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TARGET STATIONS WITH HIGH BEAM MULTIPLICITY

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ABSTRACT

A target station is proposed that produces many simultaneous charged particle beams of high intensity, high quality, and a reasonably high degree of flexibility and compatibility. It is suitable for use at an intermediate station in a way that does not destroy the EPB or ahead of the beam dump with the simultaneous production of several neutral beams.

I. INTRODUCTION

Effective use of the 200-GeV facility requires the support of a relatively large number of simultaneous experiments. For the most part the setups will be more expensive and larger than the corresponding projects of today; hence, for economic reasons alone, a given setup may be expected to last for a relatively long time. At the same time, however, the number of groups attempting to use the facility and the scientific program anticipated on the basis of experience with present accelerators will both be larger than ever.

For these reasons it is particularly important that a careful search be made for ways of assuring a high degree of compatible operation among a large multiplicity of experimental arrangements. The problems are partially separable into those related to the distribution of target stations and those concerned with the detailed development of a given target station. We will consider in detail only the latter. However, it is important to note the choices that are available with regard to the distribution of the target stations. Assuming that a single EPB channel supplies the entire experimental program, two extreme arrangements of target stations are shown in Fig. 1.

In the first case, all stations are end stations, fed by splitting off adjustable fractions of the beam from the EPB main line. In the second case some experiments are performed on intermediate (nondestructive) stations. The first arrangement allows more flexibility, better shielding, and a larger number of beams per station. Moreover, changes in one target station will not interfere with the performance of the others. On the other hand, the nondestructive channel is potentially very useful when "thin" targets are required, and generally it turns out that beam usage is more efficient when targets are cascaded.[1]

In the following we describe an arrangement that can be used in either an intermediate or an end station to produce simultaneously eight charged secondary beams. In the latter case several neutral beams can be produced as well.

II. SPECIFICATION OF SECONDARY BEAMS

A general purpose target station should provide secondary charge particle beams with the following characteristics:

1. High multiplicity of channels
2. Independent control of:
   a) Intensity
   b) Momentum
   c) Sign of charge
3. Good optical quality
4. Provision for changing optics
5. Provision for adding mass separation
6. Accessibility or durability of components
7. Noninterference with the remainder of the experimental programs
8. Low cost

These characteristics are necessarily conflicting to some extent. We believe, however, that the station proposed here satisfies most of these criteria very well.

III. TARGET STATION DESIGN

Figures 2 and 3 show the proposed design for an intermediate station. (Note that longitudinal and transverse scales differ by a factor of ten.) Figure 4 shows (schematically) how neutral beams can be produced at an end station.

Each secondary beam is produced near zero degrees. The quadrupole apertures for each channel are of radius

$$R_c = 5 \text{ inches} \approx x_1 p_o / p_c , \qquad (1)$$

where x_1 is the distance from the target to the center of the first lens, p_c is the channel momentum and p_o is the transverse momentum within which 50 percent of all secondaries are produced. In what follows we use $p_o = 0.350$ GeV/c, independent of p.[2]

All secondaries plus the 200-GeV proton beam are given an initial deflection $p_m = 2$ GeV/c. Because $p_m >> p_o$ the production cones of particles of widely differing momenta are well separated, and it is possible to accept a relatively large flux into each channel. As a given channel is tuned to different momenta the expected flux is given in terms of the yields calculated in Ref. 2, assuming a circular acceptance aperture. In the present case the entrance aperture is essentially elliptical; hence, the yields (Fig. 5) for each channel have been reduced by the factor by which the horizontal aperture is reduced. For reasons to be discussed later, we believe that these flux estimates are, if anything, pessimistic.

In the separation of the secondary beam channels from the EPB and from each other, use of a strong front magnet is necessary; its use is a mixed blessing, because it forces the sharp cutoff in the sensitivity of each channel to off-channel momenta (Fig. 5). An advantage of this restriction, however, is that each channel is bombarded by relatively few off-momentum particles, so that the beams in the experimental areas will be relatively free from general background.

Because of the dispersion d_o introduced by the front magnet, a small correcting septum magnet has been included in each channel.

Independent control of intensity should preferably include remotely controlled collimators ahead of the quadrupoles. This can supplement large "permanent" collimators, which are more easily used in the experimental areas. The advantages of collimating early are to keep background out of the experimental areas, to improve beam optics through more reliance on peraxial rays, and to match any change in optics such as reversing the polarity of the front doublet. The adjustable uranium collimator should be of order one meter long, enough to eliminate the hadrons. The muons cannot reasonably be stopped in an adjustable collimator. A rough calculation shows that, for the geometry of Fig. 3, about 0.6 percent of the pions decay ahead of the collimator; hence, collimator attenuation factors of at least one hundred should be usable. Preferably horizontal and vertical collimation should be separately adjustable. The 15-GeV channel is rather crowded; it will be difficult if not impossible to provide an adjustable collimator. The momentum is low enough, however, that it might not be unreasonable to provide all the necessary collimation in the experimental area.

It is obvious that the polarity of the front magnet selects the charge for each set of channels. With the front magnet off both sides can receive at most a very small amount of beam for tuneup.

The proposal to put the major dispersing dipoles after the quadrupoles instead of using long septum magnets ahead is somewhat arbitrary.

Although septum coils can bring the effective aperture for a dipole relatively closer to an interference, the space needed for magnetic flux return limits the number of high field septum dipoles that can be placed side by side. The use of low field dispersing magnets ahead of the quadrupole would push the quadrupoles too far from the target, leading to unnecessarily large apertures. From Fig. 3 it appears that the best solution for the 60 and 120 GeV/c beams is the combination of a modest septum dipole ahead of the quadrupole and a larger dipole after. Another possibility is to move the quadrupole closer to the target, reducing its size. These alternatives have not been studied in any detail.

In order to provide a narrow septum the first lens of each quadrupole doublet has narrower coils and no outside return yoke in the median plane (See Fig. 6). The feasibility of omitting the side yokes has been well demonstrated at BNL and LRL. With the proposed polarity of each doublet the beam does not fill the full aperture of the front lens horizontally. Hence, it should be possible to bring the coil to the edge of the nominal (circular) aperture. In fact, with an elliptical vacuum pipe, the usable vertical aperture can be somewhat larger (dotted surface) than that assumed in calculating the channel fluxes given in Fig. 5. The coil of the second lens in each doublet is fourfold-symmetric. This provides a horizontal acceptance somewhat improved over that assumed previously for the first lens. Hence, the fluxes given in Fig. 5 are probably pessimistic.

The target is assumed to be imaged onto a line 360 inches from the incident EPB line, i.e. at the entrance to the experimental area. At this point a collimator can be used to select a momentum width for the ensuring experiment. With the quadrupole polarity shown, enough dispersion is provided in each channel so that with reasonably small target width (1 mm), the size of the target image represents a beam momentum width much less than e.g. the pion mass. This condition still permits some latitude in the selection of the dispersing dipoles. It is important, however, to select deflections that keep the channels well separated in the experimental area.

IV. BEAM OPTICS

As is implied by (1), there are some important scaling laws pertaining to the set of secondary beam channels. For equal acceptance each channel can use the same aperture lenses provided that their distances from the target are proportional to the channel momenta. This "law" breaks down for several reasons:

1. Inaccuracy of "thin lens" approximation
2. Irreducible end effects in the construction of hardware
3. Source size
4. Dispersion introduced by the front magnet

These effects are important enough that high multiplicity, high intensity target stations have not been achieved at the existing accelerators. The problems are easier at the higher momenta, as is clearly indicated in Fig. 3, and aside from questions of cost and decay in flight, are easier with long, large aperture systems.

