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DESIGN OF AN ADDITIONAL EXTRACTION/INJECTION AREA FOR THE FERMILAB BOOSTER

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INTRODUCTION

In order to allow for high energy colliding beams with Fermilab accelerators it is necessary to provide beams which circulate counterclockwise in the Main Ring tunnel (in addition to the usual clockwise direction). For the Booster to provide such beams from its present extraction point, a very large bend (~ 180°) would be needed. Instead, a new extraction area has been designed and a tunnel to the main ring constructed (see figure 1). This transfer line to the Main Ring uses only small bends to accept (normal) counterclockwise circulating Booster beam and create counterclockwise Main Ring beam.

Present plans to provide $\overline{p}$'s for 2 TeV colliding beam experiments at Fermilab involve targeting an 80 GeV beam from the Main Ring and collecting $\overline{p}$'s at the energy (near 5 GeV) where they are most plentifully produced. These $\overline{p}$'s will be decelerated in the Booster to energies (200 MeV) where electron cooling and stacking can be carried out to obtain a bright, intense $\overline{p}$ beam. The Booster will then re-accelerate the $\overline{p}$'s to Main Ring injection energy. Injection of $\overline{p}$'s for deceleration and the subsequent extraction of the re-accelerated beam will be carried out with the extraction/injection area described here.

The Booster lattice was designed to provide for vertical extraction in its long straight sections.[1] Normal extraction[2,3] is carried out at Long Straight 13 (L13) using a septum magnet[4] (MP01) in the aperture to deflect extracted beam above the Booster magnets, where it is bent horizontal by a similar magnet (ML01) which is powered in series with the septum. Circulating beam is raised close to the septum by a 3-magnet orbit bump called BEXBMP, using magnets in L12, L13, L14. A fast rising kicker magnet moves the beam across the septum, sacrificing only one of 84 circulating bunches. Since the Booster vertical tune is nominally 6.8 and the periodicity is 24, the phase advance per cell is .283 (2π). This allows a kicker at L12 to provide almost maximum amplitude kick at the L13 septum. Fifteen cells away (L3), then, the phase advance is 4.25 (2π) and maximum displacement is again obtained from the L12 kicker. Since L3 was suitably directed for Main Ring reverse extraction/injection, the tunnel to the Main Ring begins near there. Since the existing extraction system has largely been described, [1-4] this report will concentrate on new aspects of the design.

INJECTION APERTURE EFFECTS

With any extraction septum lowered into the vertical aperture the Booster acceptance is restricted. The extent of this effect depends on the degree to which the Booster good field aperture A_B (required for injected beam) is smaller than the physical aperture A_M. The extracted beam, traveling only one pass, allows poorer field quality. The problem will be aggravated for $\overline{p}$ injection because a lower septum position is required to transfer lower momentum beams of the same invariant emittance.

It is possible to avoid this problem with more intricate systems of pulsed extraction magnets such that the septum does not reduce the injection aperture, but powerful magnets and power supplies would be required. Instead it was decided to deflect the low momentum beam below the septum and then raise it again beyond the septum with 4 magnets in the long straight section.[5]

Figure 2 is a schematic diagram of the extraction area design for L3. Figure 2a shows the beam at extraction energy. To reduce kicker requirements the circulating beam is raised up until it grazes the septum. Then the fast extraction kicker deflects it above the septum and the septum magnet bends it above the downstream Booster magnet. The septum, of thickness t, is located so a beam passes a distance t_S above the septum to stay in the magnet's good field region.

Figure 2b shows a 200 MeV (injected or decelerated) beam of emittance as large as the Booster acceptance. To accommodate the height A_B, the beam must be displaced downward within the long straight section L3 in order to pass below the septum, which sits at height s above the centerline. At 200 MeV this deflection must be provided within the straight section by magnets D1-D4. At higher momenta the beam is adiabatically smaller but stiffer. Since the beam is smaller, the local magnets can be aided by programming BEXBMP 3-Bump to deflect the beam to the bottom of the aperture of the neighboring Booster gradient magnets. Analysis of the requirements on magnets D1-D4, with and without BEXBMP, follows.

