster. This means $7.2 \cdot 10^5 \bar{p}$'s will be circulating in the booster before deceleration.

IV. 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 so 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/extraction 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 ensure 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 not possible. 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 and ground water from activation.

The emittances of the beams to be transported by the system have been discussed in the original proposal,⁵ along with many other parameters. However, we note here that the entire system must be capable of transporting $\epsilon_x = 2\pi$ mm-mr, $\epsilon_y = \pi$ mm-mr in the reverse direction. These are the normal booster values at 10 GeV/c injection into the MR. However, we will provide $\epsilon_x = \epsilon_y = 4\pi$ 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 $\epsilon_x = 2\pi$, $\epsilon_y = 1.3\pi$ mm-mr will survive deceleration 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 transport system.

V. 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 Fig. 6. Extraction takes place in the straight section at F17 where a septum magnet will be placed. A kicker magnet an odd number of quarter wavelengths upstream must also be provided. Mini-straight F15 has sufficient space for the kicker as currently conceived. Extraction will be in the vertical direction because less angular deflection is required to miss the following dipole than for horizontal extraction. The MR extraction/injection system is described in Section IX. The nearest MR dipole must have a special coil so that the beam pipe can pass next to the magnet steel, under the end-loop.

The extracted beam is pitched flat 19 inches above normal orbit height by a special 13-foot dipole of the EPB (External Proton Beam) 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 Fig. 6, 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-foot dipoles, encroaches upon tunnel space more than may be considered desirable. This can only be avoided by using special order dipoles tailored to fit in the alcove, which must also house an Energy Doubler cold box.

The extracted proton beam then enters a length of 10 inch pipe, buried in the ground, which serves as a permanent radiation barrier for the next enclosure. In analogy with older Fermilab external beam enclosures, we call the latter PBAR HALL. As is indicated in Figs. 6, 7, and 8, it is 130' long and contains the quadrupoles required to produce a highly focussed beam spot on

the production target in the next enclosure, the TARGET VAULT. Pbar Hall is accessible through a labyrinth, so that the elements there may be serviced in situ, and the actual target may also be reached by remote handling devices. We should also note here that it also contains two quadrupoles needed for the reverse injection beam.

Figure 7a shows the layout of the remaining parts of the beam, from Pbar Hall to booster. The target vault will be a high radiation area, so that Pbar Hall will be protected from residual activity and gas activation by a wall between it and the target vault.

The 130' target vault immediately follows Pbar Hall, with the target position as close as possible to the separating wall, as shown in Fig. 7b. It will be possible to extract the target through the separating wall on a railway cart and store it in a lead pig in Pbar Hall. The target itself is normally in a magnetic field which bends the 80 GeV proton beam downward by 5 mr. This ensures 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 an angle of 10 mr to the horizontal. 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 is sealed off from the final beam transport channel.

Antiprotons are collected by a closely spaced quadrupole triplet immediately following the target magnet (see Fig. 7b). 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. Details of the beam paths are shown in Fig. 8. The optics are described in the next section.

In the section of beam in the target vault but after the proton dump, the antiproton beam is matched to the emittance of a long FODO channel to the booster. This section also contains two more quadrupoles used for the reverse injection beam.

Following the proton dump, the antiproton beam is matched to the acceptance of a FODO channel leading to the booster.

The channel, some 1130' in length, is housed in a 4-foot diameter sewer pipe. A lens spacing of 100' and a 90° phase advance per FODO cell leads to a quadrupole which fits comfortably within this enclosure. Moreover, the channel quadrupoles do not require water for cooling - clearly a desirable feature in this circumstance.

Near the booster end of the transport system, the beam is bent through 10.9° in a northerly sense onto a line tangent to the booster orbit at booster straight section 3. Quadrupoles on both sides of the bend assist in phase space matching to the booster acceptance, the necessary horizontal momentum dispersion having been introduced by the 10.9° bend.

Finally the beam enters the booster enclosure through a 12" buried pipe. The only major component of the system within the booster tunnel is a pitching magnet which deflects the beam downward into the injection septum magnet. The design of the booster injection/ejection system is discussed in Section IX.