Another interesting scaling law relates the strength of the lens to the beam momentum and source distance. In the case of present interest, the image distance is much further from the quadrupole than is the source. Hence, the focal length F of a (symmetric) doublet is approximately x_1, where

$$\frac{1}{F} = \frac{1}{x_1} = \left(\frac{dB/dR}{B\rho}\right) L^2 \left(\frac{2}{3} L + D\right), \qquad (2)$$

and L is the length of each lens, D is the separation of the lenses, K is a constant, and

$$dB/dR = B_c/R_c \text{ and } B\rho = Kp_c .$$

Using (1) we find

$$L^2 \left(\frac{2}{3} L + D\right) = \frac{x_1 p_o^2 K^2}{B_c^2} . \qquad (3)$$

Hence, for a given pole tip magnetic field the required length L of the magnetic lens to accept a given fraction of the total flux is independent of quadrupole aperture and channel momentum, and is a relatively slowly varying function of x_1, the distance from the source to the quadrupole.

In computing the required magnetic dimensions, we have chosen the magnetic field strength for $p = p_c$ to be 5 kG on the pole tips at $R = R_c$ for the quadrupoles and 5 kG in the uniform field dipoles. Hence, the maximum fields (for $p = 2p_c$) are 10 kG with three exceptions. The front magnet, for which we are trying to minimize the dispersion, operates at 20 kG, as does the correcting septum magnet for the crowded 15 GeV/c channel when it is operated at 30 GeV/c. The septum magnet for the 30 GeV/c channel operates at up to 12 kG. (The beam characteristics do not change in any significant way if the other dipoles are made half as long and operated at up to 20 kG.) The relevant optical formulas are given in Fig. 7. The channel dimensions and characteristics are given in Table I. For any reasonable dispersion at (x_4, y_4), as is shown in Fig. 7, the effect of the front magnet is negligible and the total dispersion simply depends on the ratio p_m/p_e, approaching a constant as $p_e \to \infty$. This is the result of the particular boundary condition that y_5 ($>> y_4$) is a constant.

Significant changes in the beam optics could be made by converting the doublet to a triplet or by strengthening it to produce an image inside the shielding wall. Such modifications can be made without interfering with the basic target area configuration if only the front lens is considered "permanent", so that work could be done in the areas that are "cold" from the stand point of radiation. An improvement from the standpoint of flexibility would be to install initially a set of more conventional length modular lenses (instead of two long ones) in each channel. The polarities and strengths could then be adjusted to vary the optics considerably without going inside. In the present configuration we have neglected end effects between lenses and set the lens separation $D = 0$.

V. MAGNETS

An effort has been made to use as few different magnets as possible. Most of the elements shown may be considered general purpose in the sense that the coils, at least, are appropriate for magnets needed in the experimental areas. For the most part the required fields are not high, and coil design is assumed to be "conventional". This does not mean that state-of-the-art improvements should be ignored, but rather that they should be used to improve reliability in the very severe radiation conditions anticipated. Hence, we have not proposed any septum coils less than two inches in width, and the coils generally are assumed to be protected by some feet of uranium absorber. For the very upstream elements it is probable that special insulation should be used, or that the coils should consist of relatively heavy copper bars supported on nonorganic spacers.

Formulas for magnet current and power are given in Table II, for steel, in Fig. 9. For purposes of shielding we assume that the outside magnet cross sections are rectangular. Specific magnet parameters are given in Table III. The value used for the resistivity 1.4×10^{-6} ohm-inch is conservative but typical of large coils for which the cross section is 50 percent copper. The costs are based on assumed fabrication costs of \$4/lb for coils, \$0.25/lb for steel for the dipoles, and \$0.50/lb for steel for the quadrupoles. For power supply costs we have used \$50/kW.

VI. OTHER PROBLEMS

We have not considered in detail the vacuum system, magnet support system, or shielding. We expect that all the beam lines would be in vacuo at least to the outside of the shielding. The magnets should be supported in a way that assures maintenance of their positions relative to each other and to the target. For this purpose, piles or caissons should be used to support a relatively rigid EPB line over the relevant 3000 inch length. Changes in the position of this EPB line relative to those at neighboring stations can easily be corrected by small deflecting magnets. It is probable that subassemblies should be used to guarantee the rigidity of each quadrupole doublet and its associated adjustable collimator.

For initial shielding it is assumed that, except for beam channels, solid iron or uranium exists out to a distance of about 2 feet from the EPB line and for a length of 250 feet along the beam. For the initial deflection p_m = 2 GeV/c, this places of order 1 ft per BeV/c of iron in the way of nonchannel muons. The total amount of steel required is less than 4000 ft^3 (\$100 K at \$0.10/lb).

This shielding would need to be supplemented by concrete or earth outside the iron. For this we believe that at least some removable concrete blocks should be used to permit easy redesign of the downstream end of each secondary beam channel.

REFERENCES

[1] D. Keefe, Lawrence Radiation Laboratory UCRL-16830, Vol. II, 1966, p. 185.

[2] A. Roberts, Acceptance of Secondary Particle Beams, National Accelerator Laboratory Internal Report FN-154, June 3, 1968.

Table I. Summary of Beam Characteristics.
Momentum in GeV/c; angles in milliradians; distances in inches
$R_c = 5,\ p_m = 2,\ D = 0,\ x_5 = 360$

p_c	Channel momentum	15	30	60	120
θ_o	Deflection from front magnet	133	66.7	33.3	16.7
d_o	Target dispersion from front magnet	9.3	4.7	2.3	1.2
ϕ_o	Production flux angle (50 per-cent)	23.3	11.7	5.83	2.91
x_o	Target to front of quadrupole	220	420	800	1600
x_1	Target to center of L_1	302	520	923	1751
L_1	Length of first lens	165	201	246	302
L_2	Length of second lens	105	145	194	260
$\bar{f}_1$	First lens average focal length	119	195	318	520
$\bar{f}_2$	Second lens average focal length	186	271	400	608
$f{-}{+}/x_1$	Entrance aperture attenuation factor	2.95	2.41	2.03	1.76
$f{+}{-}/x_1$	Exit aperture factor	0.506	0.588	0.626	0.667
x_4	Coordinates of turning point at large dispersing dipole	576	911	1522	2704
y_4		68	56	48	44
ℓ	Length of dispersing dipole (B_c = 5 kG)	131	262	524	1048
p_ℓ	Strength of dispersing dipole	0.5	1	2	4
θ_f	Angle after dispersing dipole	167	100	66.7	50.0
x_5	Target to entrance to experimental area	2328	3951	6202	9024
M_H	Horizontal target magnification at (x_5, y_5)	1.79	2.26	2.31	1.93
M_V	Vertical target magnification at (x_5, y_5)	15.3	12.4	9.7	6.7
d_t	Total dispersion at (x_5, y_5)	75	112	161	213
δp_t	Target momentum width at (x_5, y_5)	0.014	0.024	0.034	0.043
S	Separation of channels at entrance to experimental areas	270	225	188	

Table II. Magnet Current and Power Formulas.

