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OPTIMIZATION OF SUPERCONDUCTING MAGNET BORE SIZE

for

HIGH INTENSITY AREA BEAM LINE

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I. INTRODUCTION

The High Intensity Area Beam Line (HIA) design has been described by Brad Cox[1]. The design report described the fine optics, sextupole corrected beam line producing a small vertical spot size at the experimenters target, or conversely, good parallelism in the vertical plane suitable for Cerenkov indentification. Typical acceptances for such a beam are expected to be approximately 18 μster-% with the sextupoles on, and 60 μster-% with the sextupoles off. For the sextupole corrected beam the main aperture limits are not in the first stage, as expected for a non-corrected beam, but rather are in 2nd and 3rd stage quadrupoles. The initial specifications called for 6 inch clear bore superconducting dipole and quadrupole magnets to transport the beam clearly through the later stages.

The present conventional HIA beam has chosen the larger acceptance, non-sextupole-corrected, optics in order to maximize the secondary/Proton flux ratio. The

current round of HIA experiments either have not required the small spot size or have learned to live with the larger spot size on their targets. Therefore, we will continue our study assuming the non-corrected, large acceptance optics, realizing that a flux loss factor of approximately 0.3 would occur if we later decide to include the sextupoles.

This study will consider the available flux as a function of both dipole and quadrupole bore sizes. This will be done for two Tevatron-era beams, namely the 750 GeV π^- beam and the 250 GeV $\bar{p}$ beam generated from $\bar{\Lambda}^\circ$ decays. We will next discuss the magnetic field equations for our shell type magnets. Cost estimates, based on our prototype development program, will be discussed for various bore size dipoles and quadrupoles Finally, some special considerations and recommendations will be presented.

II. BEAM FLUXES vs. BORE SIZE

We have analyzed the secondary beam fluxes using the TURTLE Program[2]. Routines that generate initial rays corresponding to the observed single particle cross sections were written. The rays were then transported through the high flux mode beam line and the number that did not strike magnet or slit apertures were recorded. This allowed us to make a plot of relative flux as a function of magnet apertures.

The negative pion flux was parametrized[3] as

$$E \frac{d\sigma}{d^3p} (pp \rightarrow \pi^- X) \simeq (1-x)^4 \, e^{-4P_t} \qquad \text{I.}$$

over the range $.67 \leq X \leq .90$ and $P_t < 2.5$GeV/c. This produced the relative fluxes at 750/1000 and 300/400 in Fig. 1. It is obvious that increasing the dipole aperture beyond 4" does not increase the pion flux. Increasing the quadrupole size from 4" to 5" produces 20% flux increase for the 750 GeV beam.

The $\bar{p}$ beam is generated from $\bar{\Lambda}$ decays. $\bar{\Lambda}$'s were generated using the data of E8[4].

$$E \frac{d\sigma}{d^3p} (pBe \rightarrow \bar{\Lambda}^o X) \simeq e^{-12.5x} \, e^{-2.3P_t^2} \qquad \text{II.}$$

The $\bar{\Lambda}^o$'s were allowed to decay into $\bar{p}\pi^+$ using DECAY TURTLE. The small Q value of the $\bar{\Lambda}^o \rightarrow p\pi^+$ decay produced a small angle difference between the $\bar{\Lambda}^o$ and $\bar{p}$ directions, however the requirement of a downstream decay produces a smeared apparent production target size of approximately 1.2 cm rms half-width. The $\bar{p}$'s were then traced through the remaining magnetic elements and apertures. The central $\bar{p}$ momentum was chosen to be 250 GeV (x = .25) in order to maximize the $\bar{p}$ flux and optimize the $\bar{p}/\pi^-$ ratio[5].

The resulting relative $\bar{p}$ flux curves are depicted in Fig. 2. Again there is little flux to be gained by increasing the dipole bore beyond 4". The relative fluxes for a 4" dipole and 4/4½/5¼" quads are 1.0/1.24/1.34

Although the 5¼Q option looks best, there are some strong cost arguments discussed later which may indicate that the 4½ inch Quad is most cost-effective.