B. 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 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. 8) 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 ensures that the reverse beam misses the production target and falls to the level of the MR extracted beam some 4.7 meters "upstream" of the target, where it is levelled by a separate dipole. This geometry is also shown in Fig. 8. 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. There are separate but interleaved elements, aligned along the new axis, turned on to transport the reverse beam through the target area. 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.

VI. 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 ensuring 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. 9. A FODO channel of four elements (Q1, Q4, Q5, Q6) nested among the horizontal bends with gradients set for $\sim 30^\circ$ 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. All these quadrupoles may be the MR type.

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 about fill the 4" horizontal aperture of a MR quadrupole, and a larger bore may be needed if the reverse beam emittance

is much larger than expected. We also note here that a MR quadrupole will only just fit into the alcove at F25, and must share space with an Energy Doubler/Saver cold box.

Figure 10 shows the optics used to produce a small spot in the production target. Q9, Q11, Q13, Q14 are four 10' EPB quadrupoles in Pbar Hall set to produce the small target spot. The solution shown produces $\beta_x = 5$ cm, $\beta_y = 10$ 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, Q10 and Q12, 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 accomplished.

Up to Q8, optics for production and for reverse injection are identical - gradients are simply scaled to the momentum. However, the Q8 strength is tuned differently in the two cases to make the appropriate matches. Figure 11 shows the optics for reverse beam in the target area.

B. Antiproton Collection Beam

The antiproton collection beam optics ~~XXXXXXXXXXXXXXXXXXXX~~ 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 introduction of vertical dispersion by the pitching magnet which bring the beam level; (3) a 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 IV, this will result in capture of antiprotons by a factor of 5 beyond that which will survive the adiabatic growth during deceleration to the cooling momentum of 650 MeV/c (200 MeV kinetic energy). These decisions will be further justified in Section VII.

However, we note here that if an incident beam spot size of $\sigma = 0.1$ mm can be achieved, the introduction of a "spherical lens" such as the so-called HA-HA¹⁵ lens, a Lithium current carrying cylinder, or current in a wire target,¹⁶ may increase the capture of antiprotons by producing a β of ≈ 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-packed triplet. The best competing solutions, of doublet and of quartet, were considered less favorable on the following grounds:

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

Quartet: An excellent solution was obtained with a quartet much like that used to obtain small β in the incident beam. Standard quadrupoles could be used with realistic 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 damage would be present).

The triplet solution chosen is shown in Fig. **17**. It provides a double convergence, with the vertical envelope (β_y) reduced so as to miss the beam dump. Special elements must be used here; however, the three quadrupoles may be made from laminations used for the Fermilab standard 4Q120 quadrupole. The coil must be wound on a special fixture and insulated using, e.g. 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 **17** also shows figuratively how the "C" magnet around the target splits the proton and antiproton beams as was shown in Fig. 8, 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 the required 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 four quadrupoles of large aperture, but needing only low field, to match the triplet into the FODO channel starting right after the vertical pitching magnet. A solution was found using only three quadrupoles, but four allow some freedom in placing these elements, which must be intermingled with two 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 is simplified.

The properties to note in the FODO channel are: (1) all elements have equal and small field strength (focal length = spacing/ $\sqrt{2}$); and (2) Maximum $\beta \approx 100$ meters, so that the reverse beam 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 Section VII).

(4) Match to Booster

The match to the booster from the FODO channel is accomplished by using a doublet, Q37 and Q38, after the bend point to match η_x, η_x' at the booster. Beam envelope and η_y, η_y' matching are accomplished by introducing an extra quadrupole Q36 before the big horizontal bend and allowing variable strength in the last FODO element, Q35.

VII. Beam Spot and Target Length: Theoretical Justification

We now try to justify the choices of solutions specified in the previous sections.

The production of 6 GeV/c antiprotons by 80 GeV/c protons is only weakly 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 spatial to angular width of the beam, this requirement translates to β being as small as possible at the target.

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

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, $\frac{d\sigma}{d\Omega} = \text{const}$, 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 underestimate of capture efficiency.

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

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

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

Transforming the overlap integral to r, θ variables we find

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

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

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

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 $\sqrt{a} F(a) = G(a) \xrightarrow{a \rightarrow \infty} \frac{2}{\sqrt{\pi}}$.

