TM-223
2254

PRELIMINARY DESIGNS AND DESIGN CONSIDERATIONS FOR CHARGED, UNSEPARATED BEAMS AT NAL

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I. INTRODUCTION

Designs for the secondary beams at the several hundred BeV accelerators have been considered almost from the inception of accelerator planning. Initially, the designs were guided by the possibility of obtaining very high beam intensities with quite modest magnet apertures. Later designs have illuminated several other important considerations. High energy experiments frequently require better resolution than beams in operation at existing accelerators. In turn, the requirement for resolution entails more bending magnets and attention to aberrations in the beam optics, both of which increase the expense. This historical pattern can be observed in Table I-1 which summarizes some of the beam designs proposed over the years. Longo's beam,[1] proposed in 1964, has a resolution of ±0.1% and is 970 feet long.

Petrucci's beam[2] (1967) was designed on the basis of minimizing the number of beam elements. However, the resolution is only ±0.2%. The MacLachlan-Reeder beam (1969)[3] is the first serious attempt to achieve a resolution of ±0.02%. As a consequence, it requires at least 50% more magnet length than the earlier designs.

This report discusses a number of beams which fit into a model of Area 2 (the initial experimental area at NAL) that has been proposed by the NAL 1969 Summer Study.[4] This model balances the beam needs against the requirements for a coherent area plan. Table II-1 summarizes the beams proposed in SS-37 along with some additional beams added for greater flexibility. The beams given in this report differ in a number of details.

Figure I-1 shows a physical plan of the beam lines as they might appear in Area 2.

The specific beam designs should not be regarded as final. Instead, they should be taken as an indication of the level of the needs and requirements for the beams that are ultimately constructed.

The planners for the first experimental area anticipate the need for both a high momentum (200 BeV/c, frequently designated as the 2.5 mrad beam) and an intermediate momentum (120 BeV/c, the so-called 7.5 mrad beam) high resolution beam. It is felt that in both cases arrangements should be made for alternate experimental areas at the ends of the beams.

TABLE I-1

HISTORICAL TABLE OF BEAMS

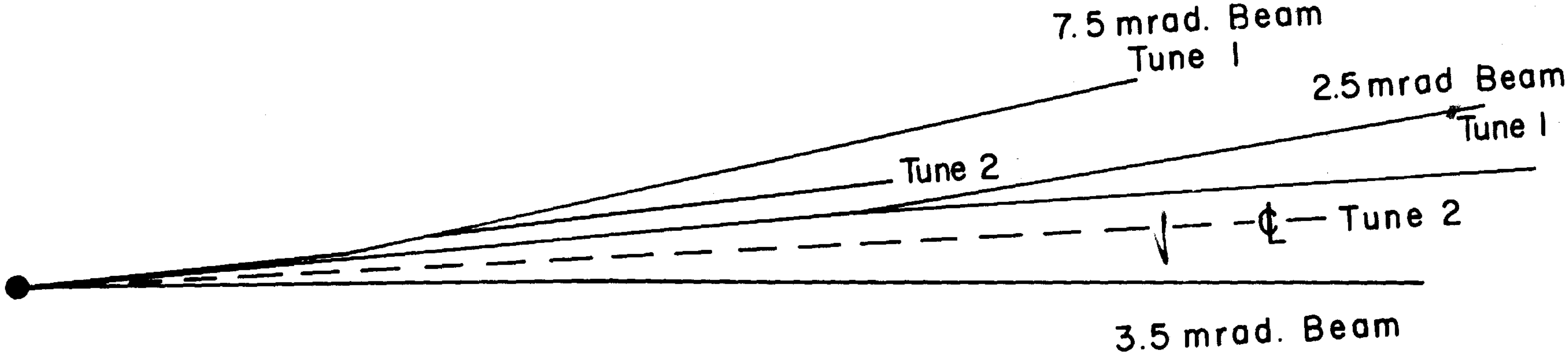
	Longo	Petrucci	MacLachlan	Reeder-MacLachlan
Reference	UCID-10124 (64)	ECFA II (67)	RFDC NAL-69	NAL SS-41 (69)
Focusing	DF	DF	DF	DF
Momentum (GeV/c)	150	300	200	200
Solid Angle (μ ster.)	3	10	0.81	1.65
Resol. (%)		±0.2	±0.02	±0.017
Max Momentum Acceptance (%)	±1	±3.0	±1	±1
bend (mrad)	71	36	98.4	99
L bend (m)	27.4	20	77	36.6
L quad (m)	9.7	28	17	33.5
B_{max} (K_g)	20	18	9.0	20.0
G_{max} (K_g/cn)	4.7	1.0	1.7	2.4
h bend (cm)	10	14	5	10
h quad (cm) (diameter)	10	20	5	10
L quad 1(m) (meters)(ft)	15 48	27 89	58 190	58 190
L total (meters)(ft)	241 790	180 590	324 1060	413 1350
X_f (mm)	±3.3	±2.5	±1	±0.5
Y_f (mm)	±0.9	±2.5	±1.4	±0.5
X_i (mm)	±1.3	14 FWHM		
Y_i (mm)	±1.3	8 FWHM		
Notes	1	2	3	3

Historical Table Continued

1. Longo: Double focus, momentum recombining beam. Bends not in divergence free region. Long sections provided for Cerenkov counters. Field lens at momentum slit. First element horizontally defocusing.

2. Petrucci: Most striking feature is lack of a vertical first focus or a field lens. Beam was designed to minimize costs. (Cost numbers are available). Is double focusing with momentum recombined. First element horizontally defocusing.

3. MacLachlan: Designed with main ring bending magnets to test effect of second order aberrations in a known condition. Double focusing, momentum recombining straight sections for magnets. No field lens. First element is horizontally defocusing. Most outstanding feature is extremely good resolution.



SS-37 Beams-Area II

Fig. I-1

Scale 1" = 200'
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TABLE I-2

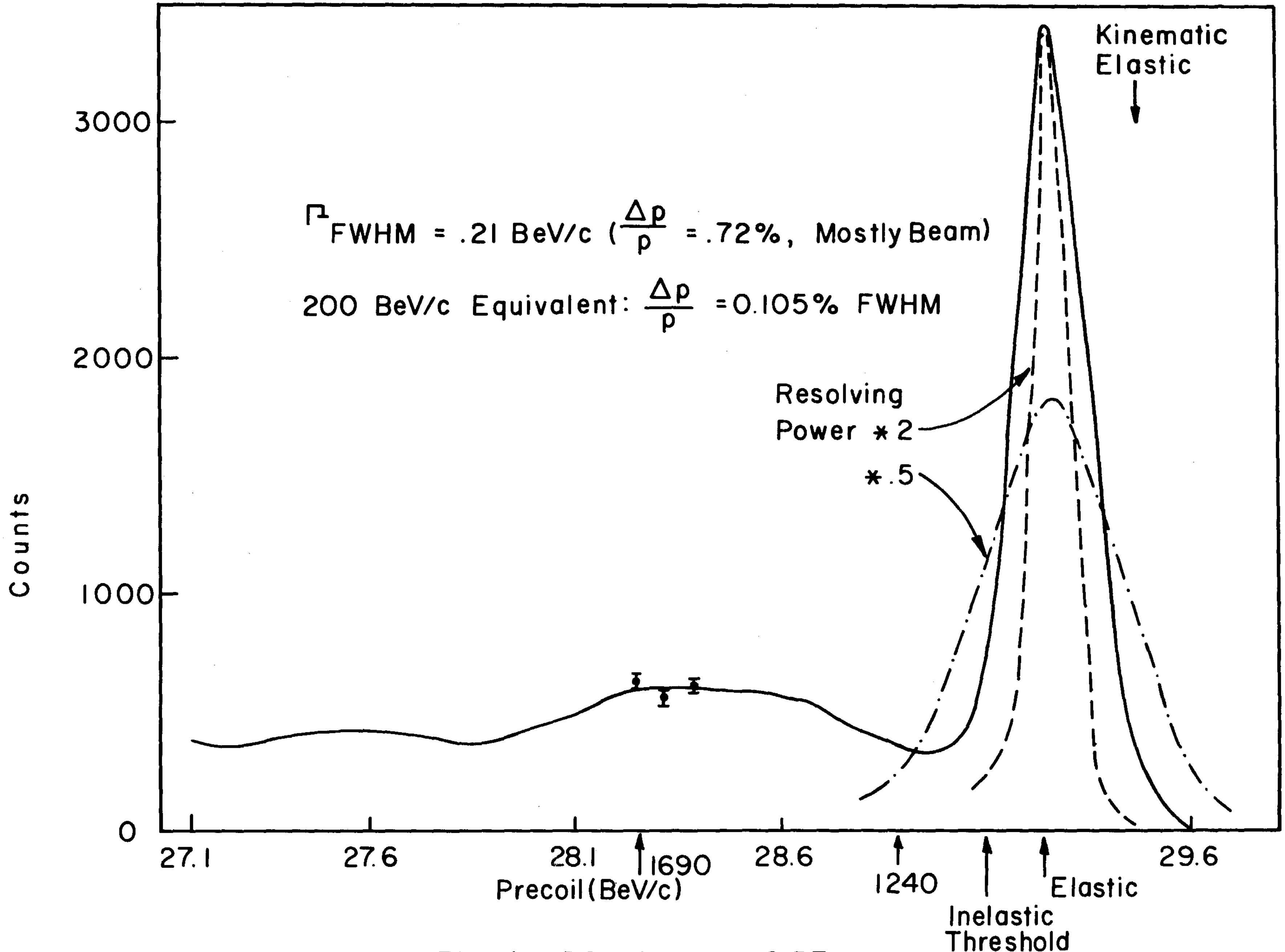
Tabulation of the Area 2 Beams Design Report

Angle (Mr)	Comments	Maximum Momentum (GeV/c)	Resolution %	Acceptance μ ster.	Intensity (3×10^{12} p) p	π	Length (ft.)	List quad (ft.)
2.5	High Resolution Y	200	± 0.017	1.65	2×10^{10}	2×10^{6}	1620	190
7.5	High Resolution Y	120	± 0.05	0.8	10^{6}	10^{6}	910	144
15.0		50	--	--	--	--	650	98
- 3.5	High Intensity Serial, 80 GeV para.	200	10	3.8	10^{10}	7×10^{8}	720	121
-15.0	RF Conv. 8 GHz	20-40K 20-47$\bar{p}$	± 0.1	5.0	10^{5} K^{+} 7×10^{4} K^{-} 4×10^{4} $\bar{p}$	1.5×10^{6}	970	66

In addition, a high intensity, high momentum (200 BeV/c, 3.5 mrad) beam for production of tertiary beams and diffraction scattered proton beams is required.

The requirements for high resolution can be understood by considering Figure I-2. In the figure, data is plotted from a 1965 BNL-CMU run[5] with a single arm wire plane spectrometer. The data was taken to measure the behavior of inelastic resonances produced in p-p interactions. The particular run is at 30 BeV/c and an angle of 25 mrad. The resolution is ±0.35% (half width), mostly due to the incident beam. A resolution of ±0.05% is required to obtain the same result at 200 BeV/c. For reference elastic peaks with half and twice the width have been included. The difference between the particle recoil momentum from a proton and a resonance is $\Delta p \cong \frac{M_r^2 - M_p^2}{2M_p}$. For the 1.238 BeV isobar this is approximately 350 MeV/c. A resolution of ±0.05% is barely sufficient to resolve the 1.238 BeV resonance. These requirements can be relaxed somewhat by detecting the recoil particles although neutrals are a distinct problem. Another alternative is to use hodoscopes placed in the incident beam. This, however, tends to limit the rates to between 10^7 and 10^8 particles per pulse.

Intense beams are clearly needed, particularly in the production of tertiary beams such as K^o beams. Present experimental equipment is fully capable of handling any



pp Elastic, -30 BeV/c, -t = -0.57

Fig. I-2

TM-223
2254

intensity level expected in these tertiary beams.

In addition to intensity and resolution, it is imperative to provide flexible beams at the lowest possible cost. At present, all signs indicate that most beam systems will be dictated by cost considerations rather than natural physics parameters such as the width of the diffraction scattering pattern for the production process.

In the beam design the production target, or rather the primary beam spot size at the production target, was assumed to be 1 mm in diameter. The primary beam angular spread was taken to be 1 mrad full width. The high resolution beam was given the angular location closest to the beam line (2.5 mrad) while the high intensity beam was put on the opposite side at 3.5 mrad. The remaining beams were positioned based on the angular space required for the quadrupoles.

The beam designs given here are generally based on detailed first and second order solutions (including the effects of dipole fringe fields and finite entrance angles), using the program TRANSPORT designed by K. Brown at SLAC.[6]

The remainder of the report discusses the individual beams and some considerations that apply to all of them. Section II discusses the economics of the beam designs. Section III considers the high momentum, high resolution beam; Section IV discusses the medium momentum, high resolution beam and Section V gives the details of the high intensity beam. Quadrupole aberrations are discussed in Section VI. Section VII considers beam instrumentation and tuning devices. Section VIII summarizes the conclusions.