III. MAGNETIC CONSIDERATIONS

The equations for the central fields and central gradients of dipole and quadrupole shell type coils are given by [6]

Dipole: $$B_o = \frac{2\mu_o}{\pi} J_o \Delta r \sum_i \sin \Phi_i \qquad \text{III}$$

and

Quad: $$g_o = \frac{dB_y}{dx} = \frac{2\mu_o J_o}{\pi} \sum_i \cos 2\left(\frac{\pi}{4} - \Phi_i\right) \ln \left(\frac{r_i + \Delta r}{r_i}\right) \qquad \text{IV}$$

where J_o is the current density, Δr is the thickness of the shell, r_i and Φ_i are the inner winding radius and half-angular extent of each shell, and the summation is over the number of shells in the coil package. These equations are for air-core coils without iron. The addition of non-saturating warm iron would increase the dipole field by about 25% and the quad gradient by about 7%. Furthermore, our quads have typically had a single angle $\Phi_i = 30°$ for each shell giving

$$g_o = \frac{\sqrt{3}\,\mu_o}{\pi} J_o \sum_i \ln\left(\frac{r_i + \Delta_r}{r_i}\right) \qquad \text{V}$$

These equations exhibit the following characteristics. The dipole field is independent of bore size. It depends only on the current density and thickness of each shell.

As long as we maintain the shell angles and a constant current density, we do not lower the number of shells required by lowering the bore size.

Increasing the current density by changing from 3.0/1.0 to 1.8/1.0 copper/SC ratio and setting all $\phi_i = 60°$ will allow us to decrease the number of shells from 4 to 3.

The summation of the logarithmic terms for the quadrupole turns out to be almost linear in the number of shells employed for a given inner winding radius. The summation also increased with decreasing inner radius. Additionally, at a constant gradient, the pole tip field also decreases with decreasing inner radius or bore. Therefore, due to the lower maximum field, the current may increase while still maintaining a constant fraction of short sample. Coupled with an increase in current density due to a lower Cu/SC ratio, we may thus produce 5½", 3 shell quads or 2 shell quads wire bores $\leq$ 4½ inches, while still attaining the required gradients at approximately 80% of short sample limit.

IV. COST PROJECTIONS

The current cost projections are based on actual prototype magnet development experience[7]. They reflect previous purchases of small quantities of items and do not include any new fabrication materials or methods.

These cost estimates for the various magnet configurations considered are listed in Table 1. They should be used for relative cost comparison between various coil configurations.

We currently have a set of 6" bore dipole fixtures. The total cost of such fixtures capable of producing 10 foot coils is now approximately $70K. We already have adequate curing ovens, lathes, coil winding tables, etc. to outfit both the dipole and quadrupole projects simulataneously. In addition, new 10 foot winding fixtures for the new quadrupole and dipole bore sizes must be fabricated. The quad fixture is estimated[7] to cost $51K. Ten dipole magnets are required for the HIA installation. The cost difference between 6" and 4" bore magnets is $65 - $50K = $15K/magnet. This is more than sufficient to justify the switch to 4" bore dipoles where applicable in HIA and for other, more general beam line use.

A possible compromise would be to opt for 4 1/2 inch bore dipole. The present 6 inch bore #1 and #2 shell fixtures could be then used to wind the #3 and #4 shells for the 4 1/2 inch dipoles. This would halve our future dipole fixture costs while negiligibly increasing our per magnet costs over the proposed 4 inch dipole.