MAGNET BEND REQUIREMENTS

Assume the Booster beam has vertical emittance ε_V which fills the injection aperture. This implies a beam half height at injection:

$$A_B = \sqrt{\varepsilon_V \beta_V}$$

where $\beta_V = 20.3$ m is the beta function of the lattice at the location of the septum. If the beam adiabatically shrinks with momentum p then it will have a half height h(p) such that:

$$h(p) = \sqrt{\frac{\varepsilon_V \beta_V p_o}{p}} = A_B\sqrt{\frac{p_o}{p}}$$

where p_o is the injection momentum. If space charge effects or instabilities increase the beam size then allowance must be made in the magnet provisions.

If the BEXBMP magnet system does not displace the beam then the magnets D1-D4 must provide a displacement

$$y = h(p) - s = A_B\sqrt{\frac{p_o}{p}} - s$$

Alternatively, if the BEXBMP magnet sets the beam edge at the bottom of the aperture then the displacement needed from the pair of doglegs D1-D4 is

$$y = (h(p)-s) - (A_B-h(p))$$
$$= 2h(p) - (A_B+s) = A_B\left(2\sqrt{\frac{p_o}{p}} -1\right) -s$$

If the deflection y is supplied by magnets D whose length is ℓ and gap is g with separation ℓ_1 and field B then

$$y = \frac{eB(\ell+\ell_1)(\ell+g)}{cp}$$

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By requiring the magnet to satisfy the requirements for displacement without or with BEXBMP, we can find the magnetic field required as a function of momentum

$$B = \frac{A_B c\sqrt{p_o p} - scp}{e(\ell+\ell_1)(\ell+g)}$$

or

$$B = \frac{2A_B c\sqrt{p_o p} - (s+A_B)cp}{(\ell+\ell_1)(\ell+g)}$$

which have maxima as a function of p at

$$p = p_o(\frac{A_B}{2s})^2$$

or

$$p = p_o(\frac{A_B}{s+A_B})^2$$

Note that for the case where BEXBMP is used, the momentum at which D1-D4 requires maximum field is at injection unless s is less than zero. Without BEXBMP that momentum is at injection only if $s < A_B/2$; otherwise the maximum displacement is required at momenta up to the extraction momentum. If the magnets D1-D4 are dc magnets (as is the case), then the maximum displacement required is conveniently expressed as the displacement α required at injection energy (giving both field and aperture required).

$$B = \frac{cp_o\alpha}{(\ell+\ell_1)(\ell+g)}$$

Table 1 lists appropriate formulas for α.

To choose s, we must allow for the beam size at extraction $2A_E$ plus the septum thickness t = 3 mm and the space $t_s \leq 5$ mm allowed for poor field quality near the septum.

$$s = A_M - 2A_E - t_s - t$$

The Booster vertical acceptance has been measured to be $\varepsilon_V = 16\pi$ mm-mr which corresponds closely to the aperture observed at the present extraction area (L13). Since the Booster acceptance determined by the good field region of the gradient magnets is unknown, the design of dogleg magnets for acceptances up to an aperture of $\varepsilon \simeq 31\pi$ mm-mr will be described. Illustrated in figure 3a are the offsets required for various septum heights (lower edge) as determined from Table 1. Figure 3b shows the septum offset required to allow extraction of various beam emittances. Present injection at $p_o = .644$ GeV/c with extraction at $p_E = 8.9$ GeV/c gives p_E/p_o of 13.8. The Booster has operated at momenta up to 10.9 GeV/c. However we wish to allow injection and deceleration of $\overline{p}$'s produced by 80 GeV beam at harmonic number 85 or 86 for the Booster. This implies transfers near 6.05 and 4.25 GeV/c. These lower energy transfers require a substantially lower septum.

MAGNET CHOICES

The septum magnet will be like the present extraction septum.[4] To maintain the present 44 mr angle requires the septum to be placed in the upstream end of the long straight section close to the Booster gradient magnet. In this limited space 18 cm long magnets D1-D4 will be placed, separated by 15 cm. A displacement of 18 mm will be produced at 200 MeV by exciting a 6 cm gap with 20 turns powered to 1200 Amps. For normal operation this corresponds to a vertical acceptance limitation under the septum of > 20π mm-mr at 200 MeV. Use of programmed BEXBMP magnets in addition will increase this to $\geq 25\pi$ mm-mr. In the case of $\overline{p}$ injection this configuration gives 20π at 200 MeV which corresponds to 3π mm-mr acceptance at 4.25 GeV/c when a programmed BEXBMP is used.