II. MAGNET AND BEAM ECONOMICS

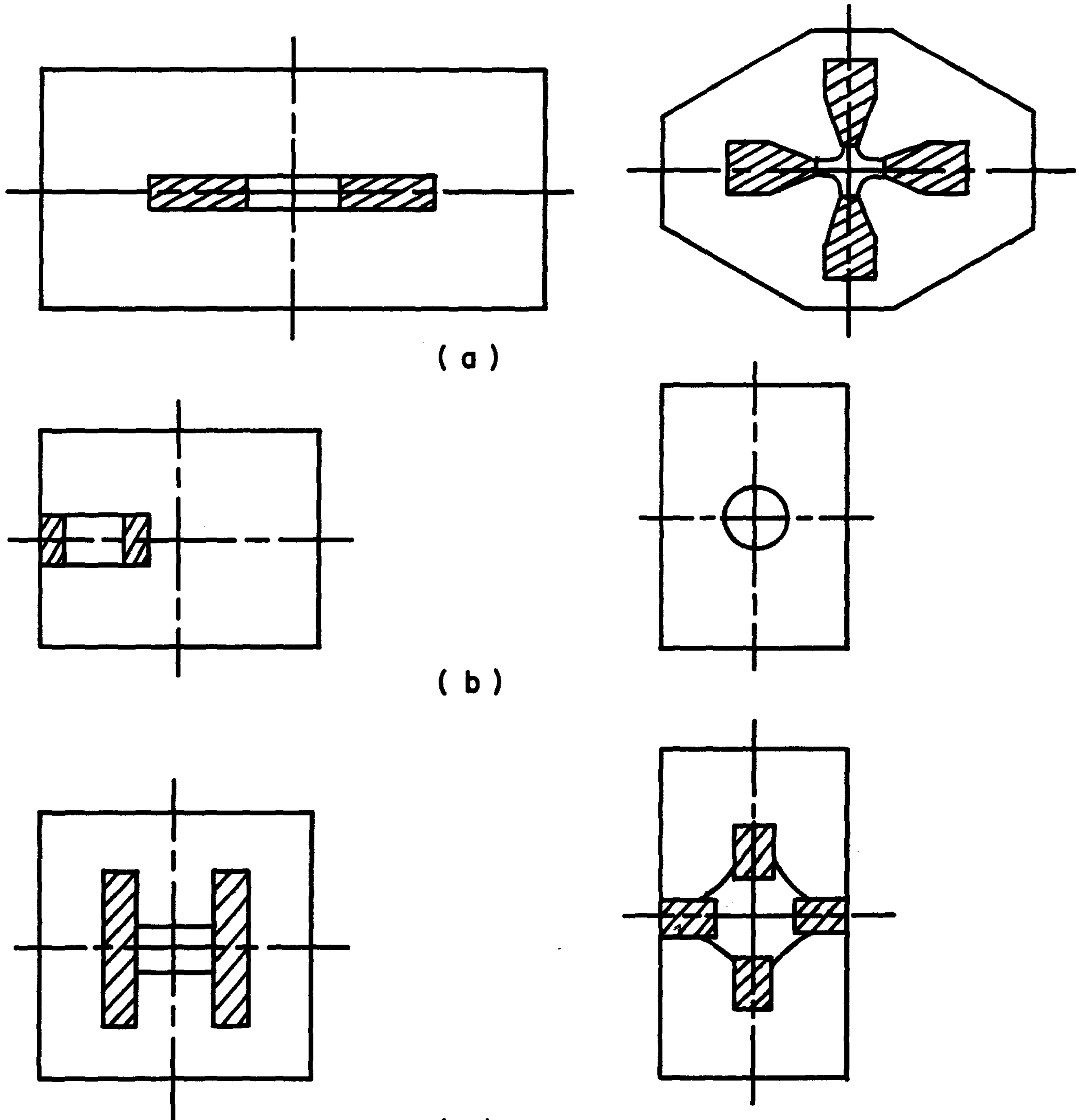
Introduction: This section is concerned with beam economics. It represents an investigation of the effect on costs or changes in beams from some starting point. This starting point is essentially the set of beams described in the remainder of this report with suitable magnets.

Cost figures for magnets and associated equipment have their origins in studies made for NAL by William Brobeck & Associates on the subject of copper coil beam transport elements. It has been convenient to lump together the cost of magnet, stand, and vacuum chamber under the term "magnet cost." The cost of power supply, wherever mentioned in this section, presumes one power supply per magnet and includes water system cost.[7] All costs are presented per magnet; fixed costs such as tooling are divided up among a reasonable number of magnets. No EDIA is included (engineering, design, inspection, administration . . . .).

Individual magnets are discussed in the next section, while beams are discussed in the last section.

Choice of Magnets: The magnets assumed for the initial mockup of costs in Area 2[8] (January 1969). They are shown in the cross section in Figure II-1a.

The quadrupole is derived from one described in the NAL Intersecting Storage Ring Design Study[9] and was scaled down from that to a 2-inch aperture. The cost of the magnet



Cross Section - Magnets
(Scale 1/10" = 1")
Fig II - 1

is $17,200 and at 15 kG excitation the power consumption is 52.3 kW. The length is 72 inches. The bending magnet costs $17,700, is 120 inches long, and at 20 kG consumes 184 kW. Neither of these costs includes the cost of power supply.

The magnets recommended by the 1969 Summer Study[4] are also shown in Figure II-1b. They were conceived as superferric; that is, iron magnets with superconducting coils. With copper coils the septum dipole coil cross section would have to be larger. Useful aperture in the dipole was to be 4" x 3"; actual aperture would be 5" x 3", when allowance is made for a sagitta[10] of 1".

In order to investigate the behavior of costs with change in aperture two programs "QUAD" and "THM1" were used. "QUAD" is a program written to evaluate, in a detailed manner, costs for a quadrupole with copper coils. "THM1" is a program written to evaluate costs for a H-frame design bending magnet. Both were obtained from William Brobeck & Associates. Cross sections for this quadrupole and bending magnet are also shown in Figure II-1. Lengths were taken as 120 inches. The quadrupole coil window is rectangular; a consequence is that the coil cross section is smaller than otherwise achievable and the magnet is a high-power type.

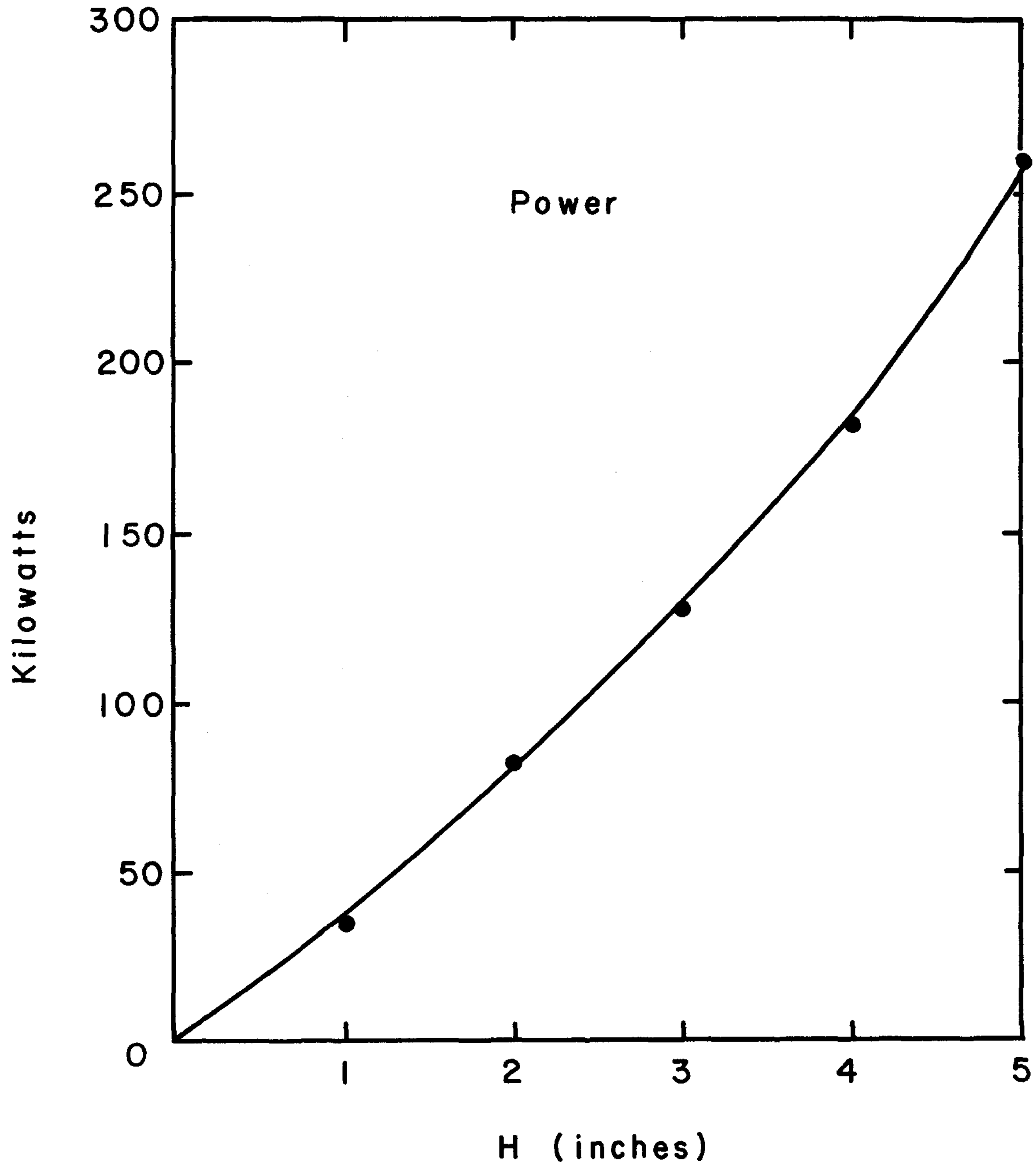
The relevant parameter for the three sets of magnets shown in Fig. II-la, b, c,

	(a) Area 2 Cost Study		(b) Summer Study		(c) Aperture vs Cost Study†	
	Quad	Bend	Quad	Bend	Quad	Bend
Maxfield (kg)	15	20	16	20	15	20
Gap height	--	2	--	3	--	3
Gap width	--	6	--	4	--	5
Aperture diameter	2	-	4	-	4	-
Coil height		2		3		10.8
Coil width		5.6		1.5		3
Length	72	120	120	120	120	120
Outside width	24	32.2	12	18	14.3	17.4
Outside height		15.6			26.2	17.2

† Figures shown correspond to only one aperture.

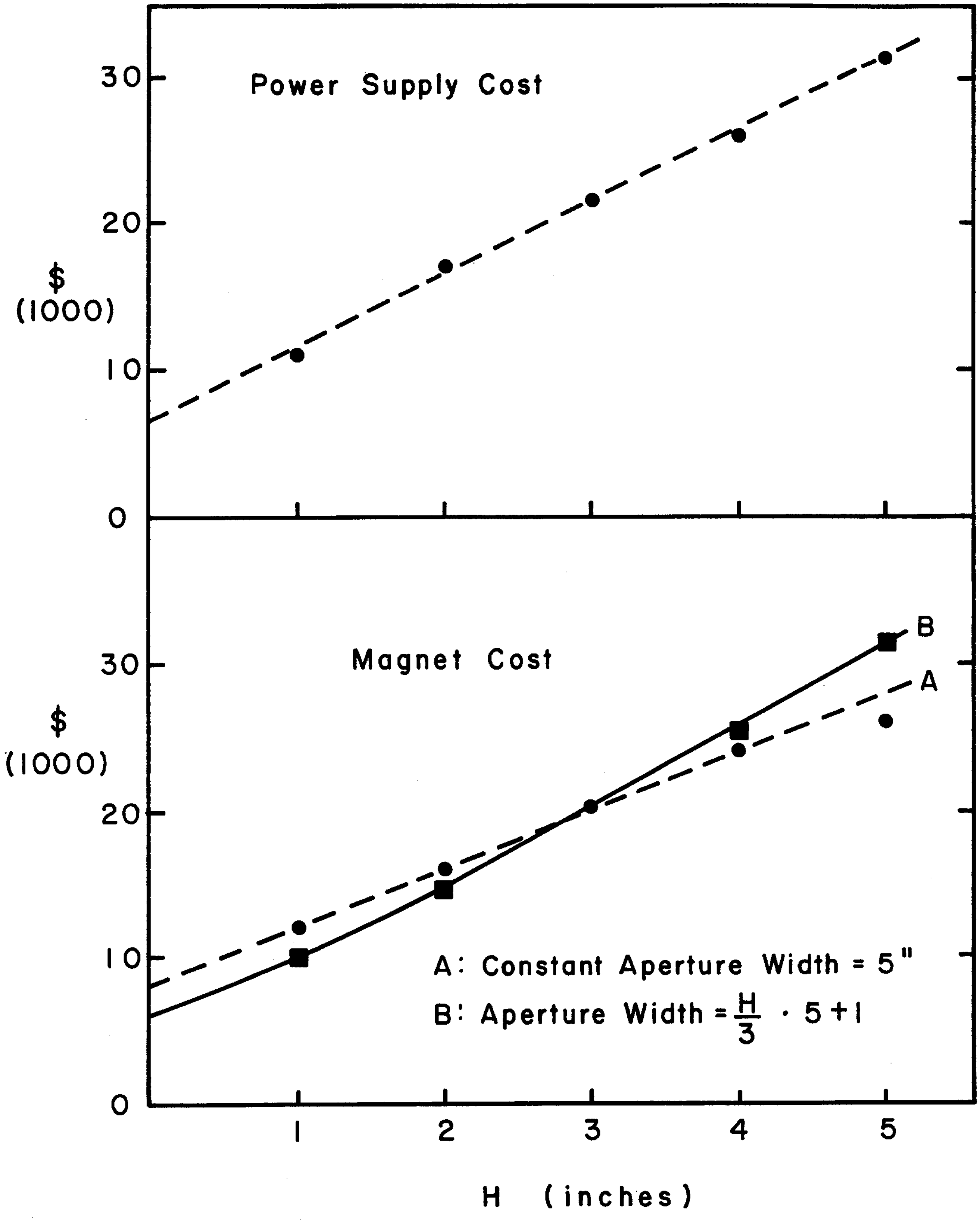
(All dimensions are in inches).