V. OTHER CONSIDERATIONS

The largest fluxes are attained when the HIA secondary beam channel is aligned at zero degrees to the primary proton beam. In this zero degree mode, a high intensity neutral beam is formed. The limiting aperture for this neutral beam before the momentum slit will be the downstream-most of the 3 dispersing bends. The deflection of the charged beam at this aperture is approximately 2.1" thereby requiring a horizontal offset to center the transported beam in the aperture. Fig. 3 shows that this offset will bring the zero degree neutral beam to within 1" of a 4" bore superconducting coil or the coil will be at 1"/175' = 0.5 mrad from the zero degree neutral beam for a 4" aperture. This may be allowable with the proper shielding. However, 6 inch bore dipoles would alleviate the problem.

Another top-of-the-head solution might be to replace the downstream 4SD120 with three 6-3-120 conventional dipoles. This still does not allow enough horizontal aperture even if we allow the neutral beam to come within 1 inch of the magnet coil. TURTLE shows that the transmitted beam has a 2 inch horizontal FWHM at this point, indicating that we would be very close to seriously cutting our beam flux with this configuration. A few 6 inch bore dipoles would be handy to alleviate the special beam loading and quenches problems associated with dumping the neutral beam.

VI. RECOMMENDATIONS AND PROPOSAL

My recommendation would be to decide in favor of the 4½ inch bore dipoles and 4½ inch bore quadrupoles for the majority of the HIA installation. As we have seen, a 4½ inch bore is about the limit we can attain at 82% of short sample current for a 2 shell quadrupole. This quad loses 19% of our maximum forseeable $\bar{p}$ flux with 4½" dipoles, yet it saves 26% of the total quadrupole cost. Dipoles of 6" bore would be extremely useful, for the HIA, TPL, and the proposed broad band electron beam neutral beam dump areas. The total number of 6" dipoles required would be only about 5 to complete all three installations.

REFERENCES

[1]B. Cox, et al, P-West High Intensity Secondary Beam Area, Design Report, March 1977.

[2]D. C. Carey, TURTLE Manual, NAL-64, May, 1978, and K. L. Brown, et al, DECAY TURTLE, CERN 74-2. DECAY TURTLE has been modified to trace neutral parent particles.

[3]E-118 Data.

[4]P. Skubic, et al, Phys. Rev. D 18, 3115 (1978).

[5]B. Cox, the High Intensity Laboratory, Fermilab Report. January 1979.

[6]H. Brechna, Superconducting Magnet Systems, Springer, New York, 1973 p64.
A. Asner, BNL 50155 (C-55), 866 (1968).

[7]Cost Estimates by R. Fast - 22 Janaury 1979 and
J. Satti - 08 June 1979.

TABLE 1. LOW CURRENT SUPERCONDUCTING MAGNET COSTS FOR 10 FOOT MAGNETS[7].

Type	Bore	Shells	I	%SS	Coil Materials	Coil Labor	Lead Box/Cryostat/Iron Materials	Lead Box/Cryostat/Iron Labor	Total
Dipole:	*6"	4	248	75%	$33.1K	$7.5K	$21.2K	$3.5K	$65K
	*4"	4	250	75%	26.6K	7.2K	20.6K	3.5K	58K
	4"	3	333	82%	20.0K	5.4K	20.6K	3.5K	50K
Quadrupole:	5¼"	3	342	75%	44.0K	7.5K	15.0K	3.5K	70K
	4½"	2	418	82%	28.0K	5.5K	15.0K	3.5K	52K
	4"	2	381	73%	25.0K	5.5K	15.0K	3.5K	49K