I. For picture-frame dipoles

A. Current density

$$i = \frac{2.02\,B}{W}$$

where B is in gauss, W = coil width in inches, and i is in amps per in.^{2}

B. Power

$$P = \int i^2 \rho\, dV$$

where V = Volume = 2LWG, ρ is in ohm-in. and P is in watts or $P = 8.16 \rho B^2 LG/W$, where L is the length of the magnet (end effects neglected).

II. For quadrupole (Fig. 6)

A.

$$i = \frac{2.02\,B_c R}{R_c W}$$

where B_c is field at radius R_c, and R, W are the inner radius and width of the coil

B.

$$P = \int i^2 \rho\, dV$$

$$V = 8LW\left(\frac{R_c^2}{2R}\right) = \frac{4LWR_c^2}{R}$$

or

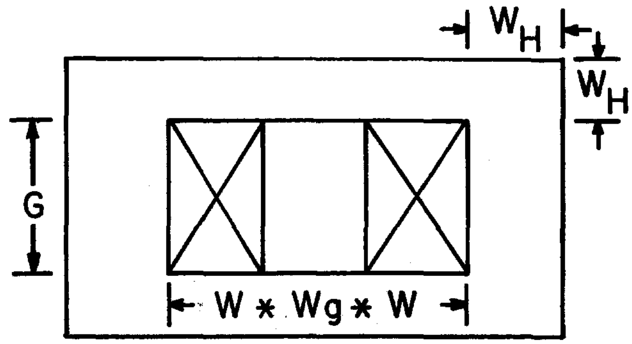
$$P = 16.32\,\rho B_c^2 LR/W$$

where L is the length of the magnet (end effects neglected)

Table III. Magnet Steel Requirements.

I. Picture-frame dipoles

A. H-magnet

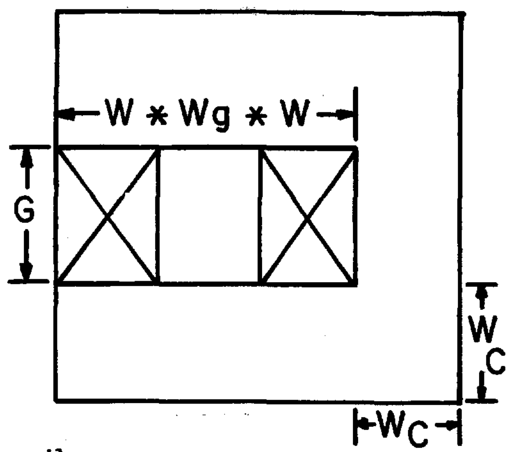


$$W_H = \left(\frac{W_g + W}{2} \right) \frac{B}{B_{fe}}$$

where B is field in aperture, B_{fe} is the maximum allowable field in iron

$$\text{Vol. of iron} = 2W_H L(2W_H + G + 2W + W_g)$$

B. C-magnet



$$W_C = (W_g + W) \frac{B}{B_{fe}}$$

$$\text{Vol. } 2W_C L(W_C + \frac{G}{2} + 2W + W_g)$$

II. Septum quadrupoles (Fig. 6)

Assume field falls linearly to zero across coil.

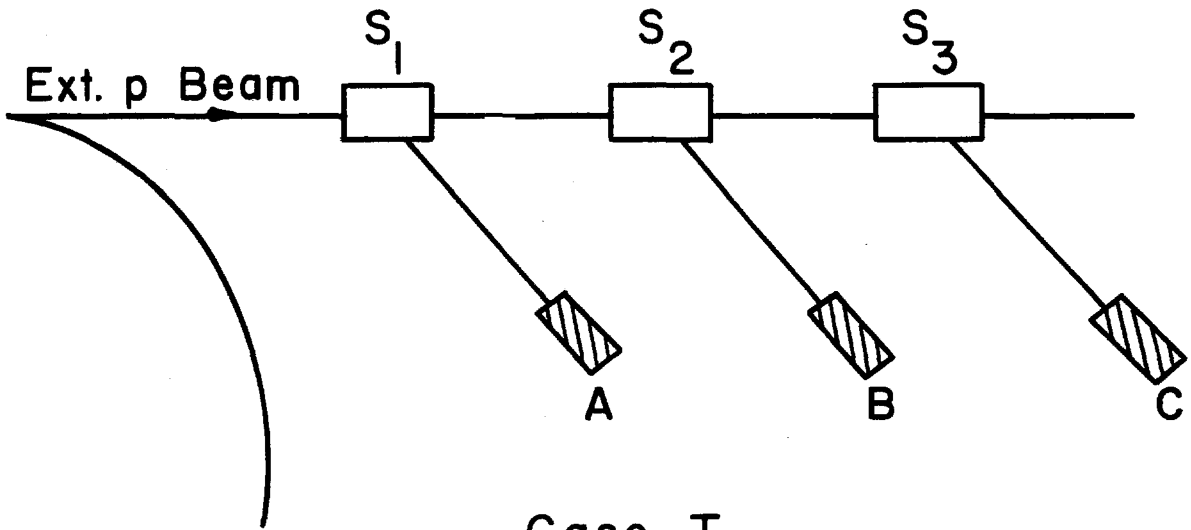
$$W_Q B_{fe} = \frac{B_c}{R_c} \left[\int_0^{R_1} r dr + \int_0^{R_2} r dr + \frac{R_1 W_1 + R_2 W_2}{2} \right]$$

$$\frac{W_Q}{R_c} = \frac{B_c}{2B_{fe}} \left[\left(\frac{R_1}{R_c} \right)^2 + \left(\frac{R_2}{R_c} \right)^2 \right] \left(1 + \frac{W_1}{R_1} \right)$$

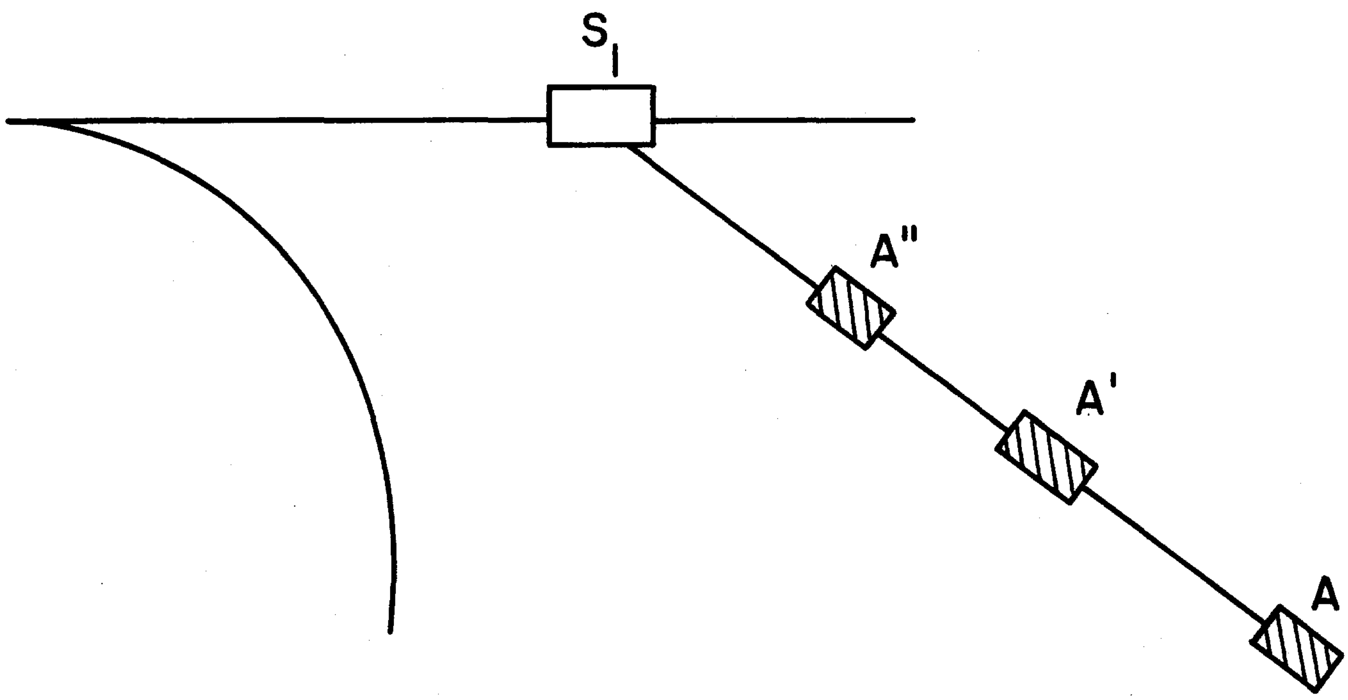
Table IV. Magnet Characteristics.