➤ These functions are shown plotted in Fig. 14b.

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

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

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

The beam parameters were chosen to be those for the beam optics of Fig. 17, where $\beta_0 = 2$ cm in both planes. To study $\beta_0 = 1$ cm, an appropriate strength, short, linear lens was considered placed immediately following the target.

Contributions to the capture integral as functions of z and δ , before booster momentum acceptance is applied, are shown in Fig. 12a. Here we see that the overlap peaks at different positions in the target as δ changes. As long as the peak does not shift out of the target over the booster momentum range, the integral over z will be roughly constant. In fact for $\delta = +0.2\%$ the integrated overlap is larger than for $\delta = 0$, as the $\bar{p}$'s can more readily escape from the downstream end of the target. (We used absorption lengths $\lambda_p = 10$ cm, $\lambda_{\bar{p}} = 7.5$ cm, which are appropriate for Tungsten.) Therefore sextupole corrections are unnecessary and dispersion may be small.

Figure 12b shows the effect of target length on yield. The peak yield changes markedly because of absorption, but the length integral changes more slowly. Note in all cases here $\sigma_b \equiv$ beam size before multiple scattering = 0.2 mm.

Figure 13 shows the effects of changing β_0 to 1 cm and σ_b to 0.1 mm, and Fig. 21 shows the effect of target length for this case. The central yield

increases but is more peaked, resulting in a smaller increase in yield than one might predict intuitively.

Figure 18 shows the effects of momentum on the integral over length. Over present booster acceptance it is quite flat. Note that for $\sigma_b = 0.2$ mm, no big gain results from changing β_0 from 2 to 1 cm, but if σ_b can be made 0.1 mm, $\beta_0 = 1$ cm will produce a factor of 2 increase in $\bar{p}$'s captured.

Finally, Fig. 19 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 cm target length. For weaker absorption, we need 6-7 cm, while for $\sigma_b = 0.1$ mm, $\beta_0 = 1$ cm, length must be reduced to 4 cm to capture the extra beam available.

VIII. Target Design

A. Energy Deposition

A Monte Carlo program for nuclear cascades was run by S. Mori for 80 GeV/c protons on Tungsten. Energy deposition density profiles are shown in Fig. 14, 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 region with $\sigma \approx 0.5$ mm. In the following we therefore assume that this is the beam size.

We also 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 report¹⁷ concluded such targets would be destroyed by full SPS beams.

B. Heat Dissipation

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

$$\frac{\partial T}{\partial t} = m \nabla^2 T$$

where m is the diffusivity, $\frac{\lambda}{\rho C}$. Here λ is the thermal conductivity of tungsten, $\lambda = 0.43 \text{ cal cm}^{-1} \text{ sec}^{-1} (\text{°C})^{-1}$, the density $\rho = 19.3 \text{ gm/cm}^3$, and the specific heat $C = 0.032 \text{ cal gm}^{-1} (\text{°C})^{-1}$. Then

$$T(r, t) = \int_0^\infty \int_0^{2\pi} T(r', 0) \frac{1}{4\pi m t} e^{-\frac{1}{4mt} (r^2 + r'^2 + 2rr' \cos \theta')} r' dr' d\theta'.$$

For a square pulse of heat of radius σ_b

$$T(0, t) = T_0 \left(1 - e^{-\frac{\sigma_b^2}{4mt}} \right).$$

In production running, the target will be bombarded by booster length batches of fast ejected protons, as only one booster turn of antiprotons can be captured at a time. The latter will be decelerated and transferred to the cooling ring, and the booster returned to capture energy at a 15 Hz rate. The target, therefore, will see 13 batches containing $\leq 2 \cdot 10^{12}$ protons in $1.5 \mu\text{sec}$, each separated by 66 msec. This is followed by ≈ 2 sec while another turn in the MR is being accelerated.

The target will be made of a Rhenium-Tungsten alloy, as discussed below. Its heat properties are like those of Tungsten. The maximum temperature rise on these assumptions is

$$T_0 = 3.82 \cdot 10^{-11} \frac{\text{cal}}{\text{GeV}} \frac{D_E N_p}{\rho C} = 990^\circ\text{C},$$

assuming $N_p = 2 \cdot 10^{12}$ protons/burst. The heat dissipation is governed by a relaxation time $t_R = \sigma_b^2 / 4 m = 0.9$ msec, so that after 66 msec the temperature along the beam axis will have fallen to 13°C above ambient. The melting point of the alloy considered is $\sim 3000^\circ\text{C}$, well above T_0 , and the interval between pulses is sufficient to allow cooling.