* 3:1 = Cu/SC, all others 1.8:1

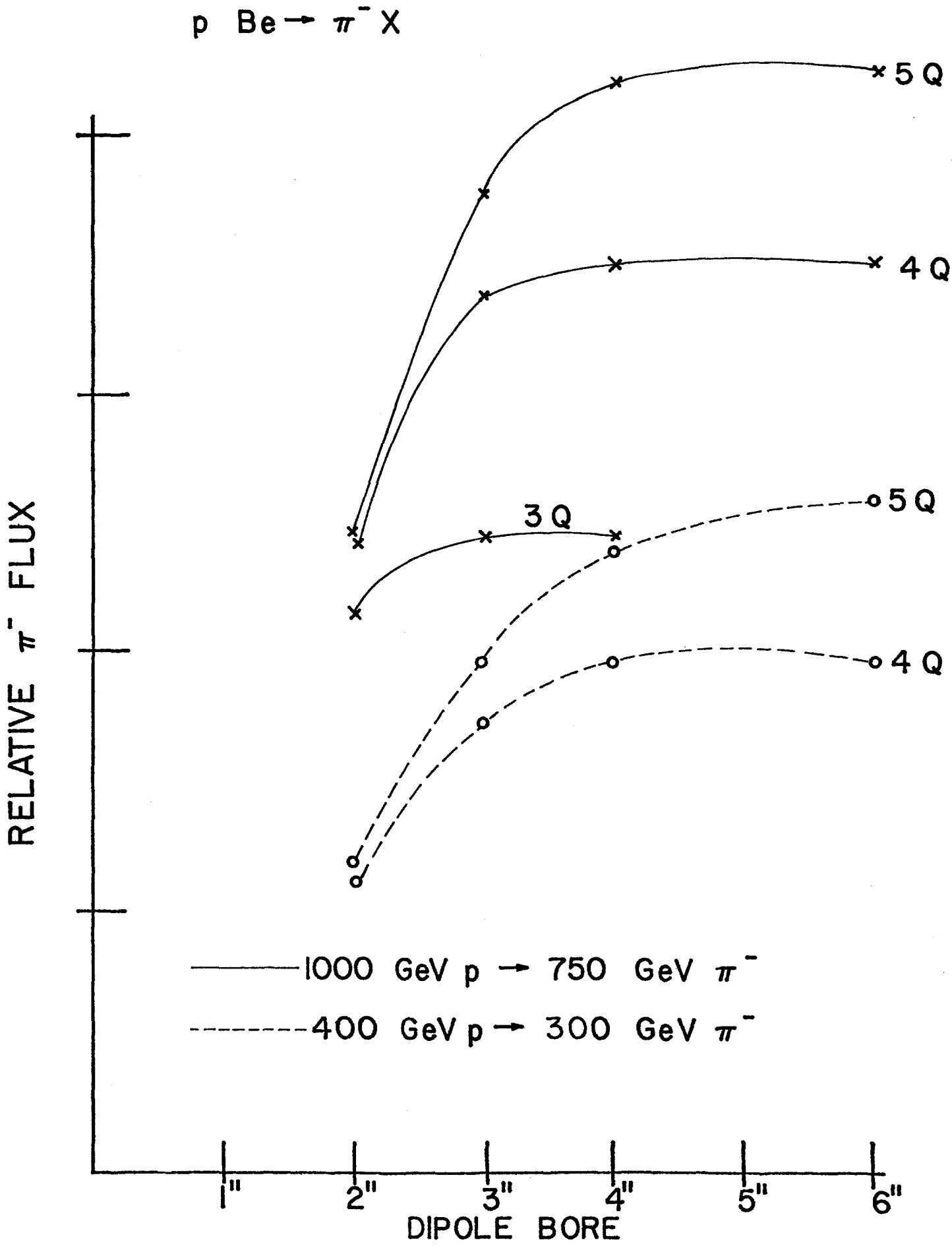
p Be → π⁻ X
5 Q
4 Q
3 Q
5 Q
4 Q
RELATIVE π⁻ FLUX
1000 GeV p → 750 GeV π⁻
400 GeV p → 300 GeV π⁻
1"
2"
3"
4"
5"
6"
DIPOLE BORE