The results of varying the aperture and using the two programs, "QUAD" and "THM1" are shown in Figures II-2 through II-7, as magnet cost, power supply cost, and power consumption per magnet. The magnet cost in Figure II-3 for the bending magnet is approximately linear with the vertical aperture. It shows little dependence however, on the horizontal aperture as can be seen by comparing the curve of constant 5" horizontal aperture with the curve where the aperture width is scaled the same as the vertical aperture (except for the addition of 1" after scaling to allow for sagitta). The power supply cost and the power consumption



Power vs Gap Height H
For H - Frame Bending Magnet

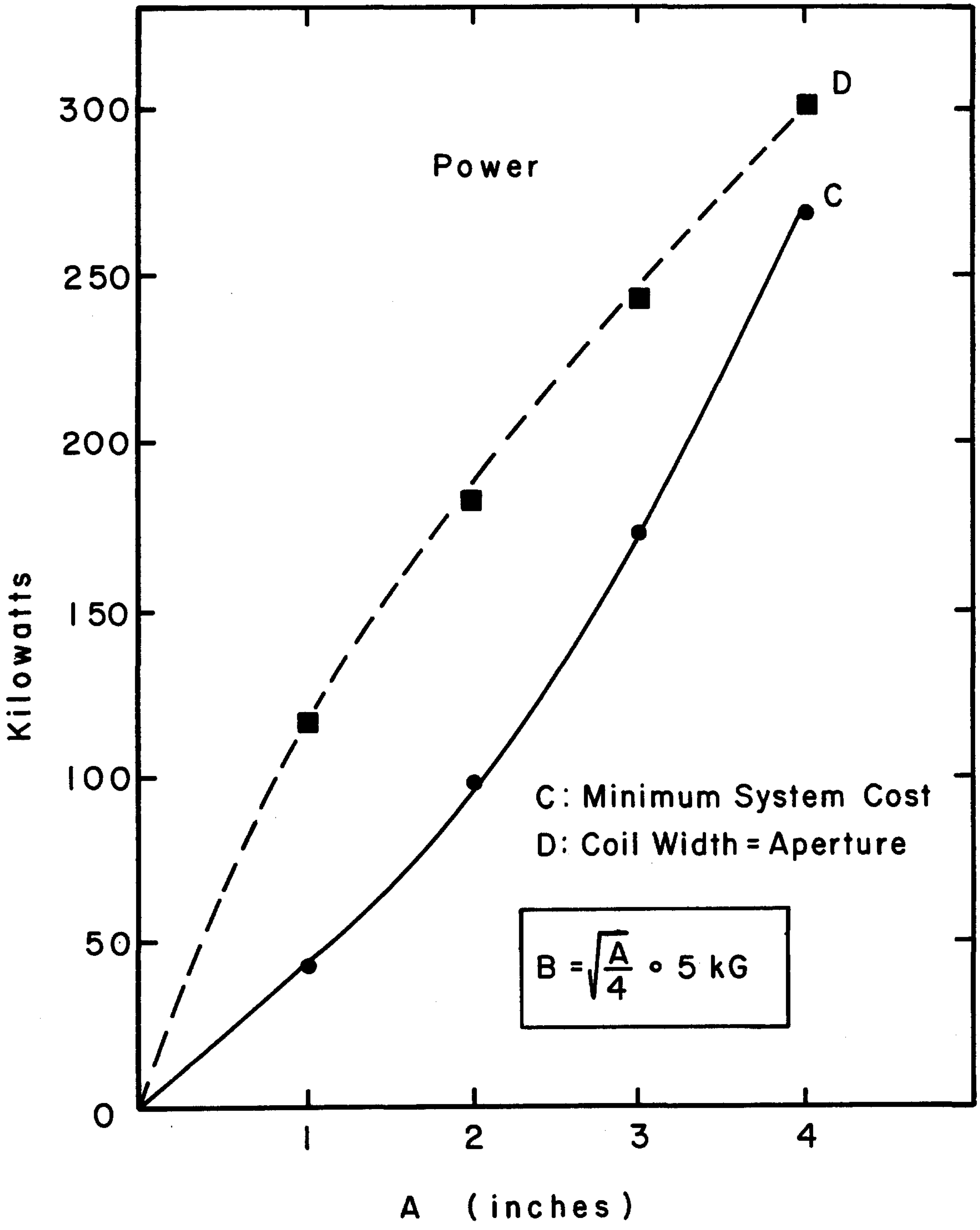
Fig. II-2



Cost vs Gap Height H

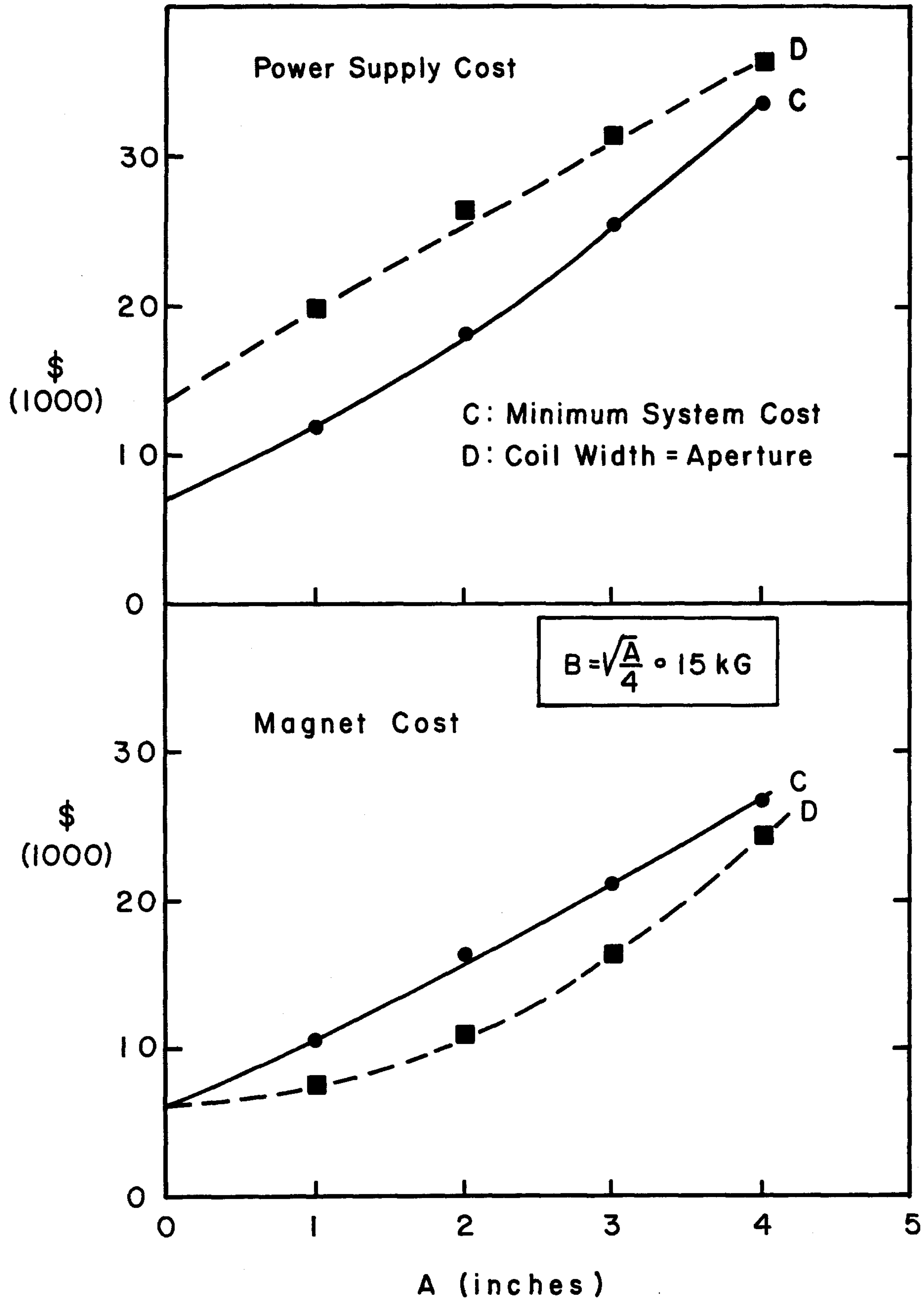
For H - Frame Bending Magnet

Fig. II - 3



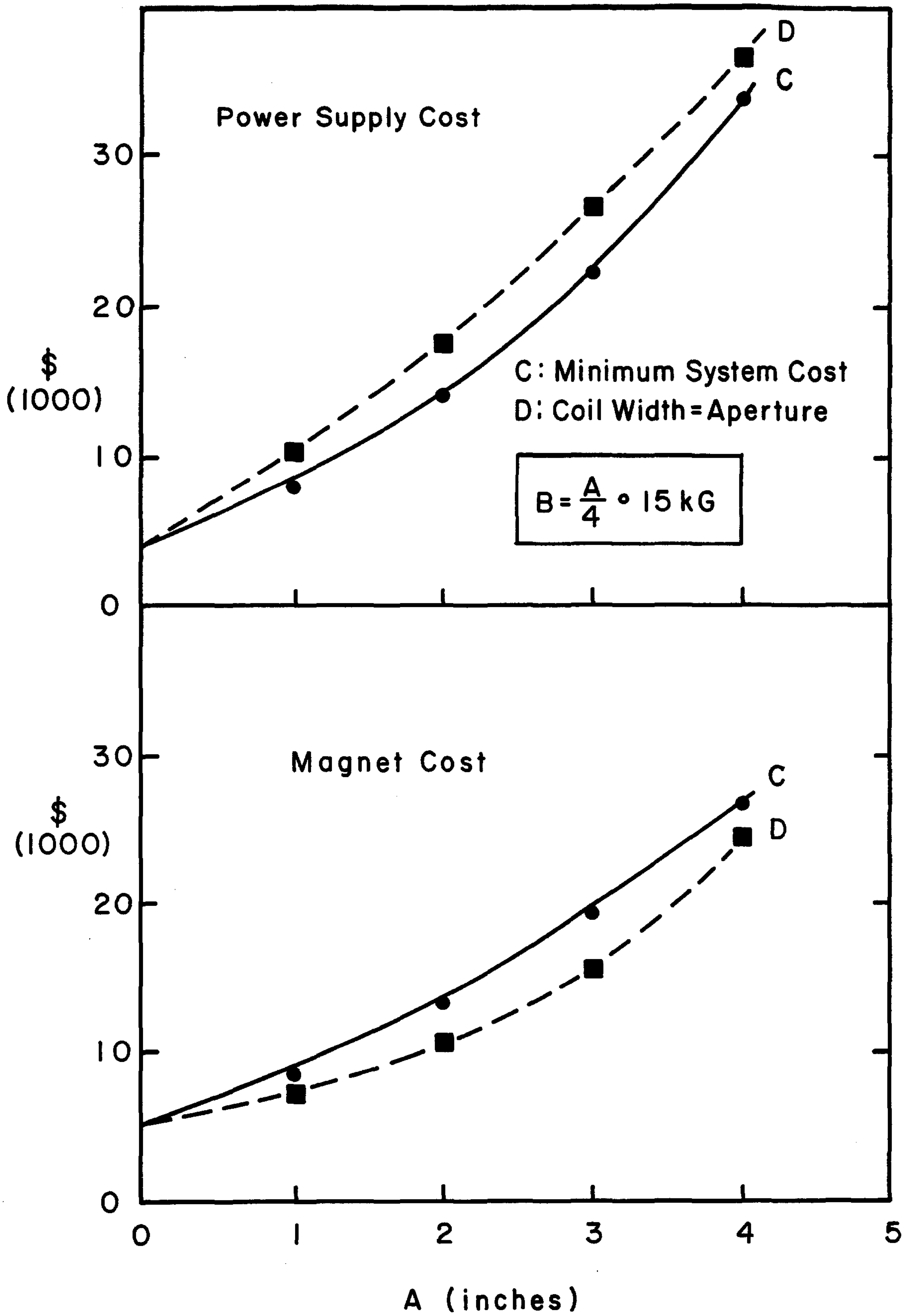
Power vs Aperture A For
Thin Quadrupole

Fig. II-4



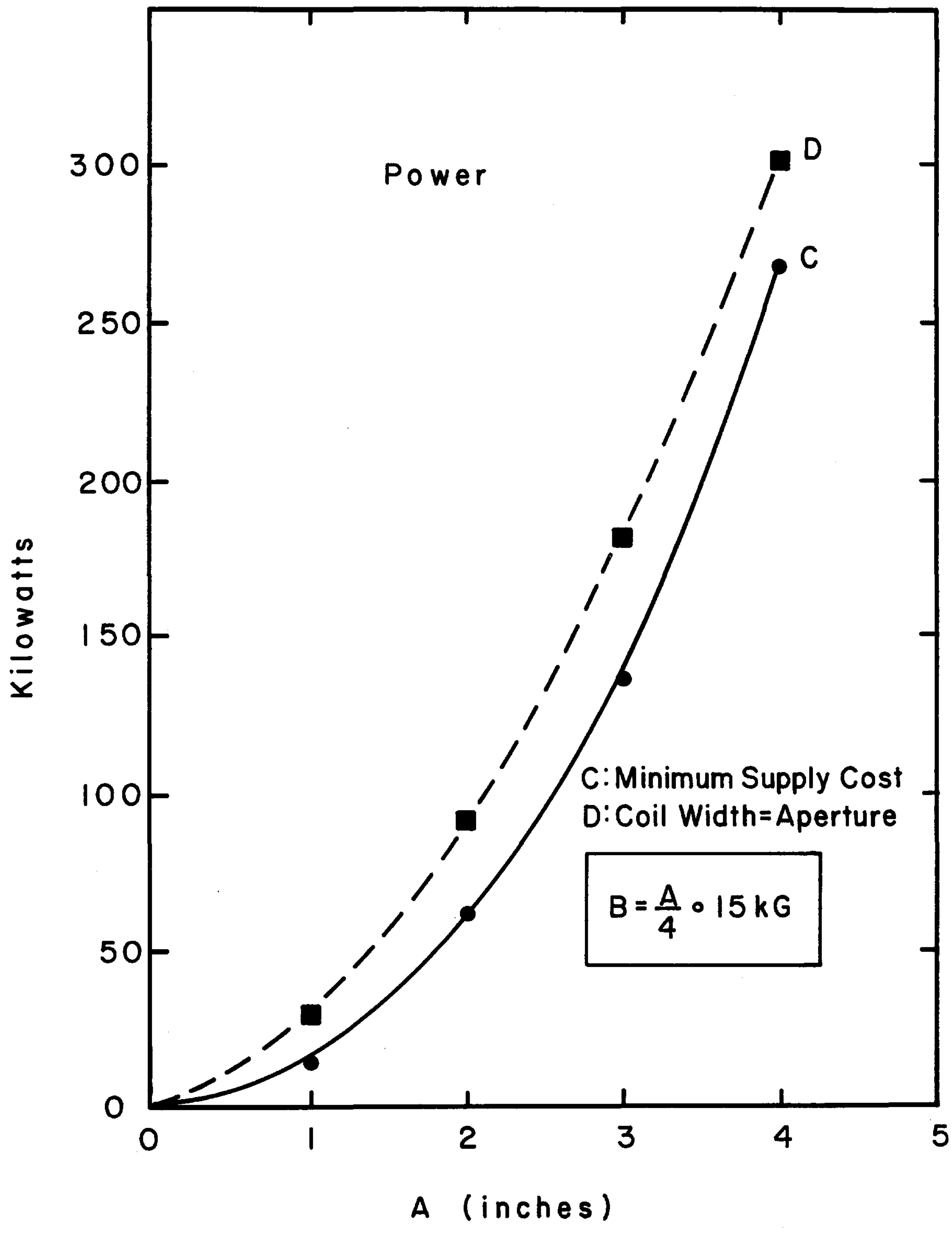
Cost vs Aperture A For
Thin Quadrupole

Fig. II - 5



Cost vs Aperture A For
Thin Quadrupole

Fig. II-6



Power vs Aperture A For Thin Quadrupole

Fig. II-7

also depend only on the vertical aperture and are essentially linear with aperture.

