TM-762
0352.010

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Booster Aperture Improvements Thru Revisions Near the Extraction Septum

Bruce Brown

January 10, 1978

The present Booster Extraction System occupies space in the vertical aperture which would otherwise be available for the injected beam. This must be the case in principle for any extraction system which consists of only a septum magnet at the extraction point with fast kicker magnets and perhaps orbit distortion magnets elsewhere in the lattice. This "in principle" limitation can only be removed by adding magnets in the extraction straight section which deflect the beam (low or high momentum) in a way which effectively enlarges the local aperture above that defined by the magnet pole tips in the lattice. If the effective aperture of a given machine as defined by the field shape (and determined by its acceptance) is substantially smaller than that determined by the pole tip sizes, this "in principle" limitation may have no practical significance since even poor field regions will probably suffice for the single pass of the beam after the kicker displaces it.

Present Aperture

In the Booster the present situation is clearly between the possibilities mentioned above. The good field aperture is clearly less than the aperture defined by the pole tips (I will take 50 mm as the pole tip aperture in the Booster for this discussion). The acceptance of the booster has been measured to be 16π.

mm-mr[1] which implies a max beam size in long straight sections (β = 20 m) of ~36 mm dia. (This value is principally limited at the extraction septum). Assuming the beam size shrinks as $p^{-1/2}$ then a 36 mm beam at 200 MeV (p = .64 GeV) will shrink to 9.65 mm at 8 GeV (p = 8.9) or 8.7 mm at 10 GeV (p = 10.9). If we add the 8 GeV beam size and 3 mm for the septum to the 200 MeV beam size we find that they nearly fill the available pole tip aperture. Operational evidence that the extraction region is an injection aperture comes from the fact that the dominant injection losses occur in the extraction region. Alternatively apparent apertures in the ring can be measured by local 3 dipole bumps in the orbit. Transmission is measured shortly after injection as a function of bump strength. One can interpret the widths between points of 50% transmission (or 0% transmission) to obtain an estimate of the good field region. Using scans of the booster made in 1975 (K. Meisner has these), we find that averaged over 21 long straight sections, the apparent height for 50% transmission varies from 30.5 to 36.6 mm with an average of 33.3 mm. At long 13 (the extraction point) the 50% transmission height is 21.8 mm. Similar numbers for full beam loss are (19 section) average height, 44 mm, while long 13 has a 33.5 mm height. Recent scans are in reasonable agreement with these results.

Thus we find that both known geometry and beam measurements tell us that the injected beam is restricted by the extraction septum, however, this information does not tell us how much an improvement will gain us. Since the 3 bump measurement of full loss width agrees approximately with the acceptance of the machine, we might hope for the gain to that of an average long straight, or 34 mm goes to 44 mm.

A short experiment to measure this effect by removing the septum resulted in a gain of about 10% in transmission after a few hours of tuning. This provides some lower limit on the improvements possible by removing the septum. The aperture numbers above indicate that the improvement may be even greater. In addition to any benefits of higher transmissions which might result from an improvement of the aperture at the extraction point at Long 13, other benefits result from such a change. The machine will be more symmetric and will be less sensitive to small tuning changes near L13, making for easier tuning. Also, the losses at Long 13 have caused considerable activation. This is due to both injected and extracted beam losses. Since the beam power lost at these times are comparable, by reducing injection losses at Long 13 and distributing then around the ring, we may usefully reduce the activation at that point. In planning the extraction for reverse injection at Long 3, we will want to incorporate some plan to avoid having two aperture limitations of the sort we now experience.

New (Old) Design

Several suggestions for revised extraction systems exist which alleviate the space limitations in the vertical aperture. These include a radial extraction scheme which employe a Lambertson deflection magnet and a more complex vertical extraction employing three magnets in the extraction long straight section.[2] Presently we will pursue a design based on deflection of the injected beam locally at Long 13 beneath the extraction septum as suggested in the original NAL Design Report.[3] This scheme will use a double dogleg set of magnets operated in series to bend the beam down and level - then back up and level as illustrated in figure 1.

Assuming that the beam fills the aperture to radius ω_o and shrinks with momentum to size ω

$$\omega = \omega_o \sqrt{\frac{p_o}{p}}$$

we can calculate the deflection required to avoid the extraction septum and the resulting beam position for this magnet scheme if it is operated DC.