Each burst deposits 137 calories. With 13 bursts, followed by ≈ 2 sec reacceleration, the target must dissipate 2.5 K watts. This is easily done with water cooling.

C. Thermal Stress

The most serious problem is the dynamic stress set up in a target by sudden heating, which travels at the speed of sound and "rings" within the target.¹⁸ The amplitude of the stress wave is $E\alpha T_0$, where E is Young's modulus ($3.3 \cdot 10^4$ kg/mm²), α is the linear expansion coefficient ($4.5 \cdot 10^{-6}/^\circ\text{C}$), and $T_0 \sim 1000^\circ\text{C}$:

$$E\alpha T_0 = 150 \text{ Kg/mm}^2.$$

The ultimate tensile strength (UTS) of pure tungsten is given as 150-400 Kg/mm², so that a pure tungsten target could shatter, if it is in the low UTS range.

The use of an alloy of 25% Rhenium in Tungsten, sintered and wrought, effectively ensures that the upper limit of UTS will be reached. The Rhenium adds ductility, so that the material does not shatter. No loss of density is expected.

D. Target Design

The design of the target and its mount is shown in Fig. 15. The target to be used will be a rod of length 6 cm, and a diameter of 1.9 cm, heat shrunk into a finned jacket and rotated about twice per second by its cooling water. The beam will be made to pass off center, so that fatigue will be spread over an increased area of the material. The massive nature of the target should contain the stresses better than a smaller cylinder would, as well as provide greater cooling area. Note the presence of the fins on the target should produce turbulence which will increase heat transfer rate.

The target will be housed in a stainless steel block containing the cooling water path, and the whole assembly inserted into a re-entrant part of the beam vacuum chamber (see Fig. 8), so that it can be withdrawn remotely from the C-magnet surrounding it as shown in Fig. 7. It is planned to provide a cart on rails which may be removed from the target vault into the beam transfer hall for servicing or removal through the Labyrinth.

IX. Injection-Extraction Systems

We now describe the injection-extraction systems at the main ring and booster end of the transport line.

A. Main Ring

As discussed earlier, injection and extraction of beam for the main ring will occur at medium straight F17 in the vertical direction. This straight section has approximately 40 feet of space available for the extraction magnet. The most challenging of the design requirements is that the system accommodate energies differing by a factor of 10 on the time scale of minutes. At 10 GeV/c, the beam to be injected is large in its transverse dimensions and beam transport magnet apertures must be sized accordingly. The relatively low energy would suggest rather short magnets. The high energy beam requires lengthy magnets; however one cannot take advantage of the smaller beam size in this design because of the injection needs. Meeting this requirement is achieved with the design of a special magnetic septum ("Lambertson"). The design parameters are shown in Table 1. For 100 GeV extraction this magnet would operate at a field of 13 kG and for 10 GeV injection 1.3 kG. The high field is substantially higher than other Lambertson magnets operating at Fermilab. The field increase was possible because the Lambertson opening angle was reduced to approximately 45° to lessen saturation of the steel laminations near the gap the beam must jump. Decreasing the magnet's opening angle was an available option since at F17 the vertical β function is near a minimum, whereas standard extraction from the main ring is at a point where the vertical beam size is large. The extraction system at F17 then consists of a single 17' long Lambertson magnet.

The other major element of an injection/extraction system is the kicker. The kicker will be located at mini-straight F15, where there is a total of 48" available. Location F15 is 70.9° in phase upstream of F17. The requirements on the kicker are severe: (1) variable fields up to 800 G to allow 100-GeV beam to jump the Lambertson gap and; (2) a fast rise and fall time to allow one booster batch at a time to be extracted. Although a detailed design has not been carried out it is felt such a device is reasonable. If, however, additional kick is required at high energy a second such device can be installed a number of half wavelengths upstream of F15 to augment the F15 kicker. F15 was selected as the primary kicker location to avoid transporting the large off orbit 10-GeV beam through the rf section.