For the quadrupole curves in Figures II-4 through II-7, the two choices for the scaling of the pole tip field are

1. $B = \sqrt{\frac{A}{4}} \cdot 15$ kG   A = aperture in inches

2. $B = \frac{A}{4} \cdot 15$ kG

These choices are discussed in the next section. The curves are not nearly as linear with aperture as those for the bending magnet.

For the quadrupole both a minimum cost (equipment only) curve and a second curve are given. The minimum cost solution is obtained by varying the radial dimension of the coil and rectantular coil window at fixed aperture. For smaller apertures the coil radial size is a larger multiple of the aperture dimension and thus the outer width does not scale as the aperture. For a situation described in the next section, it is desirable to have the outside width scale linearly with aperture and thus a second curve is presented which was produced by setting the radial coil dimension equal to the aperture.

Over-all Beam Considerations: This section discusses topics involving more than one magnet with the different choices of magnets mentioned in the previous section. One constraint on the magnets used in the beam lines occurs in the region near the production target, when multiple beam lines are planned. The effect of the crowded front-end region is that certain magnets must be narrow and, consequently, they must consume more power than otherwise necessary. The magnets in the beam designs included in this report that are affected are listed in Table II-1. To make this list the assumptions made were the 12" outside width suggested for quadrupoles by the 1969 Summer Study and a 30" outside width and 5" coil width for the septum dipole.[11] The physical layout is that shown in Figure I-1.

The power consumed in these magnets is estimated as 500 and 340 kilowatts in the quadrupole run at 15 kG and the septum dipole run at 20 kG, respectively. In order to determine the power consumed by each beam at its maximum momentum, estimates have been made for the lower power elements (away from the congested region) of 100 and 60 kilowatts for the quadrupole and the dipole, respectively. The field values assumed for these estimates stay the same as for the high-power estimates; likewise for aperture, length and maximum field. The maximum power figure for each beam that results is listed inTable II-2.

Next consider beam costs as a function of magnet aperture. As shown in Figure II-2 all costs per unit length go down as the aperture is decreased. One possible approach to reduction of costs would be to leave designs as they are and just reduce aperture, thus lowering theintensity of the beam. All quadrupole fields would go down directly with aperture decrease. This is the assumption used in Figures II-6 and II-7.

Another approach is to reduce both aperture and the distance from the target to the first quadrupole in such a manner as to maintain solid angle acceptance. This was the subject of a previous note by Danby and Good[12]. One of the limitations they envisaged was an upper limit on current density in the narrow quadrupole's coil as the outside width shrunk (assuming enough other beam lines necessitate narrow front-end magnets). The assumed cross section was one with no iron flux return horizontally somewhat like the quadrupole in Figure II-1c. They concluded that the lowest practical limit on quadrupole aperture was four inches. They assumed a doublet as the front focusing element and that the distance from target to each element in the doublet scaled down with aperture in a way that maintained acceptance.

The result of their assumption, however, is a higher pole tip field than necessary at smaller apertures. To see this consider the thin-lens formula for a doublet

$$\frac{1}{f_d} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

Since $f_1 = f_2 = f_s$ is always very nearly the case, this becomes

$$f_d = f_s^2/d$$

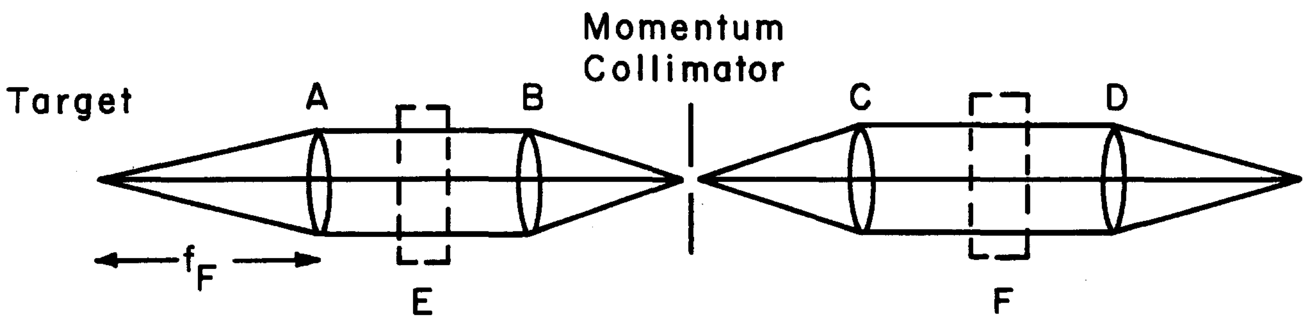
where d is the distance between singlet centers. For a doublet producing parallel rays f_d is almost equal to the target-doublet distance. The effect of their assumption is to reduce d so that f_s must be smaller than if d were kept fixed. However, with d kept fixed, the pole tip field can drop as the square root of the aperture for a fixed length quadrupole; with their assumption the pole tip field must stay constant.

With a drop in pole tip fields the current density situation is not as bad as indicated in Reference[12]. In Figures II-4 and II-5, the assumption that $B \propto r^{1/2}$ is made, where B = pole tip field and r is half-aperture of the quadrupole.

A section of beam like the front part of Figure II-8 has been assumed for the purpose of seeing the behavior of costs as a function of aperture for a beam. The model uses as reasonable numbers two quadrupoles in a front doublet, five bending magnets, and two quadrupoles following the bending to refocus. The beam has quadrupoles with apertures of 4" and 5 x 3 inches in the bending magnets as a starting point.

The nominal cost of magnet and power supply is taken as $50,000 so that 3/4 is magnet and 1/4 is power supply. The starting power figures are 100 kilowatts for the quadrupole and 60 kilowatts for the bending magnet. Apertures are then scaled by the factors 3/4, 1/2 and 1/4, using the curves in Figures II-2 through II-7 to give scaling factors for cost of magnet, power supply, and power consumption.

The intent of these assumptions is to use the



Doublets: A, B, C, D

Bending Section: E, F

Beam Model

Fig. II-8

curves in Figures II-2 through II-7 for scaling only. Although these magnets probably will not correspond to the magnets ultimately built, the model should give the trend of costs as a function of aperture.

Using curves II-4 and II-5 for the quadrupoles, assumes that the quadrupoles are moved so as to keep acceptance constant. This results in a beam with variable length. A consequence of reducing the target to front quadrupole distance is to lower momentum resolution of the beam if bending power is not increased. This is seen in the formula[3]

$$\frac{\Delta p}{p_{min}} = \frac{X_o}{\theta f_F}$$

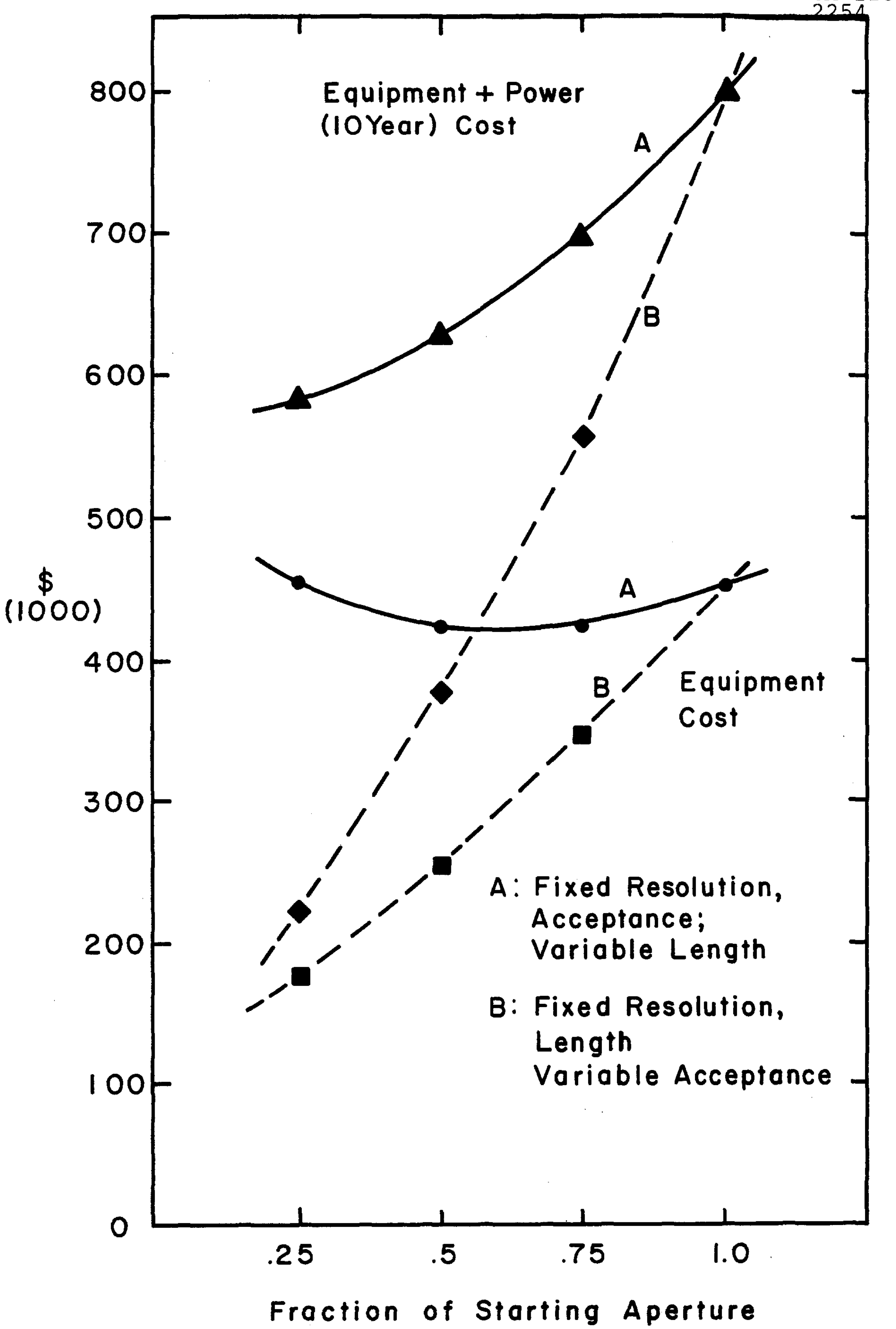
X_o = spot size at primary target

θ = bend angle in first section

f_F = first doublet focal length

which corresponds to the situation in Figure II-8, where the rays are parallel through the bending magnets.

Starting with these figures, the costs for the front section of a beam with fixed acceptance and momentum resolution have been calculated, as a function of aperture. The results are the curve labeled "A" in Figure II-9. One curve includes ten-year power cost (assumption -- 1 kilowatt for 10 years = $500) and the other is equipment cost. The equipment cost curve has a shallow minimum between .5 and .75 of the starting aperture. When power cost is included this



Cost Study of Beam Section

Fig. II-9

minimum is no longer present; the net savings from aperture fraction 1 to 1/4 is only a little more than 25%.

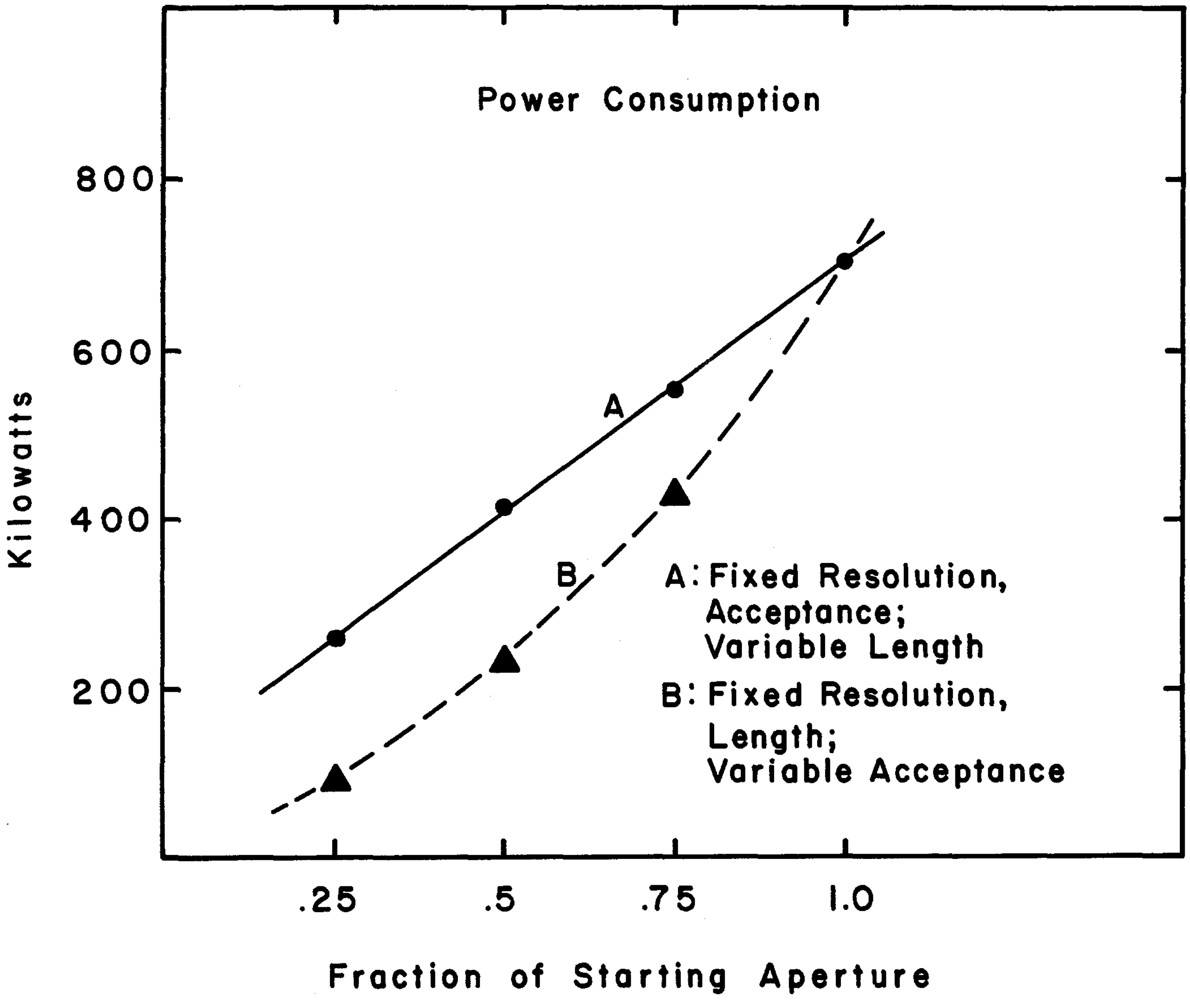
Even though all costs per unit length drop as aperture is reduced, the total length of bending at fixed field must be increased to maintain resolution. This explains the behavior of the equipment cost curve.