Beam or Channel	Coil Type	Quantity	Gap Width Wg-in.	Coil Width W-in.	Rad (Qp) Gap (Dip) R_c or G-in.	Length L-in.	Current Density i_{max} kA per in.^{2}	Magnetic Field B_{max} kG	Power (2 p_c) P_{max} kW	Costs (K$) P.S.	Cu	Fe	Total Channel	Power @ p_c p_c kW
EPB-200 GeV/c														
p_m (front magnet)	a	1	24	8	8	132	5.05	20	603	30.2	12.0	23.6	65.8	603
Septum dipole	b	8	4	2	8	132	10.1	10	302	15.1	1.5	0.7	77.0	302
Rear magnet	c	2	12	8	8	132	2.52	10	151	7.5	12.0	4.3	47.6	151
EPB Total									2113				190.4	2113
15 GeV/c (each channel)														
Cor. dipole	d	1	4	2	8	50	20.2	20	910	45.5	1.1	0.9	47.5	0
Quad L_1	e	1		3.3	5	165	6.06	10	566	28.3	7.7	11.1	47.1	142
Quad L_2	f	1		5	5	105	6.06	10	360	18.0	4.9	13.2	36.1	90
Disp. dipole	c	1	12	8	8	132	2.52	10	151	7.5	12.0	4.3	23.8	38
15 GeV/c Total									1987				154.5	270
30 GeV/c (each channel)														
Cor. dipole	d	1	4	2	8	50	12.1	12	330	16.5	1.1	3.0	20.6	0
Quad L_1	e	1		3.3	5	201	6.06	10	690	34.5	9.4	13.5	57.4	172
Quad L_2	f	1		5	5	145	6.06	10	496	24.8	6.8	18.3	49.9	124
Disp. dipole	c	2	12	8	8	132	2.52	10	151	7.5	12.0	4.3	47.6	38
30 GeV/c Total									1818				175.5	372
60 GeV/c (each channel)														
Cor. dipole	d	1	4	2	8	40	8.58	8.5	132	6.6	0.9	0.1	7.6	0
Quad L_1	e	1		3.3	5	246	6.06	10	842	42.1	11.5	16.5	70.1	210
Quad L_2	f	1		5	5	194	6.06	10	666	33.3	9.1	24.5	66.9	166
Disp. dipole	c	4	12	8	8	132	2.52	10	151	7.5	12.0	4.3	95.2	38
60 GeV/c Total									2244				239.8	528
120 GeV/c (each channel)														
Cor. dipole	d	1	4	2	8	40	4.54	4.5	37	1.8	0.9	0.2	2.9	0
Quad L_1	e	1		3.3	5	302	6.06	10	1038	51.9	14.1	20.3	86.3	260
Quad L_2	f	1		5	5	260	6.06	10	890	44.5	12.1	32.8	89.4	222
Disp. dipole	c	8	12	8	8	132	2.52	10	151	7.5	12.0	4.3	190.4	38
120 GeV/c Total									3173				369.0	786

For 8 secondary beam channels, Max power = 20.6 MW, Capital Costs $2.07 M.



Case I



Case II

Fig. 1. Arrangements for independent and cascaded target areas.

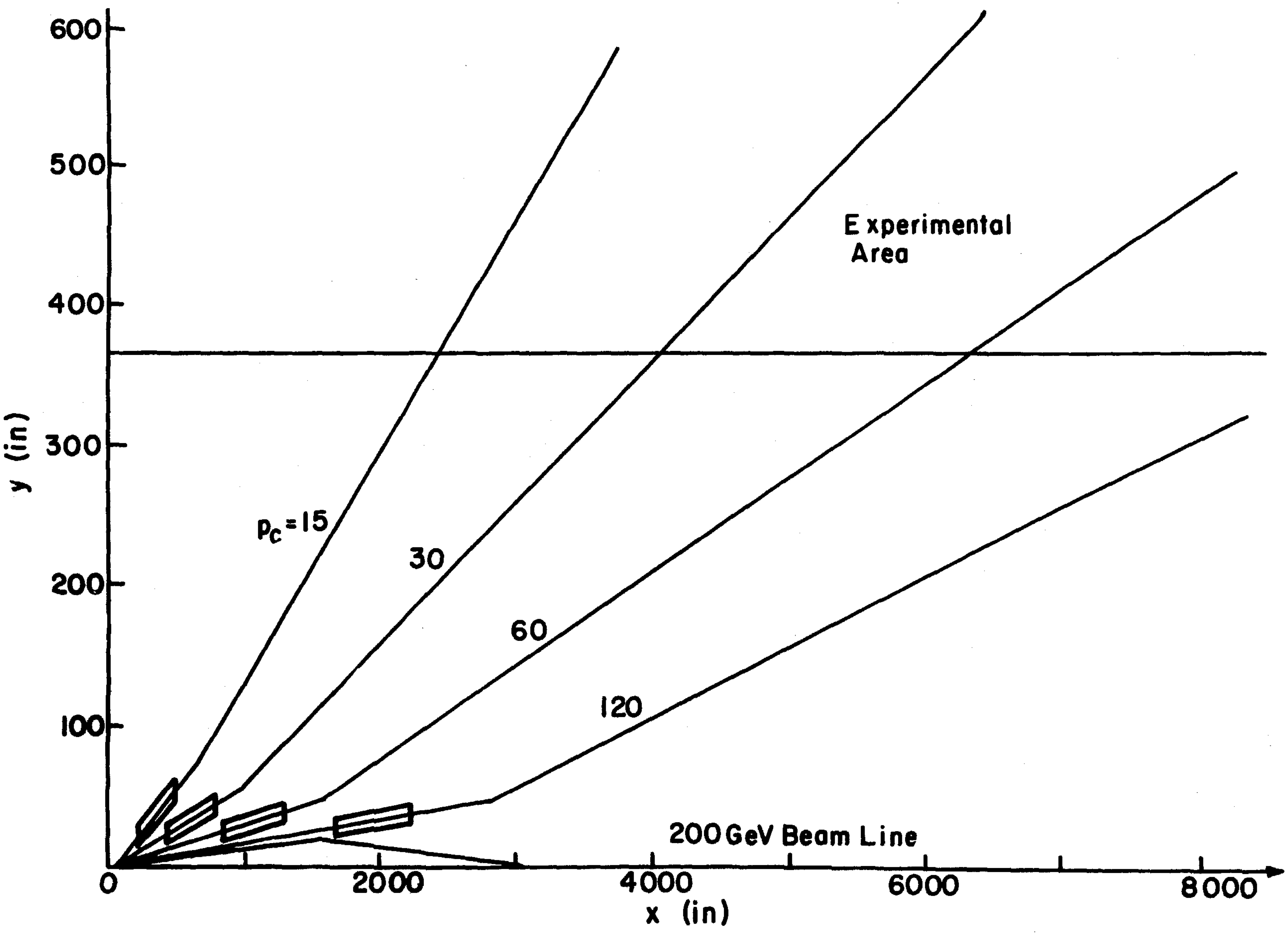


Fig. 2. Beam design for intermediate target station.