B. Booster

(Never Written)

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Radiation Safety

This report considers the radiation levels expected for the antiproton target area and the reverse injection line. Specifically the radiation hazards at the ground level will be discussed along with ground water activation around the target area. The construction will consist of a target vault 5' wide by 130' long approximately 20' deep. This vault will connect with the 6' x 7' tunnel exiting the main ring at station F2 and connect with a 4' diameter sewer pipe tunnel buried approximately 15' to be built from the vault to the southwest booster stairwell.

Casim Runs

Casim is a Monte Carlo computer program which can simulate the development of hadron cascades in multiple beam line elements surrounded by various shielding elements. The beam line configuration is indicated in Fig. 1 and the geometry of the enclosure is shown in Fig. 2.

The output of CASIM is normally given in radial bins, and since the realistic geometry is not azimuthally symmetric we have made two symmetric simulations which can provide information in the one case, for dose rates at ground level (Casim run No. 5135) and in the other case for soil activation (Casim run No. 7048). The difference between the two runs is in the amount of additional steel shielding, since for the ground level dose rates the amount of steel between the loss point and the point of interest is much less (4" versus 2') than for the soil activation. The geometry used in the program is indicated by the dashed lines in Fig. 2.

One special aspect of the beam line is that the production target is in a magnet which deflects the noninteracting proton into the dump. However, the design is such that even if this magnet trips off, the protons will still hit the dump.

III. Ground Level Dose Rates

A. Dose rates above the $\bar{p}$ production target, assuming: (1) 10^{13} p/sec; (2) 8×10^{-6} rem/star//cm³ (Fig. VI.7 in Reference 1), we find a dose rate of 29 mrem/hour when the star density is 10^{-13} starts/cm³ incident proton.

Figure 3 shows the star density contour from Casim run No. 5135) with 4' of Fe shieldings). We have approximated the shape of the 10^{-13} star/cm³ incident p contour by the dashed line in Fig. 3. The dashed line represents the additional concrete necessary to reduce the dose rate to approximately 30 mrem/hour. The step sizes chosen correspond to a particular set of concrete shielding blocks. The actual sizes will depend on what is most easily available at the time of construction, however, the philosophy will be the same, i.e. to perform an approximation to the shape of the designed contour. The reason 30 mrem/hour was chosen is that this is a dose rate much lower than 100 mrem/hour and hence would not require the protective actions necessary for levels above 100 mrem/hour. In particular a fence will be adequate.² The next lowest level to attempt to achieve would be 2.5 mrem/hour; however, realistically assessing the mode of construction (there will be numerous cracks where the shielding blocks join each other and the walls) it is probably that it would be difficult to achieve this dose rate. The transverse dimension has not been indicated; however, they will be less than the vertical distance due to the increasing slant height as one goes transverse to the beam direction.

B. Dose Rates at the Manholes in the Reverse Injection Line.

The basic assumptions for the intensity of the reverse injection line are:

- 1) 5×10^{13} p/pulse
- 2) 3 pulse/hour

The next two calculations use the result of Appendix I, which is based upon experimental results⁴ at 8 GeV/c. First we shall assume a uniform loss of 1% of the total intensity occurring over the entire length of approximately 335 m. We have ^{3h} dose (rad^h/interacting) at 4.6 m = 1.8×10^{-13} . Hence we expect:

$$\begin{aligned} \text{Dose (rad/hour)} &= 3 \frac{\text{pulse}}{\text{hour}} 5 \times \frac{10^{13} \text{ p}}{\text{pulse}} (.01) \frac{1}{335} 1.8 \times 10^{-13} \text{ rad/int p} \\ &\quad \text{loss length} \\ &= .8 \text{ mrad/hour} \end{aligned}$$

Next we calculate a worst case condition which would correspond to an obstacle in the pipe directly under the manhole

$$\begin{aligned} \text{Dose (rad/hour)} &= 3 \frac{\text{pulse}}{\text{hour}} 5 \times 10^{13} \text{ p/pulse } 1.8 \times 10^{-13} \text{ rad/int p} \\ &= 27 \text{ rad/hour} \end{aligned}$$

A more likely scenario is that the 1% losses will be concentrated in the quadrupoles. This is a realistic condition since the quads are located where the beam is largest. Assuming that the 1% beam loss is spread equally between 10 quads one has .001 beam loss in a quad. However, the estimate of the dose above a manhole due to these losses is difficult to estimate, hence we have made two separate calculations which use different assumptions about the nature of the

losses. In both calculations we have made conservative assumptions.