If the septum is at a height y_1, above the center of the aperture then the beam must be deflected by an amount y below the aperture center given by

$$y = w - y_1 = w_o \sqrt{\frac{p_o}{p}} - y_1$$

If this deflection y is provided by a pair of magnets of length ℓ, gap g and strength B separated by a distance ℓ_1, then

$$y = (\ell + \ell_1)\ \theta = (\ell + \ell_1)\ \frac{.3B\cdot(\ell+g)}{p}$$

By equating these deflections we can find the momentum p at which B must be largest

$$B = \frac{1}{.3(\ell+\ell_1)\ (\ell+g)}\ [w_o\ \sqrt{p_o p} - y_1 p]$$

$$0 = \frac{\partial B}{\partial p} \Rightarrow \frac{1}{2}\, w_o \sqrt{\frac{p_o}{p}} = y_1$$

So the maximum deflection field is required at

$$p = p_o \left(\frac{w_o}{2y_1}\right)^2$$

at which point

$$y = y_1$$

$$B = \frac{W_o^2 P_o}{1.2\ y_1 (\ell+g)(\ell+\ell_1)}$$

This set of equations assumes a beam centered vertically in the lattice. Once the beam size has shrunk a bit, one can use an orbit distortion using magnets in the long straights to help avoid hitting the extraction septum, thus putting smaller requirements on the local bumps. For the geometry we have (and expect to have) in the booster, we cannot gain much from orbit distortions since almost the full kick is required for the 200 MeV beam alone. This is illustrated in figure 2 where we plot deflection required for a septum 10 mm above the beam centerline and also the deflection provided by a constant magnetic field. We see that constant field only provides ~ 4% more than the required 15 mm deflection at 200 MeV energy (p = .64 GeV) if it matches the required 10 mm deflection at p = 1 GeV/c.

Using the above equations and the assumptions w_o = 25 mm y_1 = 10 mm and letting ℓ = 5", ℓ_1 = 14", g = 2.75, we find that B = 3.51 kG. To be conservative we might wish to plan a magnet which allows us to lower the septum a bit more. For example if we lower the septum to 7 mm above the beam we need ~ 5.1 kG to move the beam enough at 2 GeV. (This will move beam about 22 mm at injection while we only need to move 18 mm.) Should we raise the booster injection energy by a factor of 2 (prebooster) and still fill the aperture, we would then need the lowered septum to accommodate the larger beam size (assuming the MR could accept it) and these magnets would need > 10 kG. Thus we find that the magnet dogleg pair may be designed with 5" pole tips and separated by 14" with fields of 3.5 to 5 kG for present injection or up to > 10 kG for higher momentum injection.

Magnet Design

The design of a set of magnets for the double-dogleg system is substantially restricted by space requirements. In particular there is very limited space upstream of the MP01 magnet. Since the high activation levels on that magnet preclude moving it, we choose to live with a severe space limitation rather than replacing MP01. The limited space along the beam causes us to choose an unconventional design which allows us to place the magnet coils where they do not add space requirements along the beam line. This design, figure 3, consists of a pair of U poles which together form one dogleg. The coil is placed at the base of the U and allows the space between the poles to be occupied by beam detectors and vacuum valves as desired. The coil and poles must be then designed to satisfy requirements of field strength and uniformity.

The poles will be chosen to be 5" along the beam line and separated by 14" as being the largest numbers available, given existing equipment upstream of MP01. To obtain good field uniformity over a 50 + 20 = 70 mm = 2.75" vertical aperture, we choose to build the magnet with 6" high poles. The 5" wide by 6" high magnet will be provided with Rose shims[4] to improve field uniformity. For availability of material and machineability, we choose 1010 or 1020 steel stock. No lamination is required since they operate D.C.

The design of the coil is governed by requirements on the field strength and the availability of power supplies and copper stock. For this simple geometry, the following simple procedure gets one to the correct ball park. First, choose gap and field.