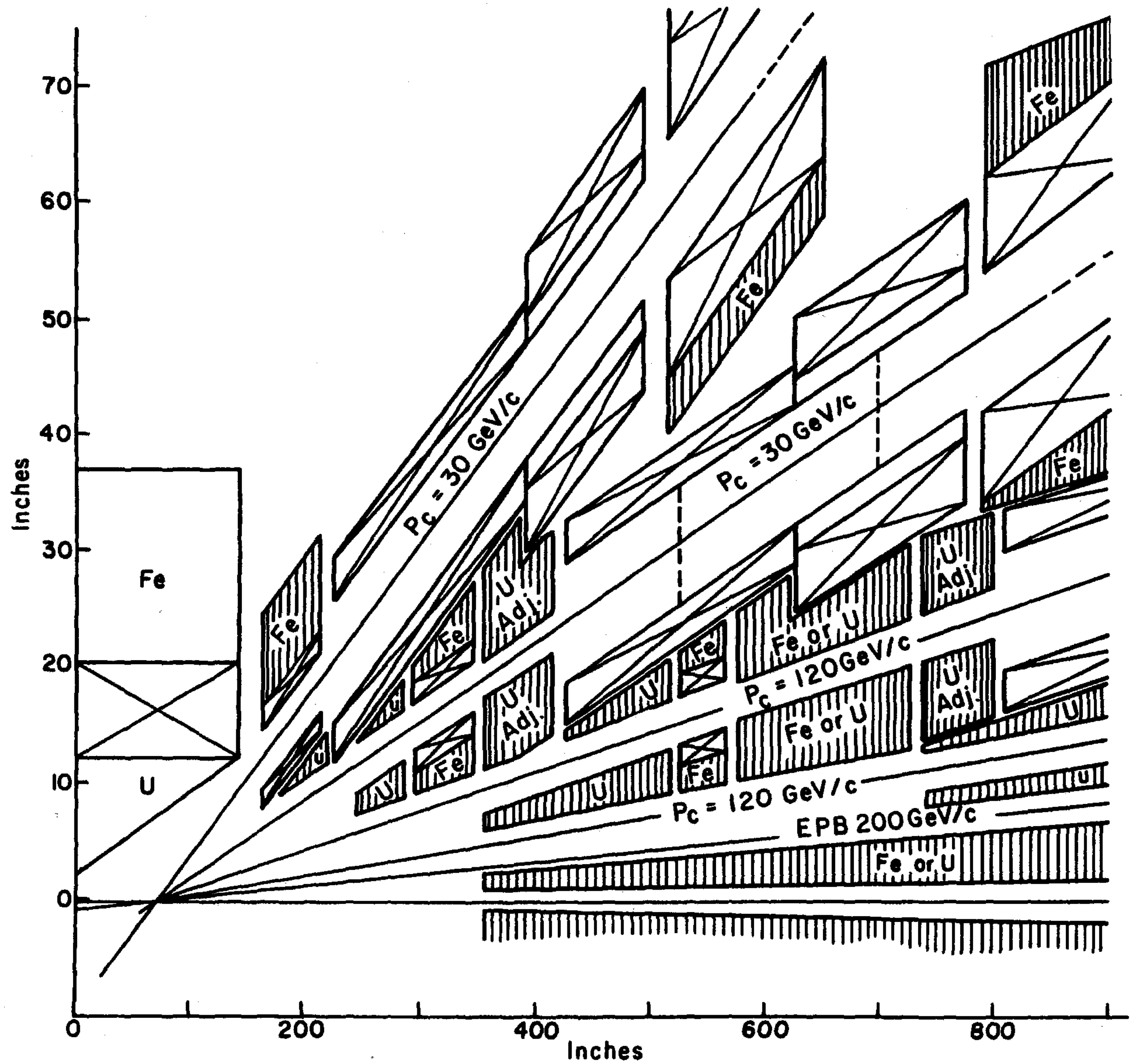


Fig. 3(a). Target region and first part of secondary-beam region.