The first calculation is in some sense a thick target calculation. We assume the quad is a source of neutrons produced uniformly in solid angle and then perform a labyrinth attenuation calculation. The dose rate for attenuation purposes is calculated at a distance of one foot from a uniform source of neutrons. This assumption is made since one foot is a representative quad dimension. For the purpose of making the calculation we have assumed that 65 neutrons are produced per interaction⁴, also we must choose a conversion between n/cm^2 and rem. Assuming 200 MeV as a representative neutron energy we find from the Radiation Guide $1.8 \times 10^7 n/cm^2 = 1 \text{ rem}$. Choosing 200 MeV is a reasonably conservative energy since the evaporation neutrons are certainly less than this. The reason for stating that the choice is conservative is that the conversion factor decreases with energy. Hence we expect

Dose (rem/hour at surface of quad)

$$= 3 \frac{\text{pulse/hour}}{4\pi(30 \text{ cm})^2} \cdot 5 \times 10^{13} \text{ P/pulse} \cdot (.001) \frac{(65 \text{ n/p})}{1.8 \cdot 10^7} \text{ n/cm}^2/\text{rem}$$

$$= 48 \text{ rem/hour} \quad \text{loss in quad}$$

Now we must calculate the attenuations of these neutrons as they propagate along the sewer pipe and up the manhole. The general results of reference 5 will be used, in particular graphs 5 and 6.

One of the main results of reference 6 is that their graphs have a wide range of applicability if one uses a scaled distance, where the scale factor is the square root of the area of the penetration in question. In our case $\overline{\text{Varea}}_{\text{sewer pipe}} = 3.51$ and $\overline{\text{Varea}}_{\text{manhole}} = 5.3'$. The closest distance of any quad to the manhole will be 20'; hence the scaled distance along the sewer pipe is $3.5' = 5.7$ units, and the scaled distance along the man-

hole is $15.3'/5.3 = 2.9$ units. We shall use the results for a cul-de-sac one unit deep; however, in fact we have a big cul-de-sac namely the rest of the sewer pipe. From fig. 5 of reference 6 we find an attenuation of approximately .1 and from fig. 6 of reference 6 we have an approximate attenuation of .01, hence our final result is:

$$\text{Dose (rem/hour) at top} = 48 \text{ rem/hour} \times .001 = .048 \text{ rem/hour}$$

The second calculation again uses reference 3. We use figure 4 of reference 3 to obtain an estimate of the dose in rad/interacting p in the forward direction of 5×10^{-11} rad/interacting p at 1 meter. We shall assume conservatively that all the dose is due to neutrons and assume the same attenuation as above, hence we have

$$\begin{aligned} \text{Dose (rem/hour) at the top} = \\ 3 \text{ pulse/hour} \times 5 \times 10^{13} \text{ p/pulse} \times 10^{-3} \times 5 \times 10^{-11} \text{ rad/int p} \times 5 \text{ rem/rad} \times 10^{-3} \\ \begin{array}{ccccccc} & & \uparrow & & \uparrow & & \uparrow \\ & & \text{loss in a quad Fig. 4 cm ref 6.} & & & & \text{attenuation} \end{array} \\ = .037 \text{ rem/hour} \end{aligned}$$

The dose above ground due to losses in a quad is negligible. To show this we calculate the worst case which corresponds to losing the entire beam in one quad. We shall use a Casim run of AVG at 30 GeV/c (CH101), and a conversion factor of 8×10^{-6} rem/star/cm³ from fig. VI 7 of reference 1.

$$\begin{aligned} \text{Dose (rem/hour) at ground level} \\ = 3 \text{ pulse/hour} \times 5 \times 10^{13} \text{ p/pulse} \times 10^{-12} \text{ star/cm}^3 \text{ incp} \times 8 \times 10^{-6} \text{ rem/star/cm}^3 \\ = 1.2 \times 10^{-3} \text{ rem/hour} \end{aligned}$$

The soil activation calculations are based upon a memo from S. Baker⁶ (1/23/78) in which he gives the allowable amount of ^{22}Na production as a function of elevation. The reason that the allowable ^{22}Na production is a function of elevation is that one of the parameters entering the calculation is the vertical transit time for the ^{22}Na to reach the aquifer. Also as detailed in Baker's memo ^{22}Na production is more important than tritium production, hence we shall only deal with ^{22}Na production.