We will use a 2.75" gap to allow adequate space for vacuum chamber and clearance to the magnet. With a coil on each leg but 2 gaps, we can calculate for one coil (using 1 gap).

$$NI(\text{kA-Turns}) \cong 2 \times B(\text{kG}) \times G(\text{in})$$

If we use the 5 kG previously calculated then we find the NI required is 27.5 kA (3.5 kG => 19.25). We will then assume a square coil pack (and later gain from observing that it can be quite round). A square coil of core width w, height h and coil thickness T and length L carrying current I(=NI) will dissipate power

$$P = \frac{\rho[2w+2h+4T]}{TL} I^2$$

We will seek to operate 4 such coils in series (then ripple on the one power supply for the double-dogleg will only affect the position in the bump - so regulation requirements can be very loose.) We will try to match to a 50 Amp-40 volt supply. This will give us 500 watts available per coil. Since

$$P = \frac{\rho}{L} \left[\frac{2(w+h)}{T} + 4\right] I^2$$

then

$$T = \frac{2(w+h)}{\frac{PL}{\rho I^2} - 4}$$

if we use for ρ a value at elevated temperatures ($7\times10^{-7}\Omega$-in) we can calculate the coil thickness required.

P = 500 watts, L = 12", I = 27.5 x 10^3 A, W = 5", H = 6"

$$\frac{PL}{\rho I^2} = 11.3$$

$$T = 3"$$

which gives a copper area of the coil to be 36 in^2. If we supply

27.5 kA-Turns with 50A we need 550 Turns. This then gives us a wire area of .065 in^2. A couple of stock sizes could about fill this requirement. Number 2 square stock is nominally .255" on a side or .065 in^2. A standard rectangular size is .208" x .408" or .085 in^2. I will try a design using that wire size.

For winding we would like to avoid corners, however it is also desirable to maintain a large area for the core <u>and</u> keep it not much wider than the 5" wide pole tip since that plus the coil thickness adds to the pole length and thereby increases the leakage flux. The proposed core will have a 5" diameter cylinder split to provide the top and bottom with a 3" x 5" center section. This will have 34.6 in^2 cross section compared to the 30 in^2 at the pole tip. The stock material will be wound solenoid fashion on its .408 side which requires about .415"/turn including insulation. Thirty turns/layer will require about 12.45 of the 14" available. Eighteen layers will yield about 540 turns which gives 27 kA turns for 50 A. For each layer we will include .208 cu + .007" insulation or .225"/ layer. This gives a total coil thickness of 4.05". We can expect a mean turn length of $\pi(5+4) + (2x3) = 34.3"$ so 540 turns gives 1543.5" or ~ 490 lbs. For this area cu we expect

$$R = \frac{\rho L}{A} = \frac{7x10^{-7} \text{ x } 18522"}{8.5 \text{ x } 10^{-2}} = .152\Omega$$

So to get 50A requires 7.6 volts and dissipates 380 watts. If we just assume a radiative surface of a cylinder 13" in diameter plus a rectangle 3" high or each side 12" long and with end caps we have ~ 900 in^2 which would heat to about 160°F if cooled only by convection and radiation. However, if the core is cooled to room temperature 1 foot from the ends of the coil, then with even 500 watts input, the hottest point in the coil will only get to about 190°F. It is easy to cool this well or better so the coil will be wound with 200°F insulated solid copper.

Design of this system is proceeding. Procurement of long lead time items has started and installation is planned for the Spring 1978 shutdown.

References

1. See D. F. Cosgrove, et al., IEEE Trans. N.S.-24 (1977) 1423 "1977 Particle Accelerator Conference".
2. Private Communication, C. M. Ankenbrandt, R. P. Johnson.
3. Design Report, National Accelerator Laboratory, July, 1968, pages 9-37.
4. S. C. Snowdon, "On the Calculation of Rose Shims", TM-710, January 28, 1977.