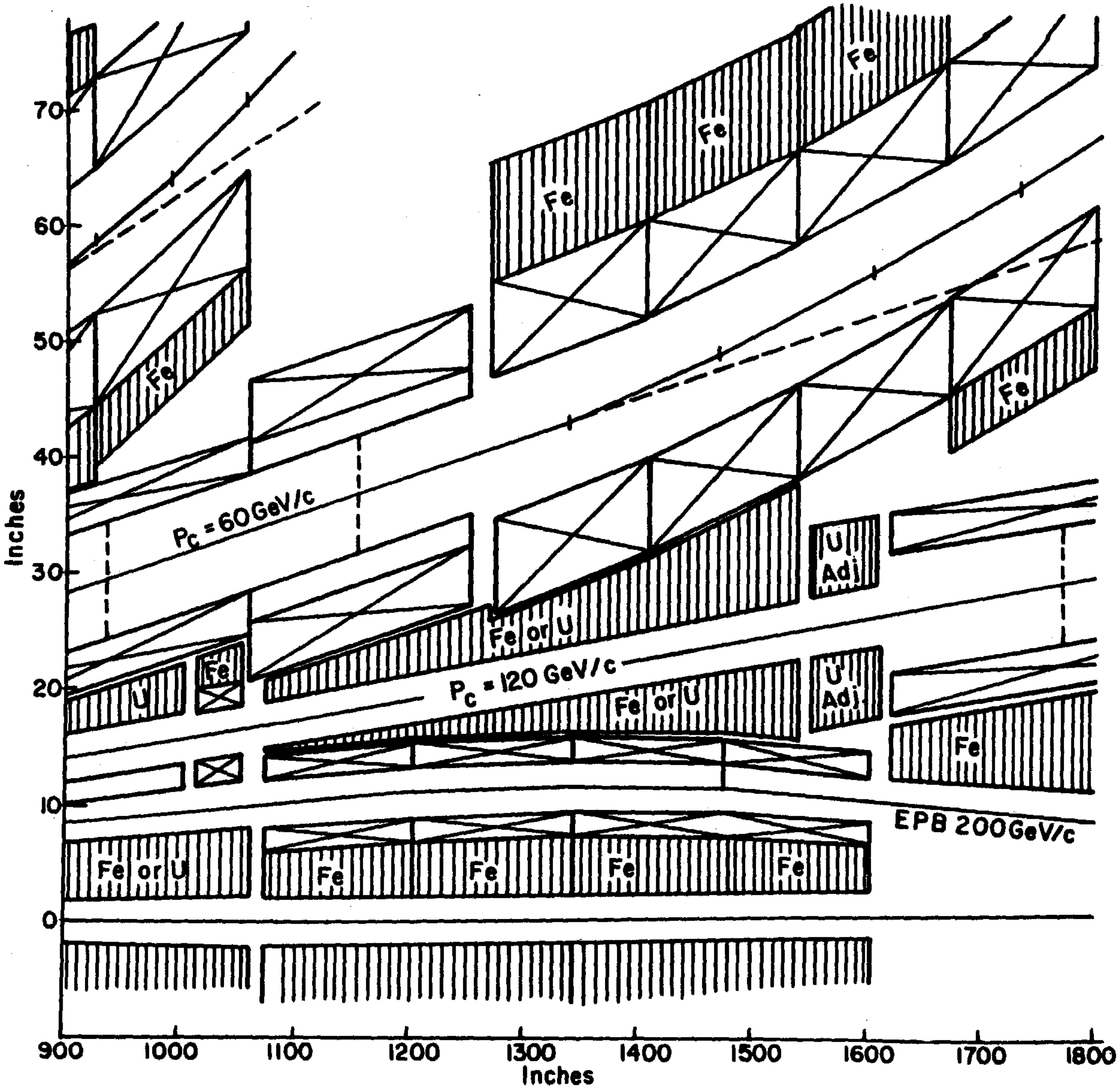


Fig. 3(b). Second part of secondary-beam region.

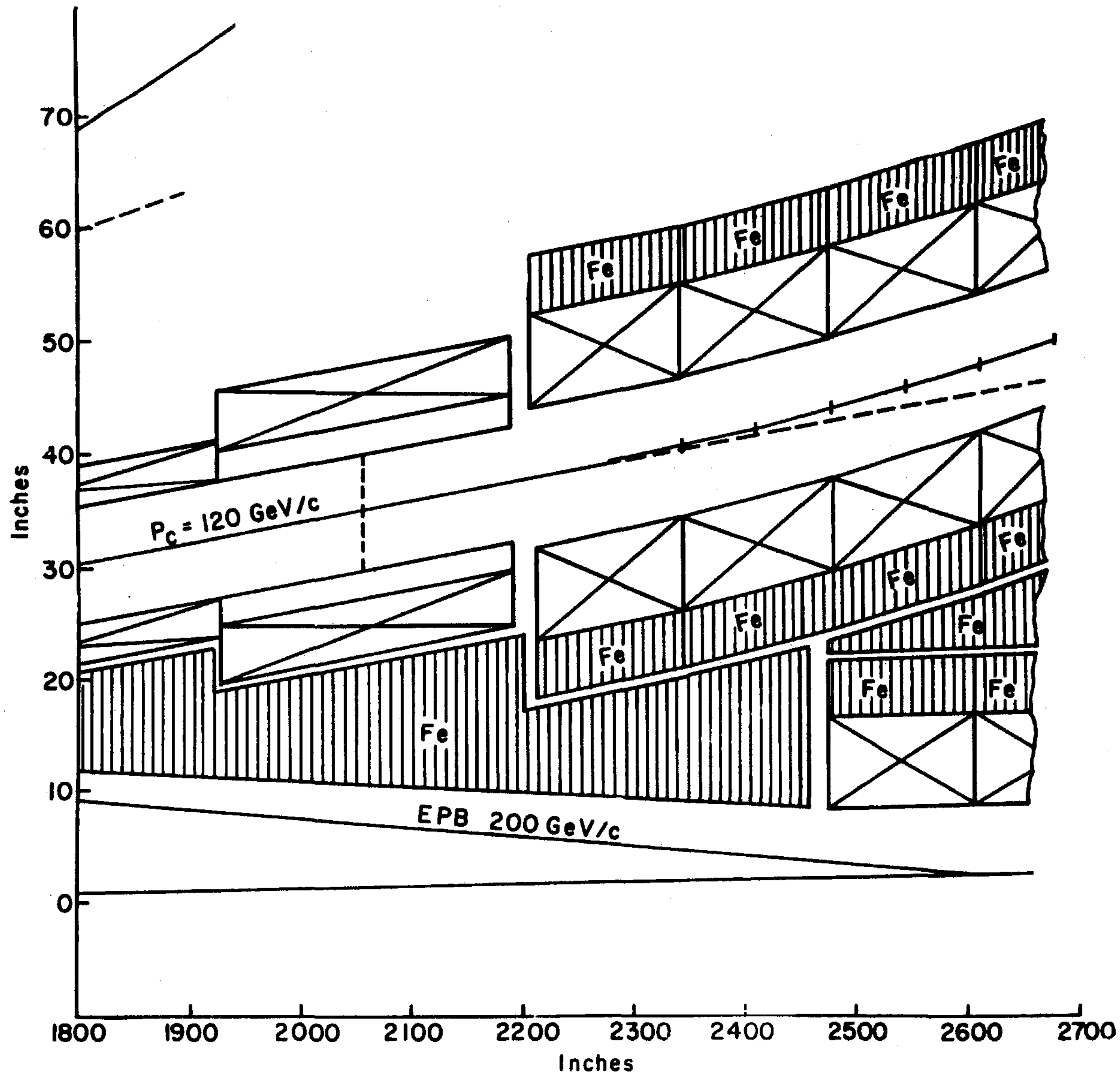


Fig. 3(c). Last part of secondary-beam region.