A Casim run (#7048) was made which gives the star density in soil. Figure 4 gives the star density contours for this situation and figure 5 shows the longitudinally integrated star density as a function of radius. The radial dependence has been approximated by an exponential as indicated by the straight line in figure 5. Using this approximation, one is able to determine the total number of stars outside any given radius R_0 by integrating from R_0 to ∞ . This number of stars is then converted into curies of ^{22}Na . The calculation is as follows:

$$1) \quad N \text{ (Stars/inc p)} = \frac{1}{2} \int_{R_0}^{\infty} A C^{-br} dr = \frac{A}{2} \frac{e^{-bR_0}}{b}$$

The factor of 1/2 is due to the fact that the bathtub will collect water from points which are symmetric about the center of the beam line.

$$2) \quad M(\text{Stars/sec}) = N \text{ (Stars/inc p)} * F \text{ (p/sec)}$$

$$3) \quad M(\text{Stars/year}) = 3.15 \cdot 10^7 \text{ sec/year NF}$$

$$4) \quad M(^{22}\text{Na}/\text{year}) = .011 \times 3.15 \cdot 10^7 \text{ NF} = 3.74 \times 10^5 \text{ NF}$$

The factor of .011 is from TM-292⁷ and refers to the percentage production of ^{22}Na with respect to all other interactions.

$$\begin{aligned}
 5) \quad M(C_i \text{ } ^{22}\text{Na Yr}) &= \lambda_{22} \frac{M}{N_a \text{ decay constant}} \\
 &= \frac{8.5 \times 10^{-9}}{3.7 \times 10^{10} \text{ disintegrations/C}_i} \quad 3.47 \times 10^5 \text{ NF} \\
 &= 7.97 \times 10^{-14} \text{ NF} \\
 &= 7.97 \times 10^{-14} \frac{A}{2} \frac{C^{-b}}{b} R_{OF}
 \end{aligned}$$

This formula gives the ^{22}Na production per year outside a given radius R_o as a function of flux (P/sec). From Casim run #7048 we find $A = .24$ Stars/cm and $b = .0205 \text{ cm}^{-1}$, and $M = 4.67 e^{-.02R_o}$ for $F = 10^{13}$ P/sec. Table I shows M as a function of R_o .

TABLE I

R_o (cm)	$M (C_i \text{ } ^{22}\text{Na/Yr})$
200	.078
250	.0277
275	.0166
300	.00994
350	.00357
400	.00128

The value of $M (C_i \text{ } ^{22}\text{Na})$ from Table I are plotted in figure 6 along with the results of S. Baker's calculations of the allowable ^{22}Na production. Smooth curves have been drawn through the data points and the depth of the bathtub has been determined from the intersection of the lines.

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Fig. 1

Fig. 2

Fig. 3

Fig 4

PRODUCTION OF 6 GeV/c ANTIPROTONS

Fig 5-

Fig. 6

Fig. 7

DETAIL OF BEAMS IN THE TARGET AREA

FiAP

REVERSE INJECTION OPTICS

Fig 10

OPTICS IN MR AND TUNNEL PENETRATION

Fig 2

Fig 11

Fig 12

Yield Overlap, Before Booster Momentum Acceptance,
for Tungsten

Fig 13

Energy Deposition in Tungsten

Fig 14

RHENIUM - TUNGSTEN TARGET
& MOUNT, CONCEPT

Fig 15

FOCUSSING OPTICS FOR 80 GeV

Fig. 16

OPTICS OF TRIPLET FRONT END & MATCH TO FODO

Fig 17

Fig 18

Fig 19

OPTICS IN FODO CHANNEL & BOOSTER MATCH

Fig 20

Fig 21