PRESENT INSTALLATION

In June 1978, Dogleg magnets D1-D4 were installed at the extraction area at Long Straight 13. This installation used magnets which had pole tips 5 inches long separated by 13 inches. In order to avoid changes in the vacuum box for MP01, the upstream Dogleg magnet was placed very near the upstream gradient magnet. Since the coils were far from the pole tips, a substantial leakage of flux into the upstream gradient magnet destroyed the symmetry of the four gaps. By shimming the pole tips and powering the upstream and downstream magnets separately, it was possible to use these magnets at 30% of the design current. They result in a modest (few percent) increase in Booster transmission.

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3. A. T. Visser and R. F. Nissen, IEEE Transactions on Nuclear Science, NS-18(1971), 991.

4. D. F. Cosgrove, R. P. Johnson, and S. C. Snowdon, IEEE Transactions on Nuclear Science, NS-24(1977), 1263.

5. This option was mentioned in Ref. 1, p. 9-39.

TABLE 1. Deflection Required at Injection

WITHOUT BEXBMP	
$s > A_B/2$	$\alpha = A_B - s$
$\frac{A_B}{2} > s > \frac{A_B}{2}\sqrt{\frac{p_o}{p_E}}$	$\alpha = \frac{A_B^2}{4s}$
$0 < s < \frac{A_B}{2}\sqrt{\frac{p_o}{p_E}}$	$\alpha = A_B\sqrt{\frac{p_E}{p_o}} - \frac{sp_E}{p_o}$
WITH BEXBMP	
$s > 0$	$\alpha = A_B - s$
$0 > s > A_B(\sqrt{\frac{p_o}{p_E}} - 1)$	$\alpha = \frac{A_B^2}{s+A_B}$

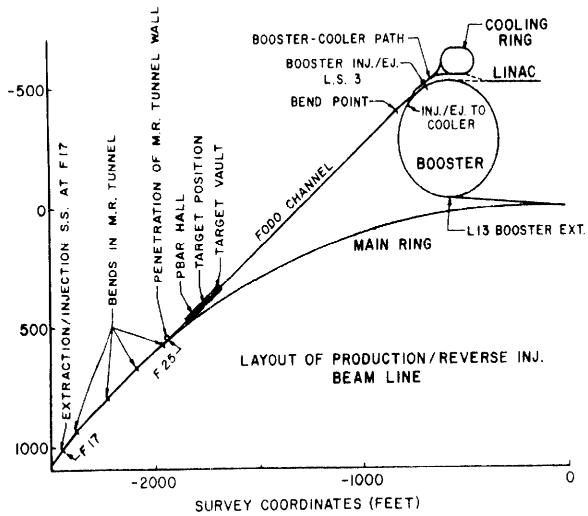


Figure 1. Proposed interconnections of Fermilab Synchrotrons for Colliding Beams. The extraction point at L3 will transfer protons or $\bar{p}$ toward the Main Ring and will accept $\bar{p}$ produced in the $\bar{p}$ target vault.