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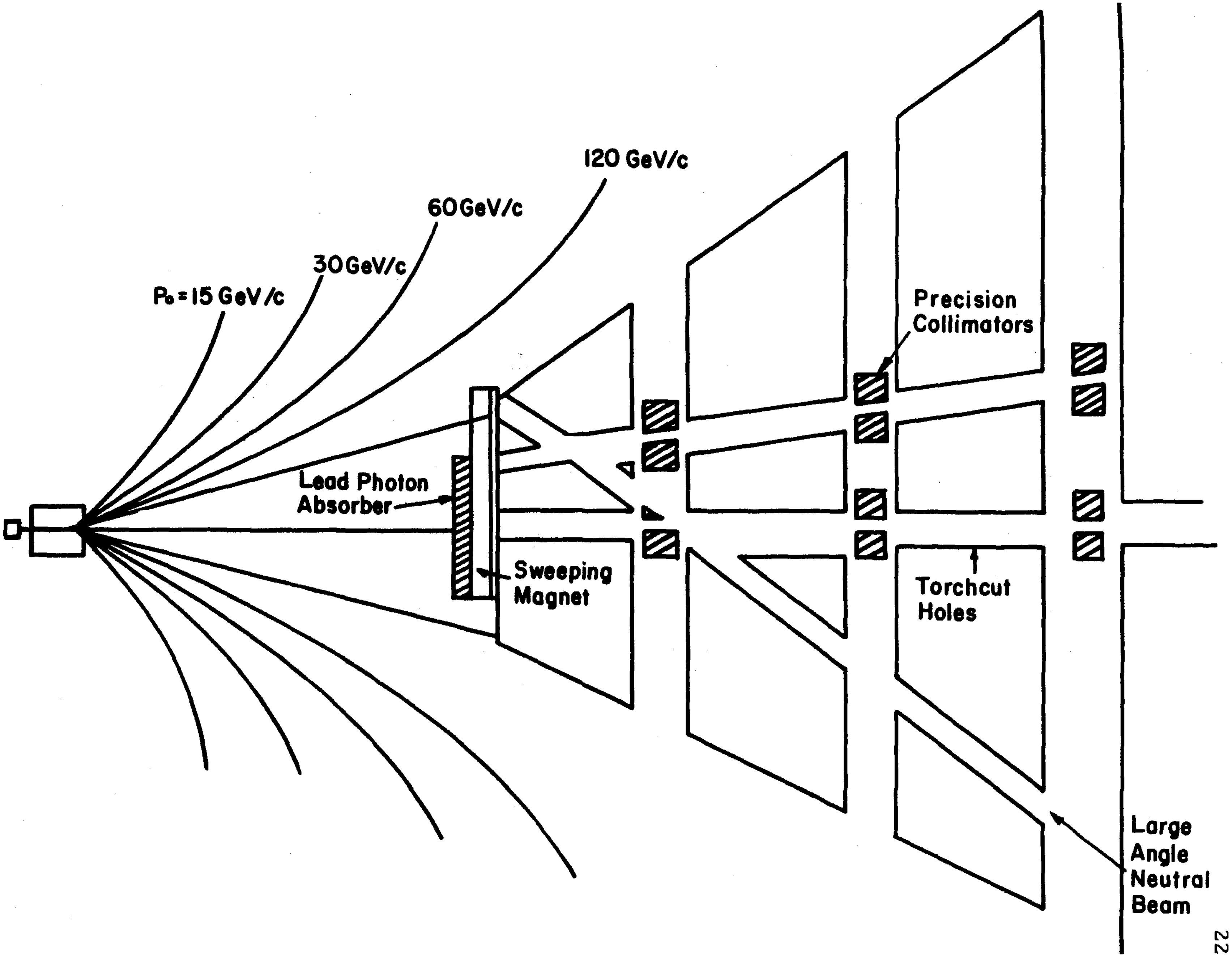
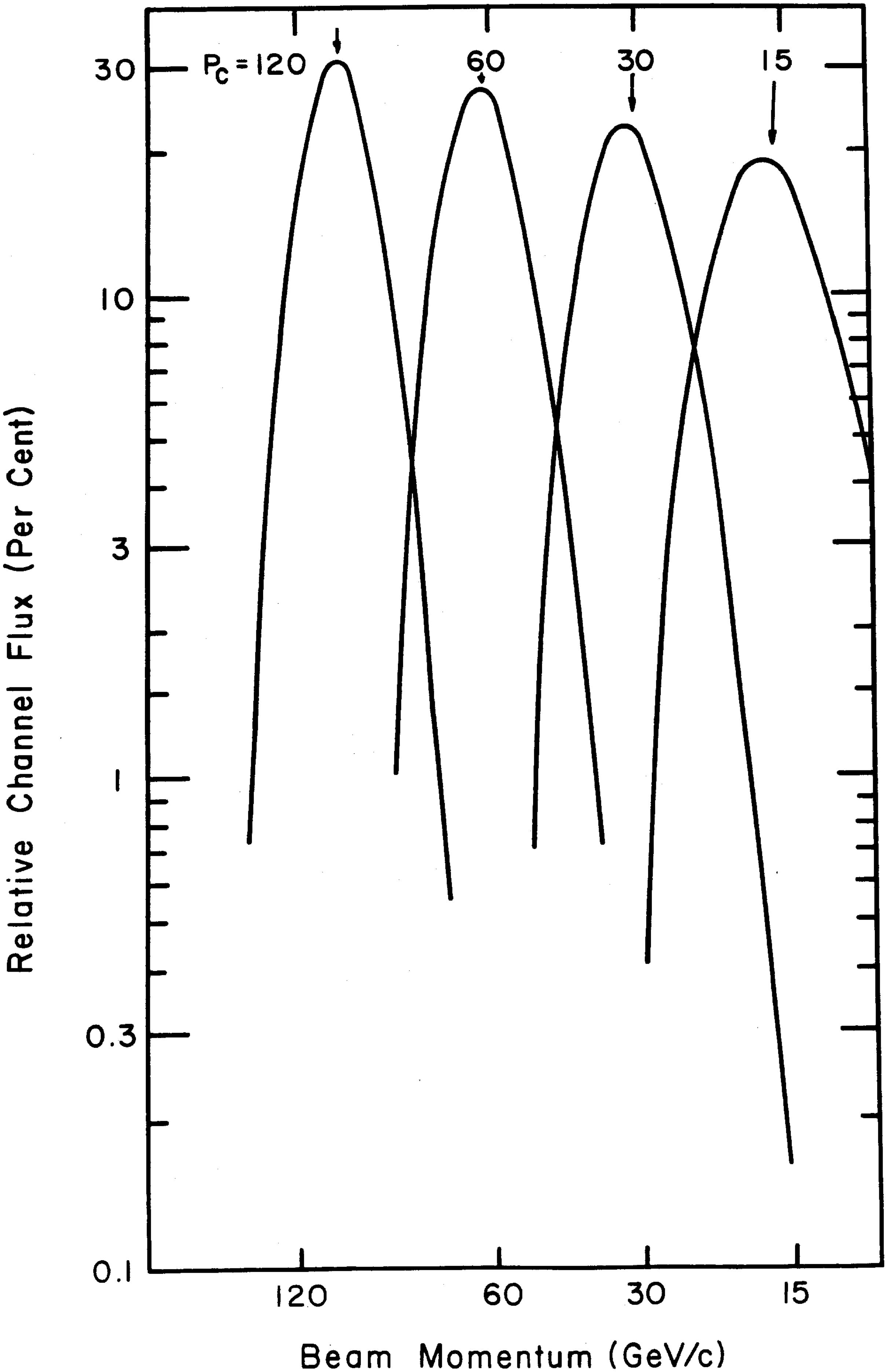


Fig. 4. Design of end station with dispersing magnet at target.


Relative Channel Flux (Per Cent)
30
10
3
1
0.3
0.1
P_c = 120
60
30
15
120
60
30
15
Beam Momentum (GeV/c)