A more effective way to reduce costs is to lower the apertures while keeping the beam fixed in length (all elements stay in place) and fixing the momentum resolution. Since the beam intensity drops as aperture squared, this may be judged as a less desirable way to reduce over-all costs than the method previously described. These results are shown by the curves marked "B" on Figures II-9, for the identical starting assumptions and using curves II-6 and II-7 for the quadrupoles.

Figure II-10 shows the power consumption curves as a function of aperture for both fixed and variable length beams.

Conclusion

The basic purpose of this section has been to investigate beam costs as a function of magnet aperture. For reasonable assumptions it has been shown that a fixed acceptance, fixed momentum resolution beam has an equipment cost curve which shows a shallow minimum between 0.5 and 0.75 of the apertures now used in the beam designs. When 10-year power



Study of Beam Section

Fig. II-10

cost is folded in the cost curve becomes monotonic with aperture. The saving going from full aperture to 1/4 aperture is only slightly more than 25%.

If the decision is made to sacrifice acceptance of a beam then the saving as a function of aperture is much greater and the figure that corresponds to 25% mentioned just previously is instead almost 75%.

Aside from cost considerations, smaller aperture magnets would involve questions of current density and optical quality that haven't been discussed here.

TABLE II-1

SPECIAL MAGNETS IN BEAMS

BEAM	2.5mr	7.5mr	3.5mr
	Q1	Q1	Q1
	Q2	Q2	Q2
	B1	B1	Q3
	B2	B2	Q4
	B3	B3	B1
	B4		B2
	B5	(+ 3 more bends needed only for clearance)	B3

#'s sequentially away from target

Quadrupoles - narrow
Bending magnets - Septum construction } See Fig. II-16

TABLE II-2

POWER FOR BEAMS

	Pole Tip Field	Gradient	Aperture	Power at Max. Field (kw)
Special Quad	15	7.5	4"	500
Normal Quad	15	7.5	4"	100
Special Bend	20		5 χ 3	340
Normal Bend	20		5 χ 3	60

Power for Individual Magnets

Power Consumed at Highest Momentum (kilowatts)		2.5mr (Tune 2)	7.5mr (Tune 2)	3.5mr (Tune 2)
Quads	Special	511	320	1503
	Normal	236	263	766
Bends	Special	1700	1020	1020
	Normal	245	116	180
Total -		2692	1719*	3469

* Does not include 4 bending magnets for clearance purposes.

III. HIGH MOMENTUM, HIGH RESOLUTION BEAM (2.5 Mrad)

The beam at 2.5mrad is to be a high resolution beam which allows two independent experimental setups. The latter requirement is achieved by changing the polarity of the second of two sets of bending magnets and retuning the quadrupoles. In each tune the beam is brought to a focus at the experimental area and is completely achromatic. It is desirable to be able to transmit a large number of particles with charge of either sign over a momentum range which may vary from 20 to 200 BeV/c.

The elements for each tune with the lengths of the long drift spaces are given in Tables III-2 and III-3. Each tune has nine quadrupoles and two sets of five bending magnets each. The quadrupoles are arranged in four doublets and a singlet. Three of the doublets and the singlet plus eight of the bending magnets are shared between the two tunes making a total of eleven quadrupoles and twelve bending magnets. Because of the requirement of achromaticity and the change in polarity of the second set of bending magnet fields between the two tunes, the optics of the two beams are different and will be explained separately.

In Tune 1 the original beam is made parallel by a quadrupole doublet. This doublet is placed 151 feet from the target to prevent interference with the other beams. If the

TABLE III-2 - Elements - Tune 1

Element	Length	Field	Aperture	Bend or Focal Length
Drift	150.9 ft.			
Quad	9.8 ft.	-5.63kg/in.	4.0 in.	-31.3 ft.
Quad	9.8 ft.	5.26kg/in.	4.0 in.	36.9 ft.
2×BM	9.8 ft.	20.0 kg	3.0×5.0 in.	29.5 mr
Drift	13.1 ft.			
3×BM	9.8 ft.	"	"	"
Drift	88.6 ft.			
Quad	9.8 ft.	4.07kg/in.	4.0 in.	47.2 ft.
Quad	9.8 ft.	-4.22kg/in.	4.0 in.	42.3 ft.
Drift	252.6 ft.			
Quad	9.8 ft.	.93kg/in.	4.0 in.	201.2 ft.
Drift	275.6 ft.			
Quad	9.8 ft.	-4.12kg/in.	4.0 in.	43.3ft.
Quad	9.8 ft.	3.96kg/in.	4.0 in.	48.5 ft.
Drift	101.7 ft.			
2×BM	9.8 ft.	18.0 kg	3.0X5.0 in.	26.6 mr each
Drift	13.1 ft.			
3×BM	9.8 ft.	"	"	"
Drift	295.3 ft.			
Quad	9.8 ft.	5.61kg/in.	4.0 in.	34.7 ft.
Quad	9.8 ft.	-6.07kg/in.	4.0 in.	29.0 ft.
Drift	131.2 ft.			

All drift spaces not shown are 1 foot.

TABLE III-3 - Elements - Tune 2

Element	Length	Field	Aperture	Bend or Focal Length
Drift	150.9 ft.			
Quad	9.8 ft.	-6.91kg/in.	4.0 in.	-25.2 ft.
Quad	9.8 ft.	7.22kg/in.	4.0 in.	27.4 ft.
2×BM	9.8 ft.	20.0kg/in.	3.0×5.0 in.	29.5 mr
Drift	13.1 ft.			
3×BM	9.8 ft.	20.0 kg	"	"
Drift	88.6 ft.			
Quad	9.8 ft.	6.30kg/in.	4.0 in.	31.1 ft.
Quad	9.8 ft.	-5.76kg/in.	4.0 in.	30.6 ft.
Drift	252.6 ft.			
Quad	9.8 ft.	1.35kg/in.	4.0 in.	139.0 ft.
Drift	275.6 ft.			
Quad	9.8 ft.	-6.30kg/in.	4.0 in.	27.8 ft.
Quad	9.8 ft.	7.17kg/in.	4.0 in.	27.6 ft.
Drift	101.7 ft.			
2×BM	9.8 ft.	20.0 kg	3.0×5.0 in.	29.5 mr
Drift	13.1 ft.			
3×BM	9.8 ft.	20.0 kg	3.0×5.0 in.	.515° each
Drift	114.8 ft.			
Quad	9.8 ft.	6.46kg/in.	4.0 in.	30.4 ft.
Quad	9.8 ft.	-6.46kg/in.	4.0 in.	27.1 ft.
Drift	147.6 ft.			

All drift spaces not shown are 1 foot.

first quad is made horizontally defocussing, the principal planes of the doublet are placed such that the aperture of the doublet is matched to that of the bending magnets and maximum acceptance is obtained. A set of bending magnets then bends it away from the center line of the area and disperses it in momentum . A drift space of 13 feet is placed after the second bending magnet to allow for the emergence of a neutral beam. A second set of quads bring it to a focus in both planes, the x focus being the location of a momentum slit, and the y a cleanup slit. Maximum phase space area of the momentum slit for a given width is obtained by minimizing its length. However, a minimum length on the order of one meter is necessary to block effectively the off momentum particles. Given this restriction on length, in order to match the phase space area of the on momentum beam with the acceptance of the narrowest possible slit the image at the slit must be horizontally magnified. This in turn requires the focal length of the second doublet be greater than that of the first.

The two intermediate foci are on either side of the quad singlet which serves as a field lens. The function of this element is to insure achromaticity in angle at the final focus. This is done by focussing the images of the sets of bending magnets as seen through the adjacent doublets on each other. The beam is again made parallel by a third doublet.