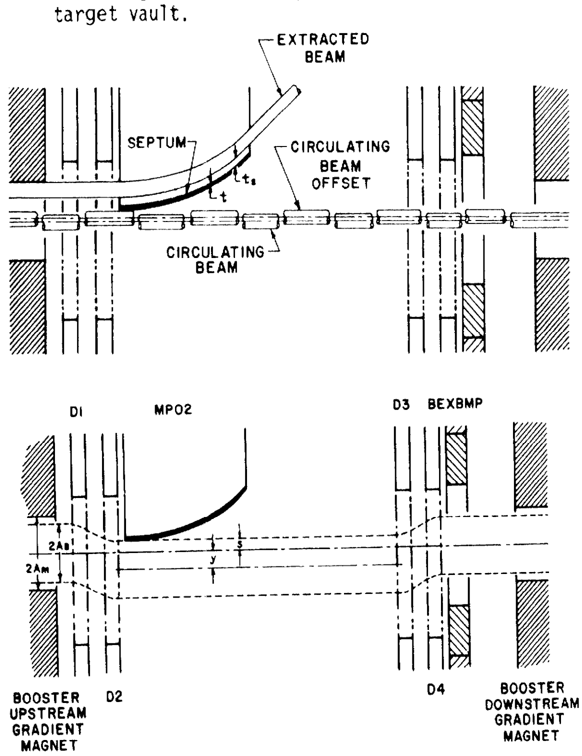
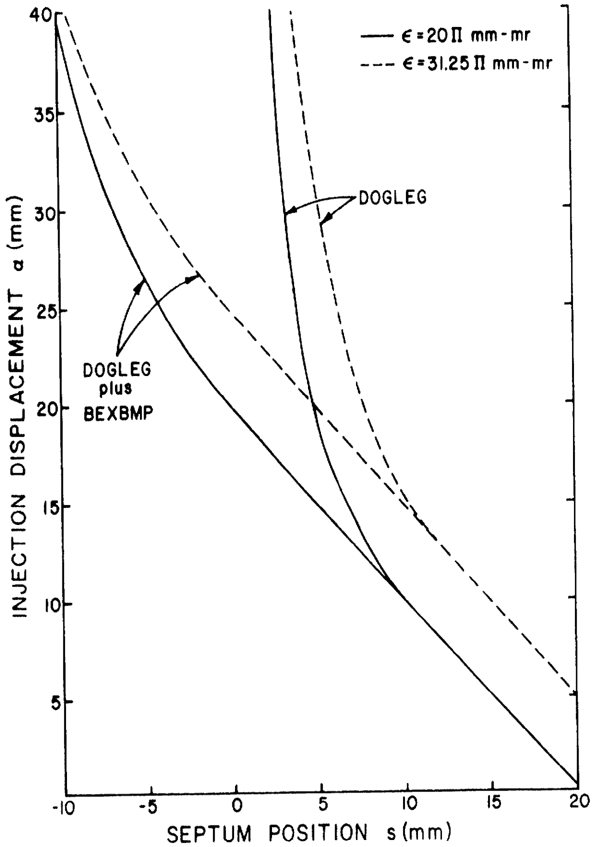


Figure 2. Magnet system designed for L3 shown in elevation view.

a) With high momentum beam for extraction of size $2A_E$.

b) With low momentum beam of size $2A_B$. Magnets D1 and D2 provide an offset y with no angle change (dogleg). Magnets D3 and D4 place the beam back on orbit.



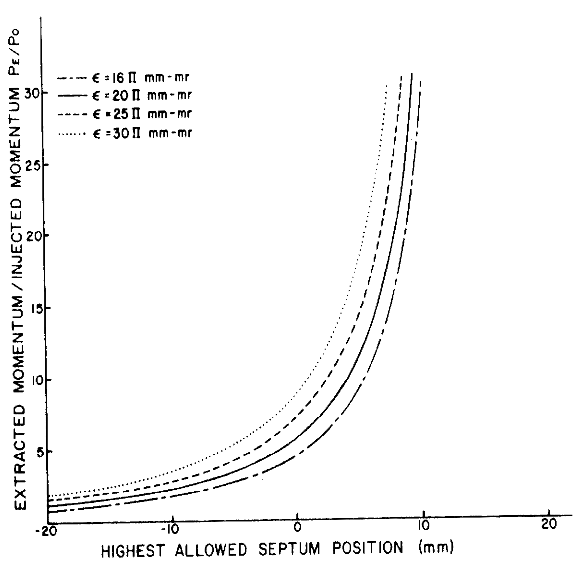


Figure 3. a) The displacement which must be supplied by d.c. magnet at injection versus septum position above the centerline. Use of the 3-bump BEXBMP to lower the beam during acceleration to aperture edge reduces the requirements on the Dogleg magnets.

b) Septum position required to allow the extracted beam to pass below the top of the gradient magnet and thru the good field region of the septum.