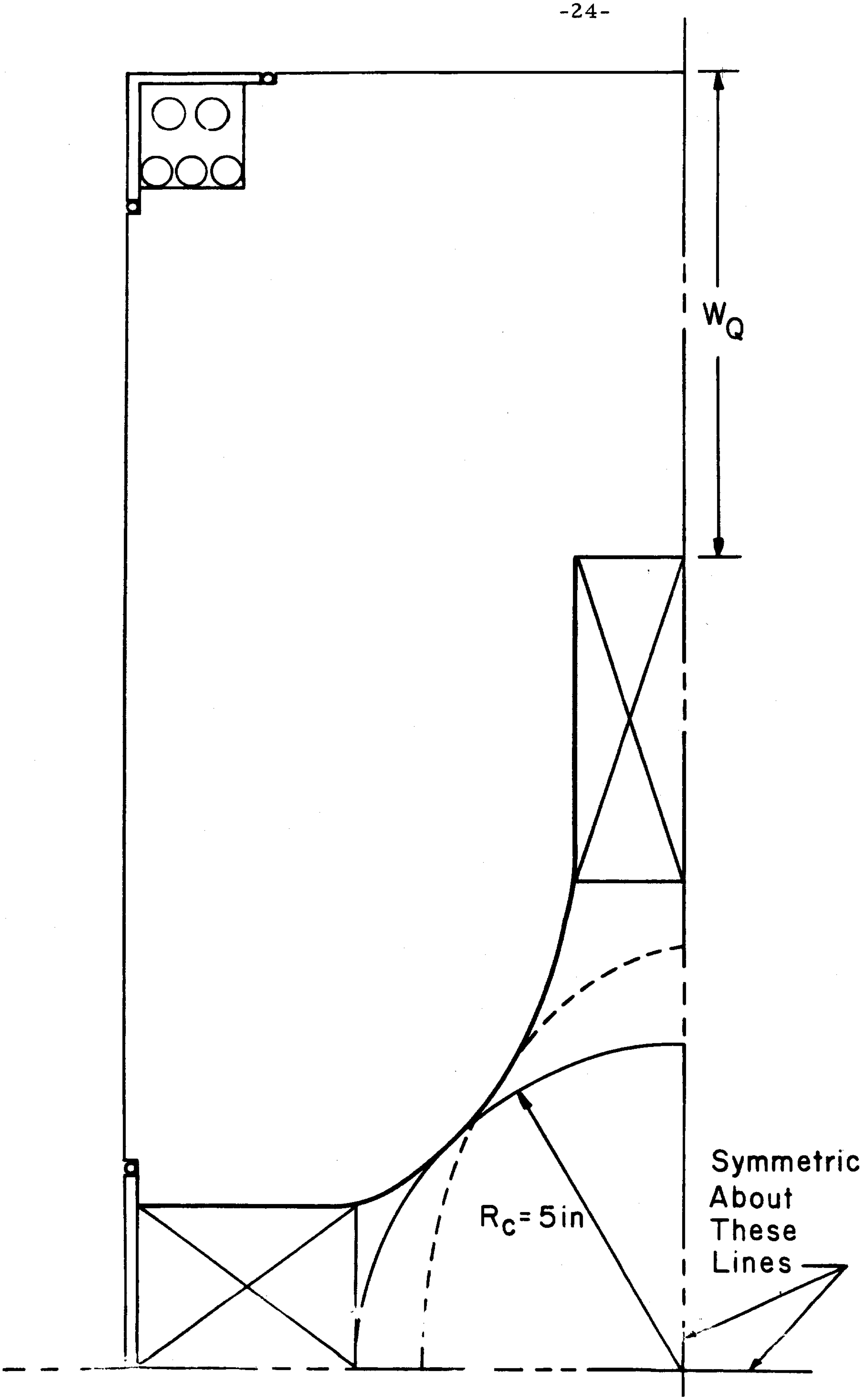
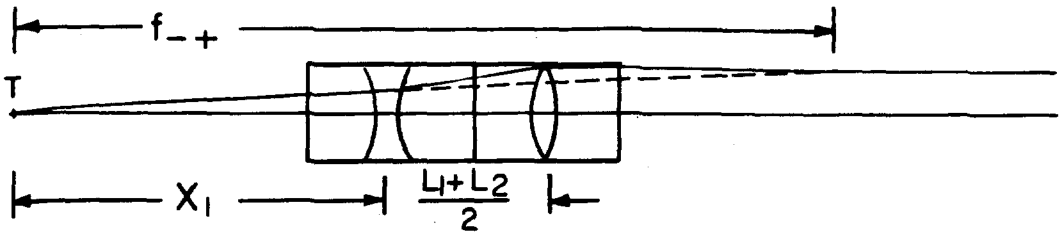
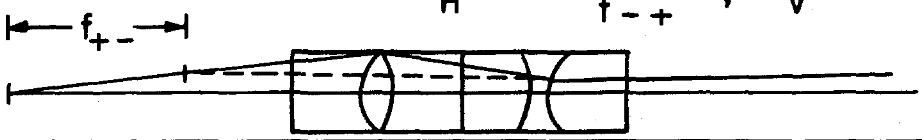


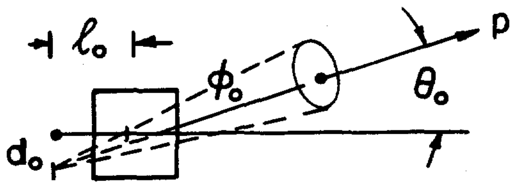
Fig. 6. Design of "narrow" quadrupole for use in closely spaced beams.



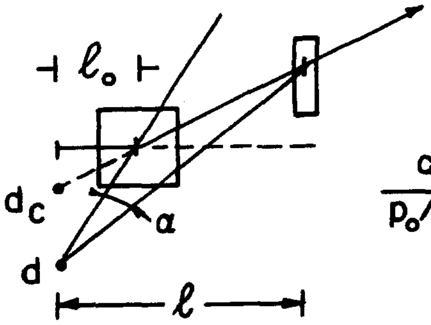
$$\bar{f} = \frac{B\rho}{L\frac{dB}{dR}} \quad ; \quad f^{+} = \bar{f} + \frac{L}{6} \quad ; \quad f^{-} = \bar{f} - \frac{L}{6}$$

$$M_H = \frac{X_5 - f_{-+}}{f_{-+}} \; ; \; M_V = \frac{X_5 - f_{+-}}{f_{+-}}$$





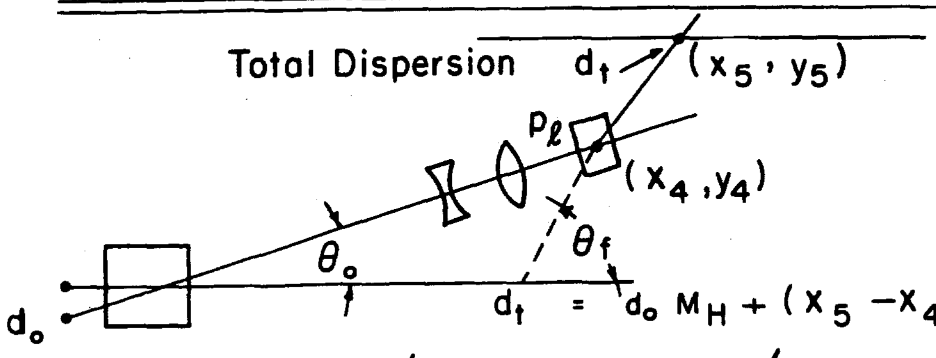
$$\theta_o = \frac{p_m}{p} \; ; \; \phi_o \doteq \frac{0.350}{p} \; ; \; d_o = \ell_o \theta_o$$



$$\alpha = \frac{p_m}{p_c}\left(1 - \frac{\ell_o}{\ell}\right)\left(1 - \frac{p_c}{p}\right)$$

$$\frac{\alpha}{p_o/p} \equiv D_1 = \frac{p_m}{p_o}\left(1 - \frac{\ell_o}{\ell}\right)(R_1 - 1)$$

where $R_1 \equiv \dfrac{p}{p_c}$; Flux $= \bar{f}\,(R_1, D_1)$



$$d_t = d_o M_H + (x_5 - x_4)\frac{p_\ell}{p_c}$$

$$x_5 - x_4 = (y_5 - y_4)/\theta_f = (y_5 - y_4)\,p_c/(p_m + p_\ell)$$

$$d_t = d_o M_H + (y_5 - y_4)/\left[1 + p_m/p_\ell\right]$$

Fig. 7. Formulas for beam optics.