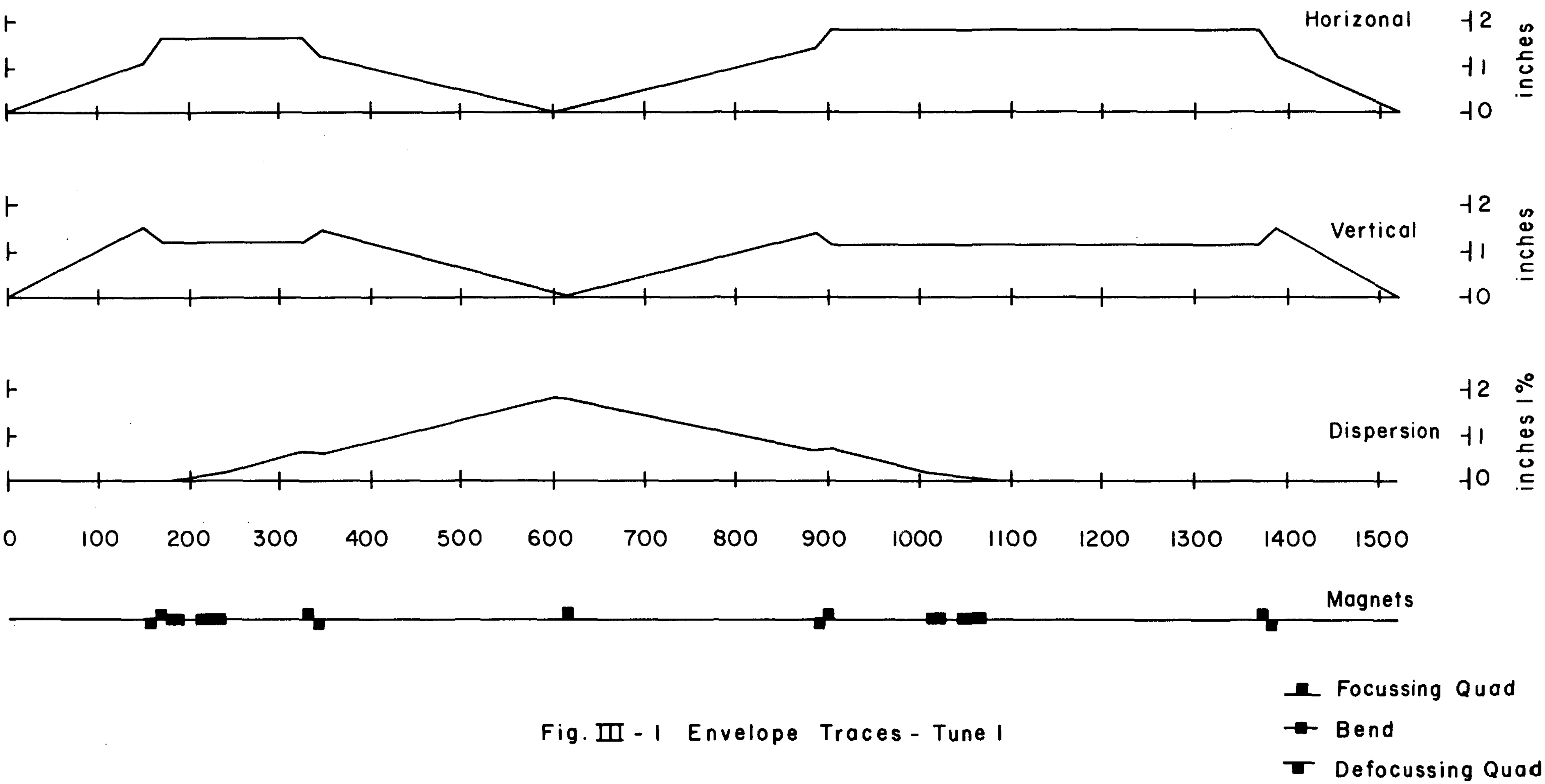


Fig. III - 1 Envelope Traces - Tune I

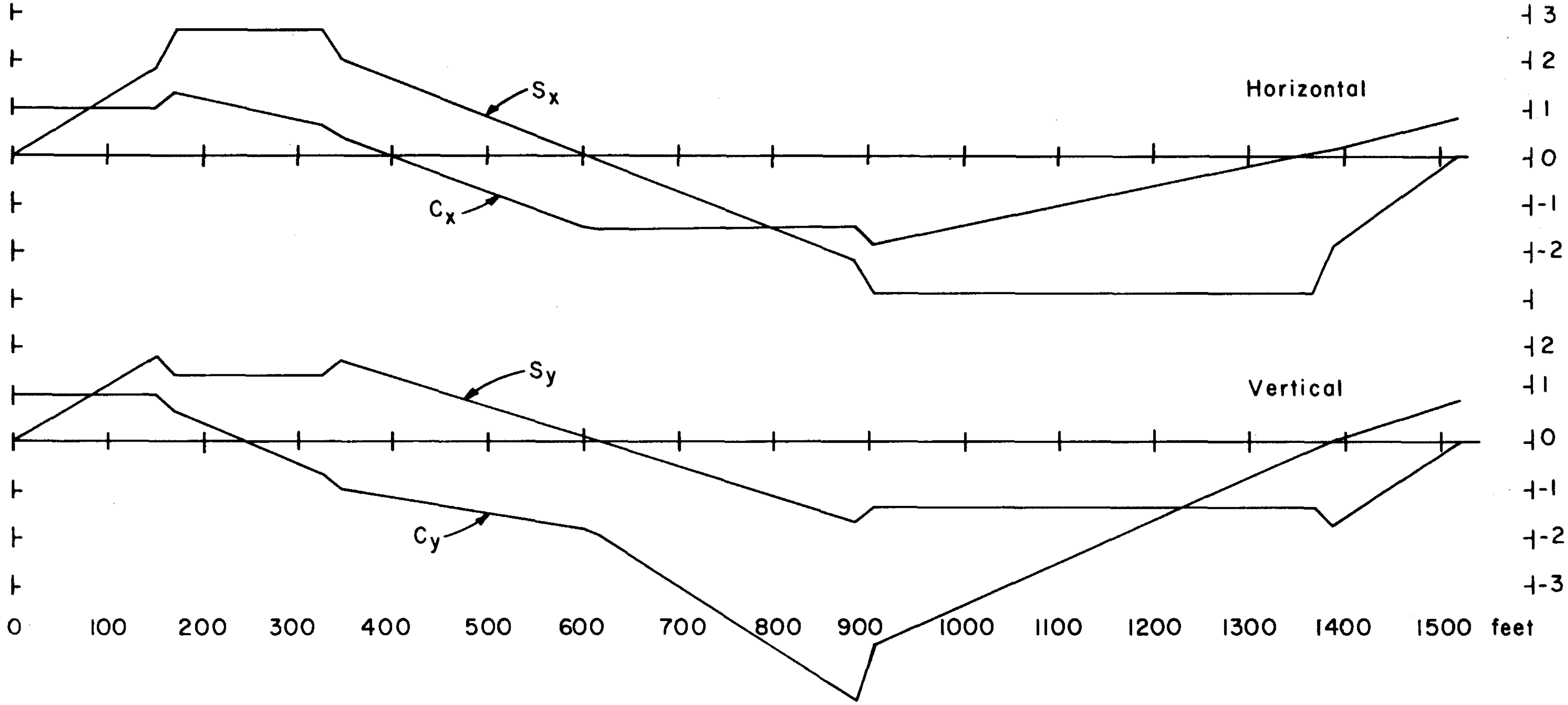


Fig. III - 2 Principal Trajectories - Tune I

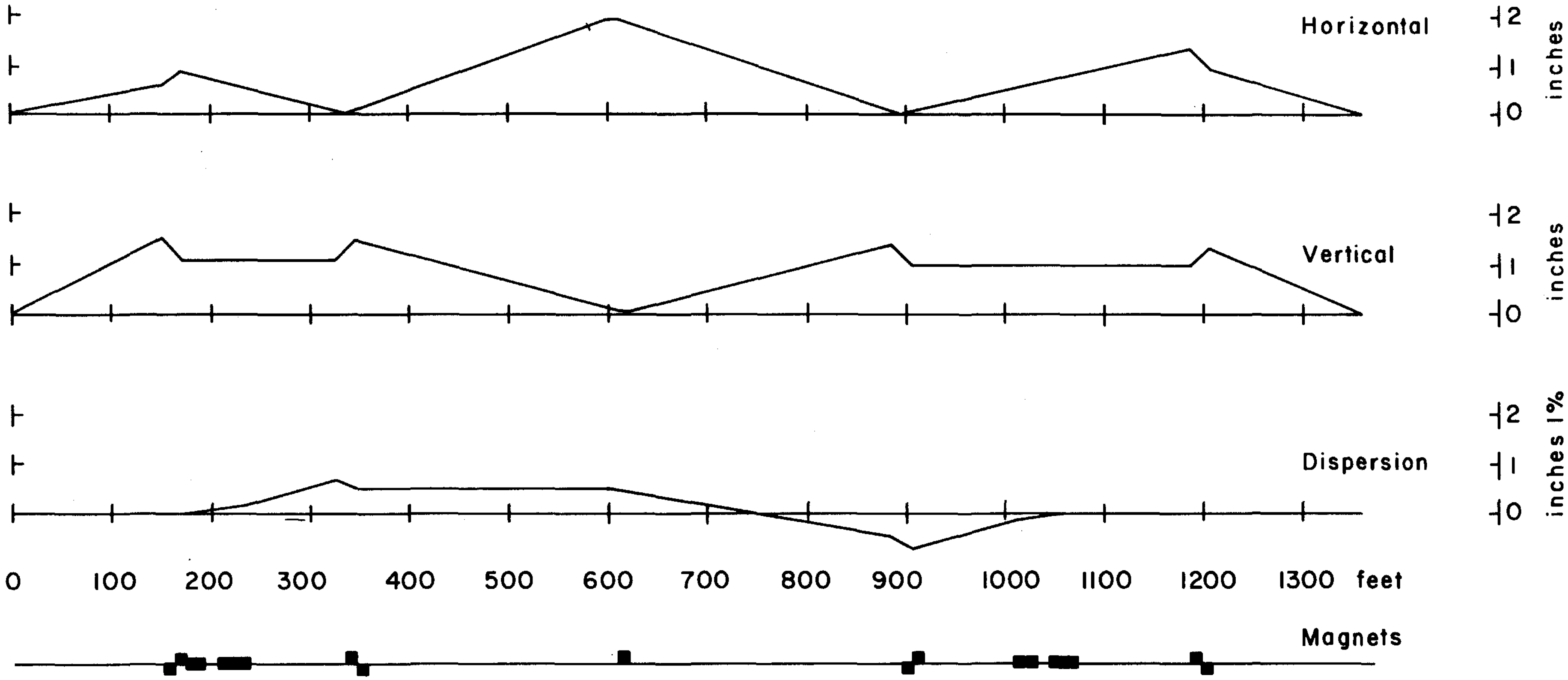


Fig. III - 3 Envelope Traces - Tune 2

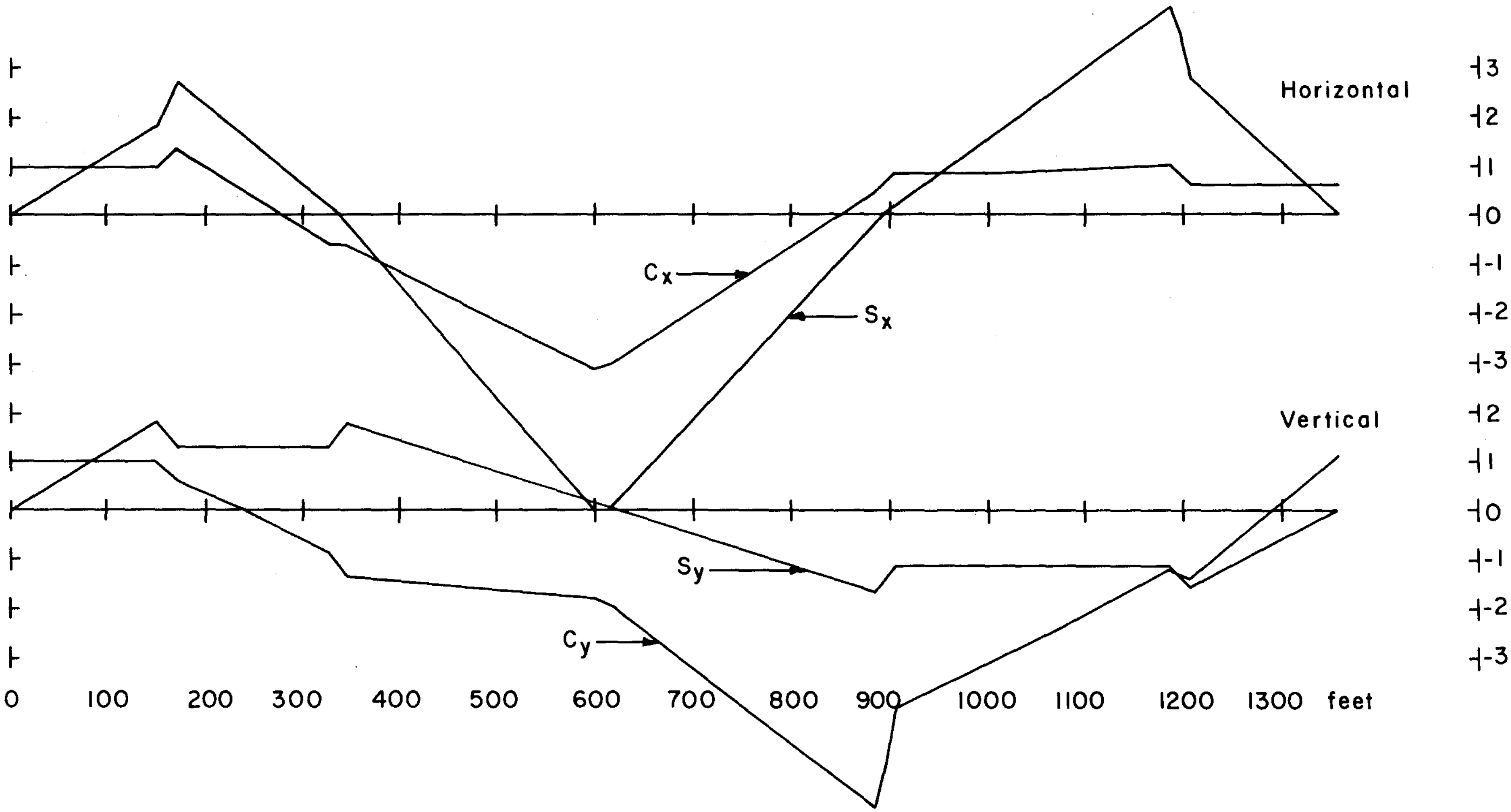


Fig. III - 4 Principal Trajectories - Tune 2

The drift space before this doublet must be comparable to that after the second doublet to insure achromaticity. Momentum recombination is effected by a second set of bending magnets. A long drift space of 295 feet is located in the parallel section after these bending magnets to allow for the placement of Cerenkov counters. A final doublet then brings the beam to a completely achromatic focus at the experimental area.

In Tune 2 the two bends are in the opposite direction requiring an additional intermediate focus to obtain momentum recombination at the final focus. This focus and the condition of achromaticity in angle at the quadrupole singlet are obtained at the expense of the parallel beam sections in the horizontal plane. The first doublet gives a parallel beam in the y plane and a focus in the x plane at the second doublet. This latter focuses the beam in the vertical plane at the singlet and acts partly as a field lens. The singlet is now used to give the second horizontal focus at the third doublet. The third doublet renders the beam parallel in the vertical plane and also helps obtain achromaticity. The final doublet then creates a completely achromatic double focus in the experimental area.

A general idea of the optical behavior of each beam may be obtained by examining diagrams III-1 through III-4. Figure III-1 contains horizontal and vertical envelope traces for zero momentum spread and the dispersion function for tune 1.

Figure III-2 shows the principal rays in both planes. Similar graphs are given in diagrams III-3 and III-4 for tune 2. Elements are indicated on the graphs. The parameters of the beam at the target and various foci along with some of the magnet statistics are presented in Table III-1. The figures given are the results of a first order calculation which includes the effect of using rectangularly shaped bending magnets. A tabulation of the magnets with their fields and apertures is given in Tables III-2 and III-3. All spaces between magnets not explicitly given are one foot.

Calculations have been performed on the effect of misalignments of beam elements in tune 1. It has been determined that a small misalignment of a bending magnet will have a negligible effect on the beam. A single random horizontal misalignment of a quadrupole of 0.010 inches will introduce an uncertainty in the position of the beam centroid at the experimental area of approximately 0.04 inches. If this quadrupole is in the first section of the beam, the uncertainty in the position of the centroid at the intermediate horizontal focus is about 0.07 inches. If the positions of all quadrupoles are uncertain by 0.010 inches, the displacements of the beam centroid will add in a root mean square fashion giving 0.120 inches at the final focus and 0.140 inches at the intermediate focus. Similar results are obtained for the vertical plane.

TABLE III-1 - Statistics

Total length	Tune 1 1520 ft.	Tune 2 1356 ft.
No. of Quads	9	9
Length of each	9.8 ft.	9.8 ft.
Total length	88.6 ft.	88.6 ft.
No. of BM	10	10
Length of each	9.8 ft.	9.8 ft.
Total length	98.4 ft.	98.4 ft.
Horizontal beam half width	0.020 in.	0.020 in.
Half angular spread	0.625 mr	0.312 mr
Vertical beam half width	0.020 in.	0.020 in.
Half angular spread	0.833 mr	0.833 mr
Horizontal image half size at first horizontal focus	.030 in.	.013 in.
Beam dispersion at first horizontal focus	1.803 in./%	.498 in./%
Momentum resolution at first horizontal focus	.033%	.052%
Vertical image half size at first vertical focus	.039 in.	.039 in.
Horizontal image half size at second horizontal focus	----	.013 in.
Horizontal image half size at experimental area	.016 in.	.012 in.
Vertical image half size at experimental area	.018 in.	.022 in.

Beam traces to second order have been made also. Because of the fore and aft symmetry of each beam, many possible aberrations are minimized.[13] The quantities in Table III-1 are essentially   to second order. These quantities do not include the effect of chromatic aberrations.

The predominant effect of chromatic aberration is to cause the focal plane at a horizontal focus to make a small angle with the beam axis. Without higher order correcting elements this angle would be 9.0 mrad in tune 1 and 15.5 mrad in tune 2. By placing a sextupole element immediately after the first set of bending magnets, it is possible to right the focal plane at the first intermediate horizontal focus in both tunes. The sextupole used had a length of 1 foot and in tunes 1 and 2 pole tip fields of 3.02 and 9.48 kilogauss respectively. The use of a sextupole at a location where the beam has a non-zero vertical width will introduce aberrations from the coupling of the horizontal and vertical planes. Means to correct such aberrations are under investigation.

Graphs of the intensities of various particles at the experimental area are given in Figures III-5 and III-6 for tunes 1 and 2 respectively. These figures are based on an original proton beam at 3.10^{12} interacting particles and correspond to the beam dimensions given in Table III-1. The in-flight decay of the unstable particles has also been included.