Fig. 1

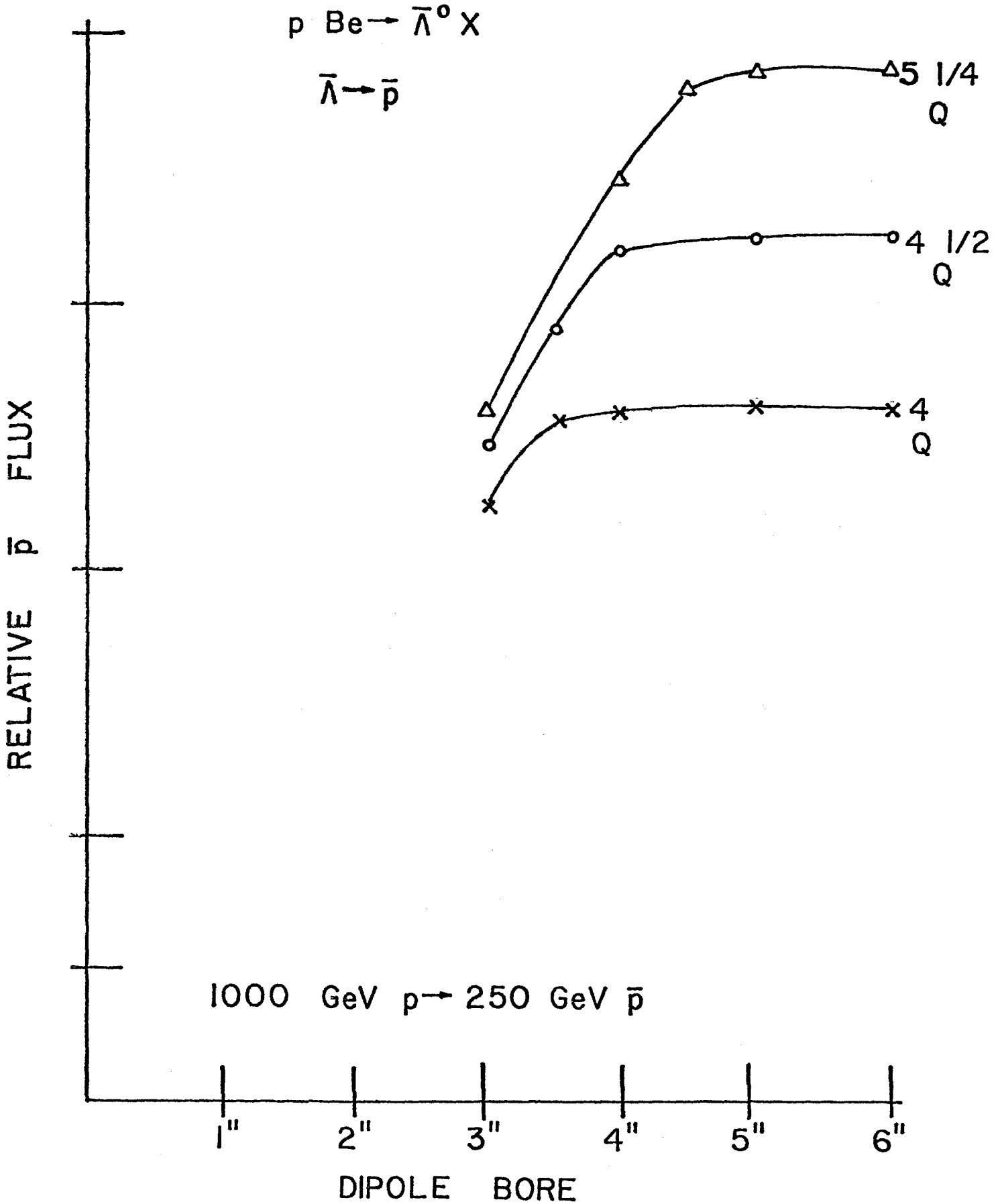
p Be → $\bar{\Lambda}^o$ X
$\bar{\Lambda}$ → $\bar{p}$
5 1/4 Q
4 1/2 Q
4 Q
RELATIVE $\bar{p}$ FLUX
1000 GeV p → 250 GeV $\bar{p}$
1"
2"
3"
4"
5"
6"
DIPOLE BORE