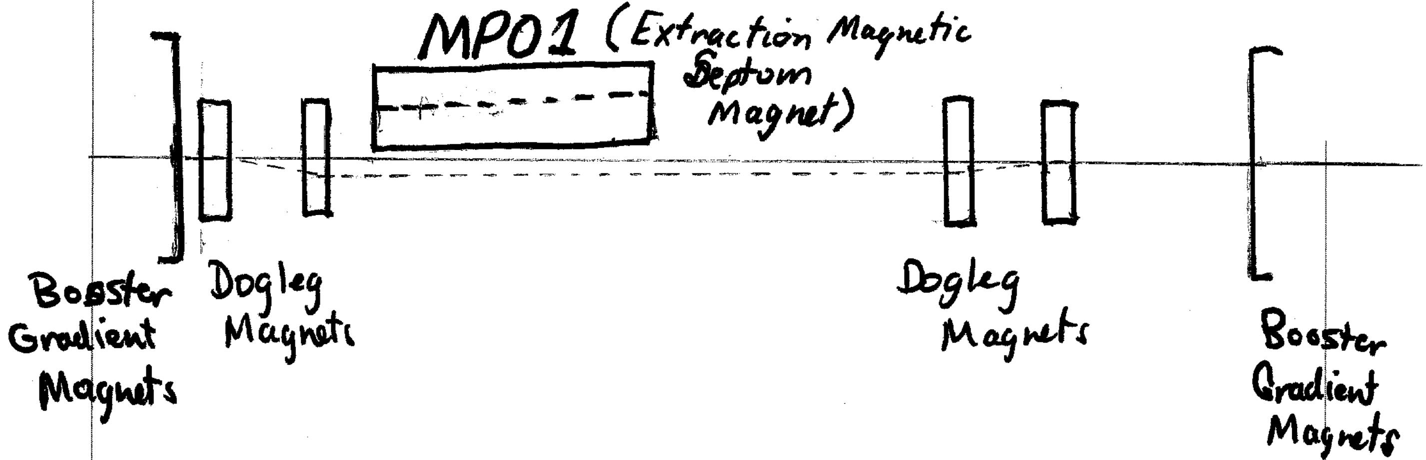
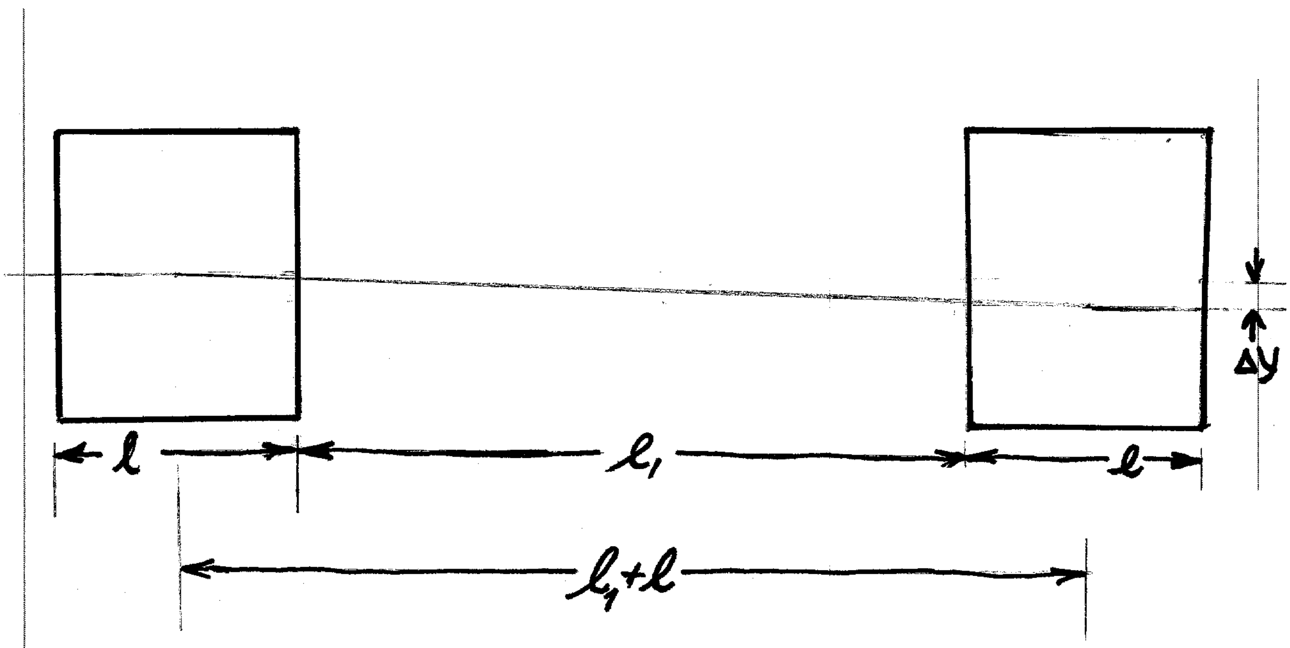


Fig 1a) Booster Extraction Long Straight (L13)