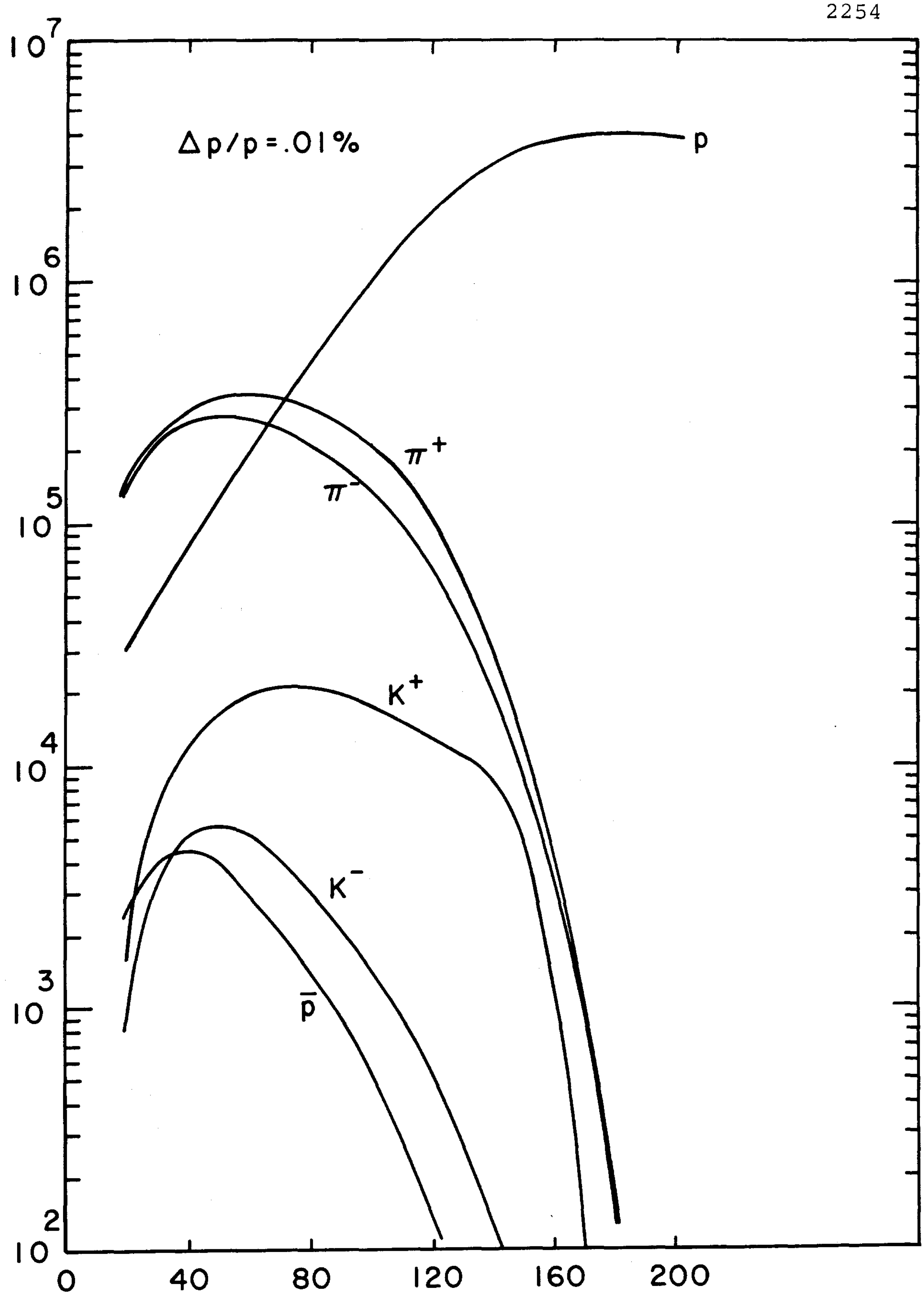


Fig. III-5: Particle Yield vs Momentum-Tune I

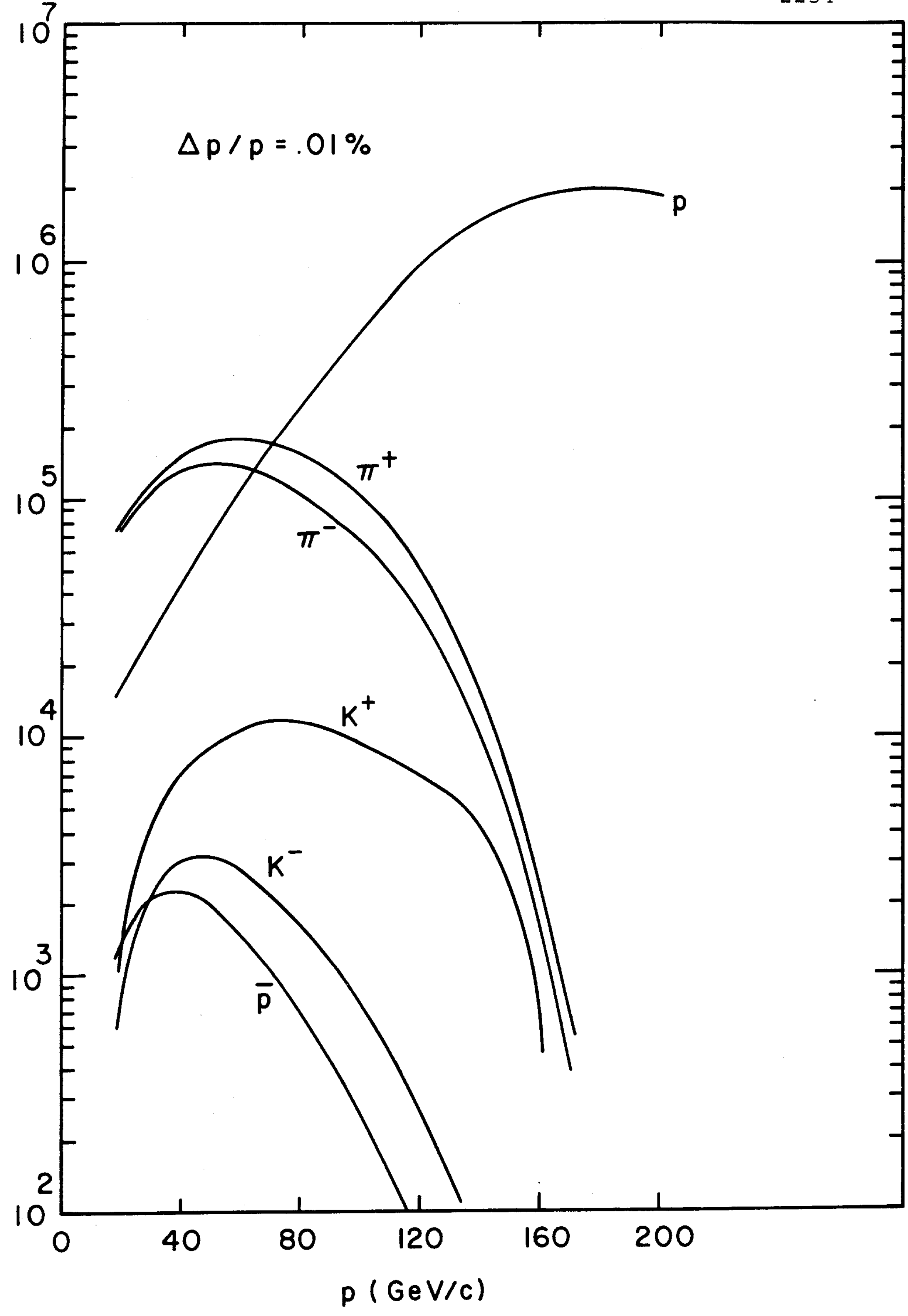


Fig. III-6: Particle Yield vs Momentum-Tune 2

The curves are normalized to a momentum resolution of 0.01 percent.

Power requirements for each beam are listed in Table III-4. These figures are based on the use of Danby quads for the first doublet and larger quads thereafter. The first set of bending magnets is of the septum type and the second is of the Billinge type.

TABLE III-4 - Power Requirements

	Tune 1	Tune 2
First Quad	273 kw	411 kw
Second Quad	238	450
Each of 5 BM	340	340
Third Quad	29	68
Fourth Quad	31	57
Fifth Quad	2	3
Sixth Quad	30	68
Seventh Quad	27	89
Each of 5 BM	49	60
Eighth Quad	54	72
Ninth Quad	63	72
Total Power	2692 kw	3050 kw

IV. MEDIUM MOMENTUM, HIGH RESOLUTION BEAM (7.5 mrad)

Description: The beam described is an unseparated charged beam with a maximum momentum of 120 BeV/c and a resolution of ±0.04% proposed by the 1969 Aspen Summer Study and designated as the 7.5 mrad beam in SS-37.[4] A "Y" in the second section provides for two independent experimental areas. By using a tune, called tune 1, with a single intermediate focus and all bending magnets of the same polarity and another, called tune 2, with two intermediate horizontal foci and bending magnets of the second section in opposite polarity, momentum is recombined for both branches of the "Y" (SS-41).[3] The element positions, lengths, excitations, and principal trajectories are given in Table I and Table II. The beam currently used for Area II studies employs more bending magnets than this one in order to fit it into the experimental area.

The following principles of optimization have been employed:

A. Copper coil front end quadrupoles of four-inch aperture and twelve-inch width described in SS-37 were assumed. The target to front end doublet distance is fixed to permit the mix of beams proposed in SS-37.

B. The primary design goal is maximum resolution.

TABLE IV-1: 120 BeV/c Beam Tune 1

Element	Length	Field KG or Grad KG/in	Cumulative Length (ft.)	S_X (cm)	C_X	S_Y (cm)	C_Y	D (cm)
Target	0.33		0.00	0.000	1.000	0.000	1.000	0.000
D	131.23		131.23	4.000	1.000	4.000	1.000	0.000
QD1	9.843	-3.621	141.08	4.975	1.165	3.660	0.844	0.000
D	0.984		142.06	5.145	1.118	3.564	0.814	0.000
QF1	9.843	3.355	151.90	6.018	1.346	3.096	0.618	0.000
D	0.984		152.89	6.018	1.341	3.097	0.609	0.000
BM1	9.843	20.000	162.73	6.020	1.292	3.100	0.513	0.022
D	0.984		163.71	6.020	1.287	3.100	0.503	0.027
BM2	9.843	20.000	173.56	6.021	1.237	3.103	0.407	0.094
D	0.984		174.54	6.021	1.232	3.103	0.397	0.103
BM3	9.843	20.000	184.38	6.023	1.183	3.105	0.300	0.216
D	49.213		233.60	6.030	0.935	3.112	-0.182	0.890
QF2	9.843	2.926	243.44	5.267	0.769	3.525	-0.307	0.907
D	0.984		244.42	5.118	0.742	3.609	-0.323	0.896
QD2	9.843	-3.083	254.27	4.269	0.557	3.933	-0.431	0.914
D	164.042		418.31	0.240	-1.140	0.429	-1.318	3.222
QFL	9.843	1.432	428.15	-0.009	-1.192	0.234	-1.428	3.224
Slit	Momentum							
D	13.123		441.27	-0.344	-1.196	-0.009	-1.653	3.043
Slit	Cleanup							
D	155.036		596.29	-4.307	-1.236	-2.883	-4.307	0.903
QD3	9.843	-3.290	606.14	-5.214	-1.424	-2.647	-1.296	0.895
D	0.984		607.12	-5.374	-1.462	-2.583	-3.751	0.907
QF3	9.843	3.064	616.96	-6.195	-1.623	-2.269	-3.173	0.901
D	49.213		666.17	-6.193	-1.389	-2.272	-2.516	0.246
BM4	9.843	20.000	676.02	-6.193	-1.341	-2.272	-2.385	0.137
D	0.984		677.00	-6.193	-1.336	-2.272	-2.372	0.128
BM5	9.843	20.000	686.84	-6.192	-1.287	-2.272	-2.239	0.065
D	0.984		687.83	-6.192	-1.282	-2.272	-2.226	0.061
BM6	9.843	20.000	697.67	-6.192	-1.234	-2.271	-2.094	0.042
D	65.617		763.29	-6.189	-0.910	-2.265	-1.207	0.067
QF4	9.843	3.828	773.13	-5.170	-0.714	-2.659	-1.277	0.059
D	0.984		774.11	-4.971	-0.681	-2.740	-1.305	0.057
QD4	9.843	-4.234	783.96	-3.825	-0.460	-3.004	-1.328	0.049
D	98.425		882.38	0.000	0.784	0.001	0.999	0.061

TABLE IV-2: 120 BeV/c Beam Tune 2

Element	Length	Field KG or Grad KG/in	Cumulative Length (ft.)	S_X (cm)	C_X	S_Y (cm)	C_Y	D(cm)
Target	0.33		0.00	0.000	1.000	0.000	1.000	0.000
D	131.23		131.23	4.000	1.000	4.000	1.000	0.000
QF1	9.843	4.567	141.08	3.498	0.805	5.157	1.209	0.000
D	0.984		142.06	3.372	0.767	5.366	1.252	0.000
QD1	9.843	-3.877	151.90	2.624	0.503	6.445	1.451	0.000
D	0.984		152.89	2.597	0.486	6.445	1.447	0.000
BM1	9.843	20.000	162.73	2.328	0.320	6.449	1.401	0.022
D	0.984		163.71	2.301	0.304	6.449	1.396	0.027
BM2	9.843	20.000	173.56	2.033	0.138	6.452	1.350	0.094
D	0.984		174.54	2.006	0.121	6.452	1.346	0.103
BM3	9.943	20.000	184.38	1.737	-0.045	6.453	1.299	0.216
D	49.213		233.60	0.393	-0.874	6.453	1.067	0.890
QD2	9.843	-4.857	243.44	0.192	-1.246	5.115	0.803	1.234
D	0.984		244.42	0.177	-1.307	4.857	0.756	1.291
QF2	9.843	6.694	254.27	-0.006	-1.486	3.526	0.481	1.448
Slit	First Momentum							
D	164.042		418.31	-3.353	2.931	-0.008	-1.419	-3.189
Slit	Cleanup							
QF3	9.843	2.029	428.15	-3.351	3.017	-0.225	-1.621	-3.273
D	168.159		596.29	0.146	1.398	-4.085	-6.649	-1.348
Slit	Second Momentum							
QF4	9.843	1.927	606.14	0.333	1.189	-4.671	-7.527	-1.125
D	0.984		607.12	0.349	1.157	-4.768	-7.676	-1.093
QD3	9.843	-2.132	616.96	0.551	0.939	-5.257	-8.403	-0.860
D	49.213		666.17	1.785	0.319	-5.263	-8.127	-0.134
BM4	9.843	-20.000	676.02	2.032	0.195	-5.264	-8.071	-0.011
D	0.984		677.00	2.057	0.183	-5.264	-8.065	-0.001
BM5	9.843	-20.000	686.84	2.303	0.059	-5.263	-8.007	0.077
D	0.984		687.83	2.328	0.047	-5.263	-8.002	0.082
BM6	9.843	-20.000	697.67	2.575	-0.077	-5.261	-7.942	0.115
D	9.843		707.51	2.822	-0.201	-5.259	-7.881	0.125
QF5	9.843	4.614	717.36	2.495	-0.277	-6.367	-9.482	0.110
D	3.986		721.36	2.140	-0.286	-7.297	-10.486	0.094
QD4	9.843	-4.411	731.20	1.635	-0.368	-8.066	-11.951	0.071
D	98.425		829.63	-0.001	-1.834	0.000	0.371	-0.011

C. Secondary importance is attached to intensity.

D. The number of magnets is minimized, consistent with the other requirements.

E. To provide some contrast with the design for the high energy beam and show the effects of shortening beams of this design, small compromises on the above optimization criteria were accepted to reduce over-all length.