Fig 2
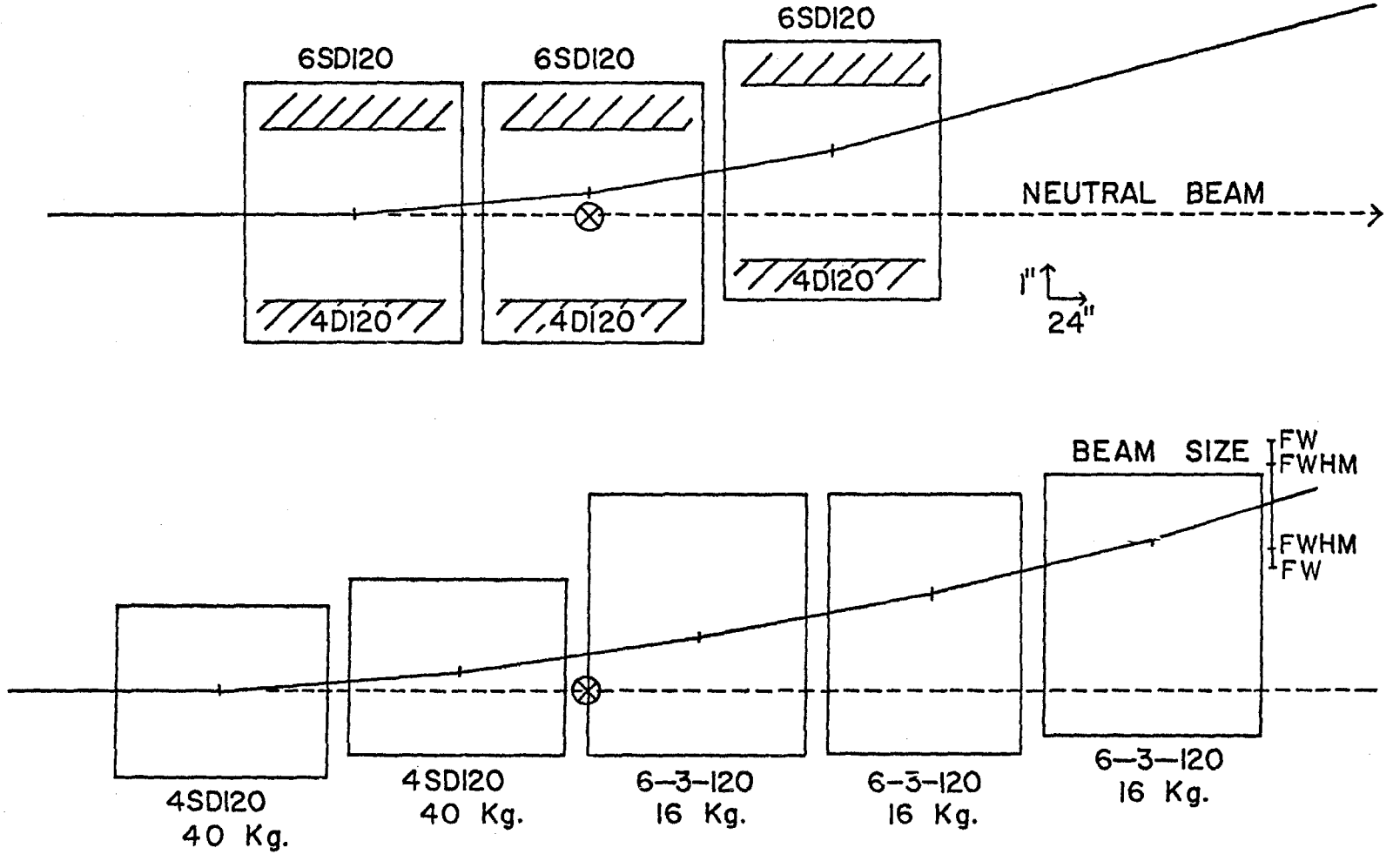
Fig. 3 DISPERSIVE BEND GEOMETERY