Fig 1 b) Dogleg Magnet Geometry



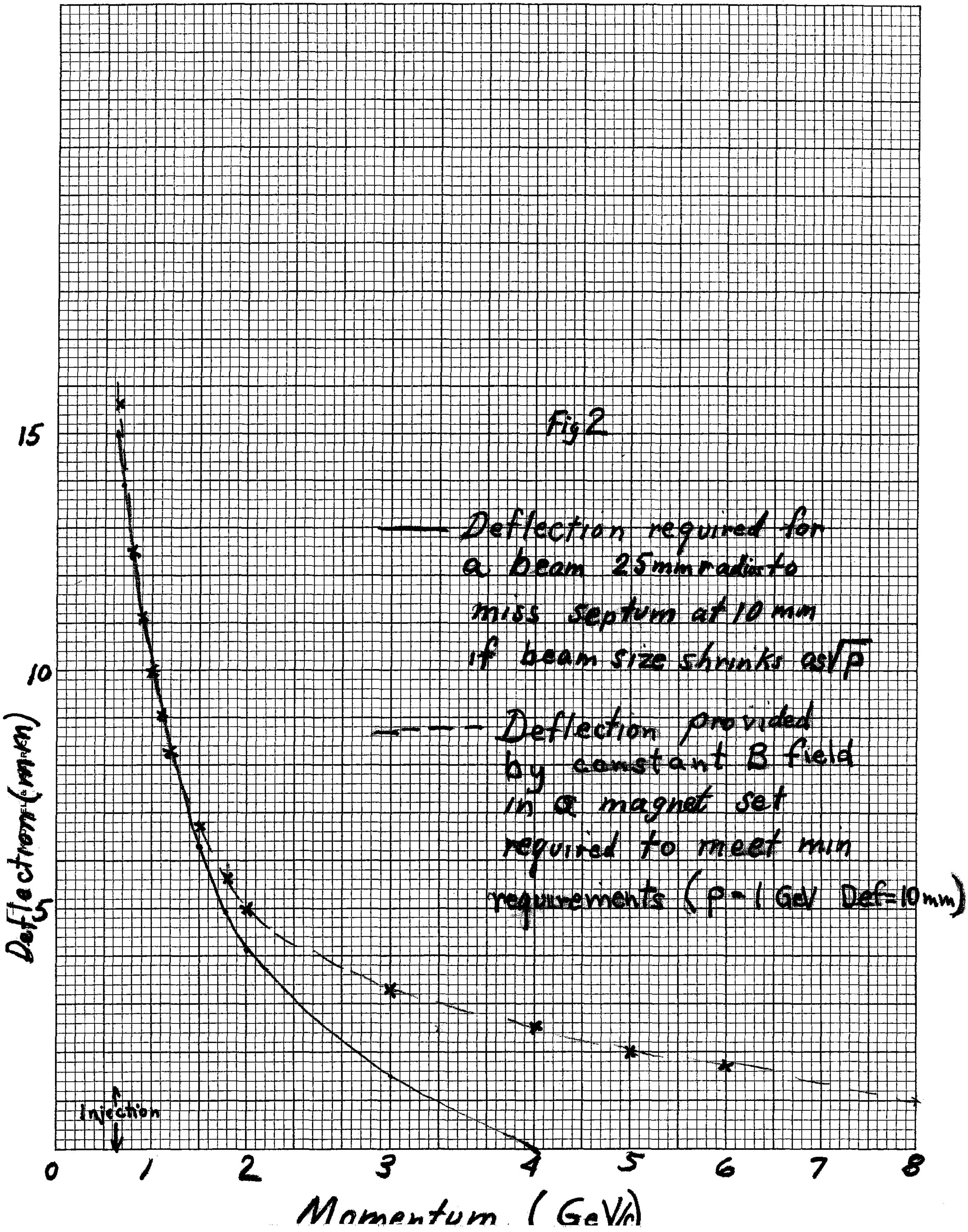


Fig 2
Deflection required for a beam 25 mm radius to miss septum at 10 mm if beam size shrinks as √p
Deflection provided by constant B field in a magnet set required to meet min requirements (p = 1 GeV Def = 10 mm)
Deflection (mm)
15
10
5
Injection
0
1
2
3
4
5
6
7
8
Momentum (GeV/c)

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Fig 3