An envelope trace for tune 1 is given in Figure IV-1. One sees that the first DF doublet renders the beam diverging from the target parallel in both planes to make maximum use of bending magnet aperture and dispersion. An FD doublet provides a horizontal focus at a momentum slit and field lens 164' beyond. A cleanup slit can be placed at the vertical focus 13' farther downstream. The length of the drift to the focus is the minimum consistent with a horizontal magnification that matches slit acceptance to beam emittance (SS-41). The field lens becomes important when the slit is widened to increase the momentum bite. Approximately, its strength is determined by the condition that it should provide point-to-point focussing from the center-of-bend of the first section to the center-of-bend of the second section and its aperture is determined by the maximum momentum bite times the dispersion. Because it is impractical to have the momentum and cleanup slits inside the field lens the field lens cannot be exactly at the on-momentum focus and there is

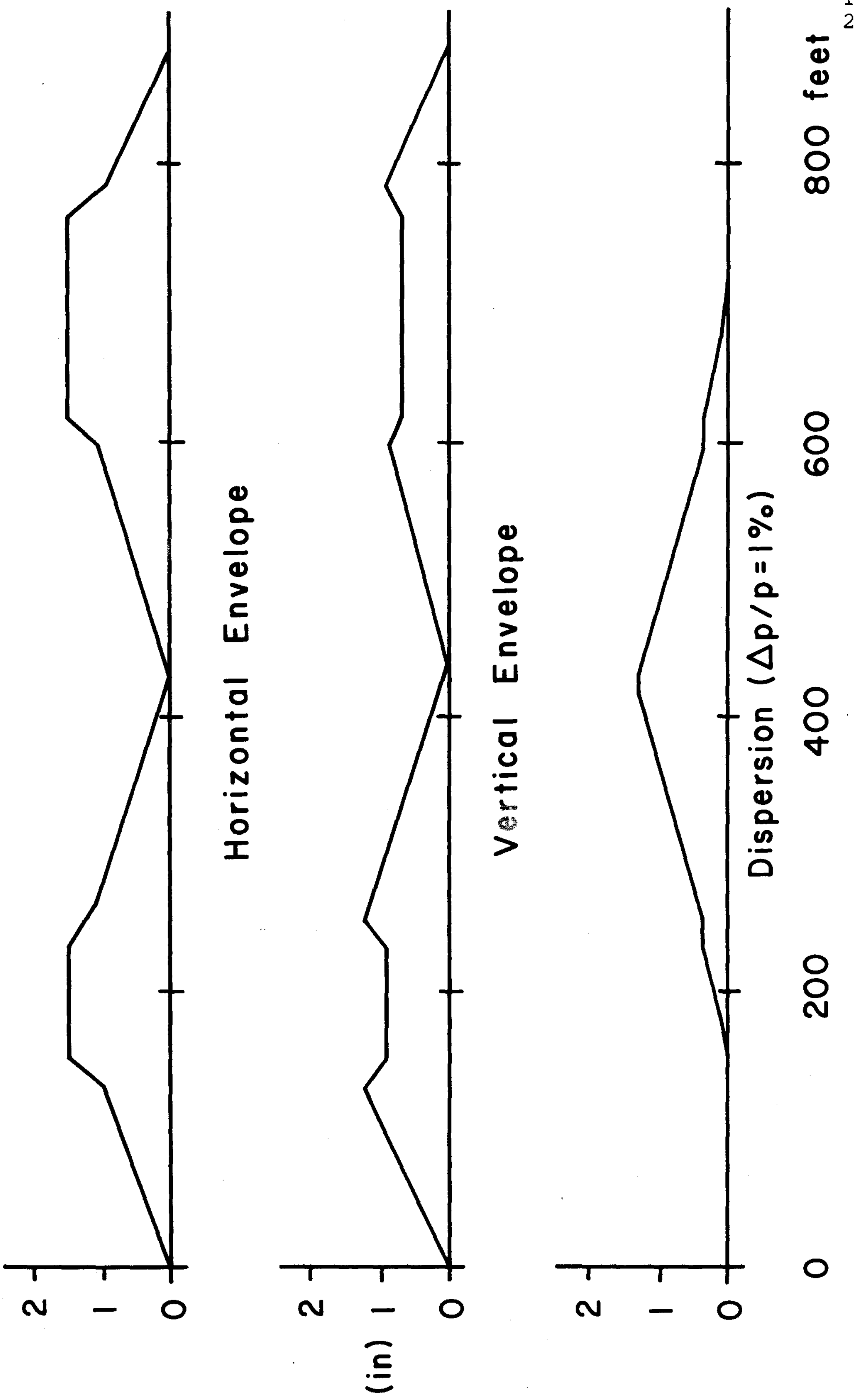


Fig. IV-1: 7.5 mrad Tune I Envelope and Dispersion thus some interaction between momentum recombination and on-momentum focussing as shown, for instance, in Figure IV-1. A second section, similar to the first, recombines momentum and brings the beam to a horizontal and vertical achromatic focus in the experimental area. The long drift of 66 feet after the bending magnets is intended for a differential Cerenkov counter or DISC and also serves to provide longitudinal separation between the experimental areas. The beam is parallel and achromatic in this section. The dispersion function for this tune is given in Figure IV-1 and the principal trajectories in Figure IV-2. These traces are also tabulated in Table IV-2.

Assumptions concerning magnets and target: The first section employs the magnets proposed in SS-37; special bending magnets are required for the second section. Because they bend opposite ways for the two tunes, they must have sufficient aperture, viz., about 18" for the final magnet. Alternatively the last one or two could be separate, septum magnets for each tune spaced downstream and staggered so that the inactive magnets clear the active beam line. The quadrupole used as the field lens should have a six-inch aperture or more.

The beam spot is assumed to be 0.039" (1mm) in diameter and the production target 4" long so that at 7.5 mrad the horizontal radius is 0.035" and vertical radius is

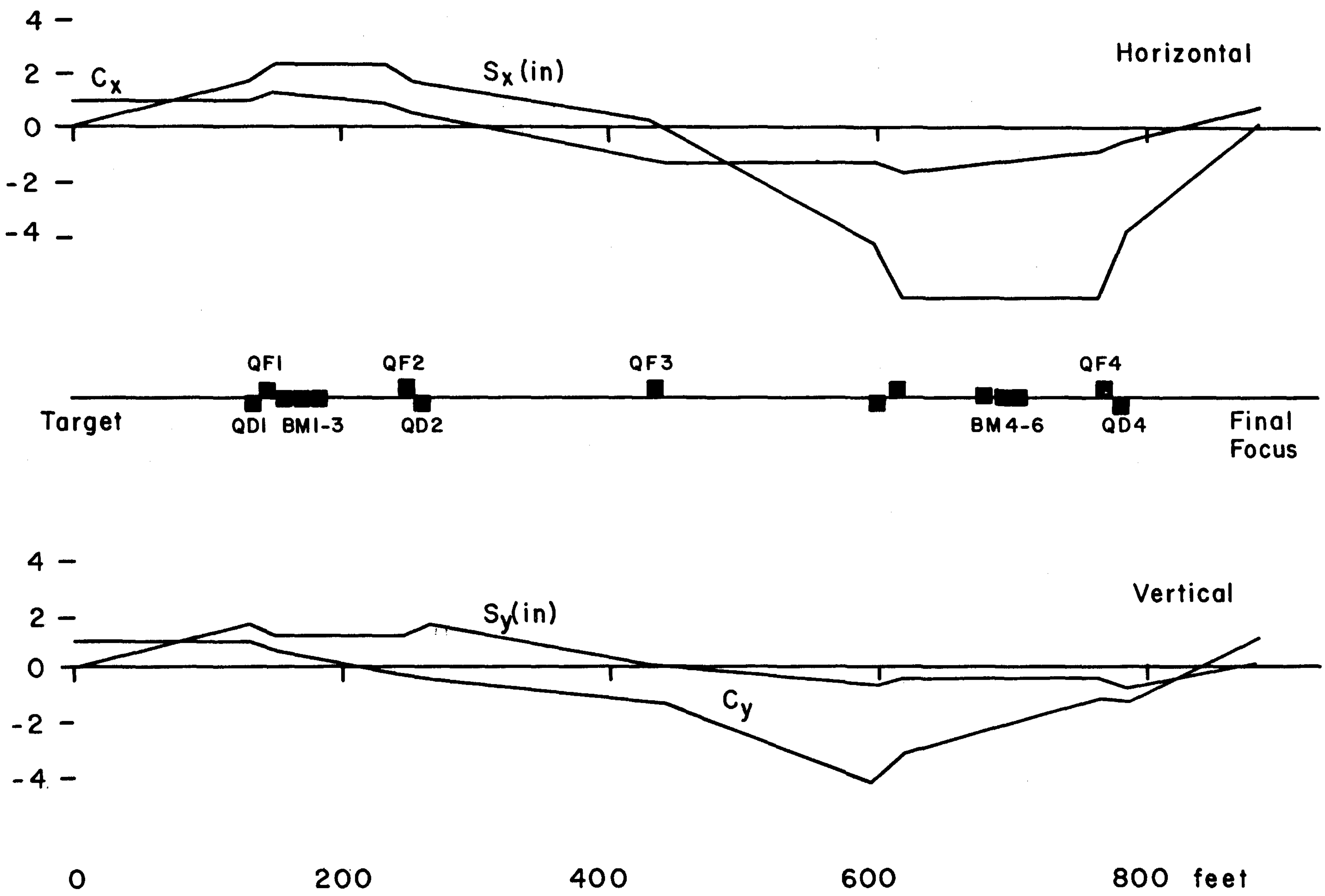


Fig. IV- 2 7.5 mrad. Principal Trajectories - Tune I

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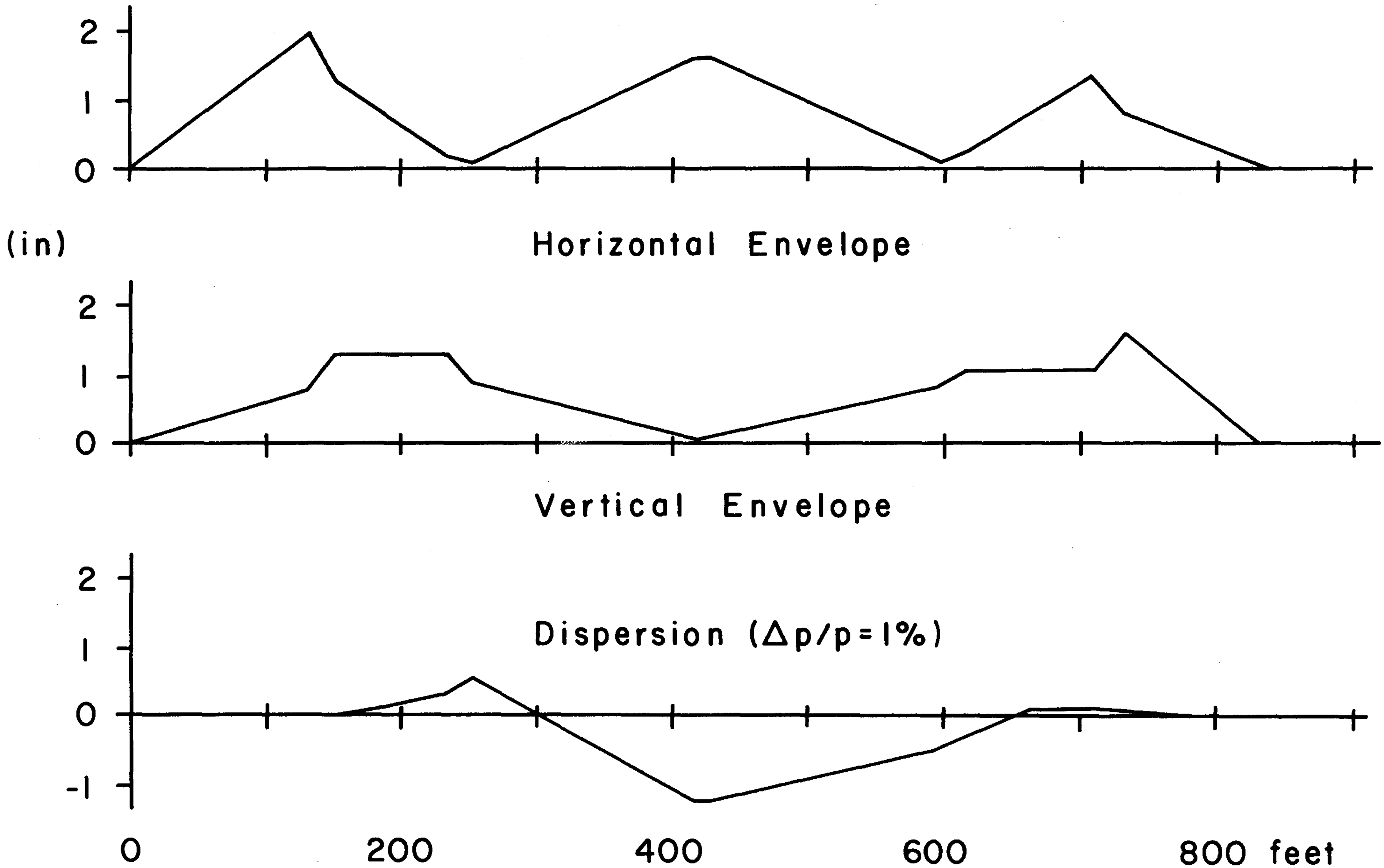


Fig. IV-3: 7.5 mrad Tune 2 Envelope and Dispersion

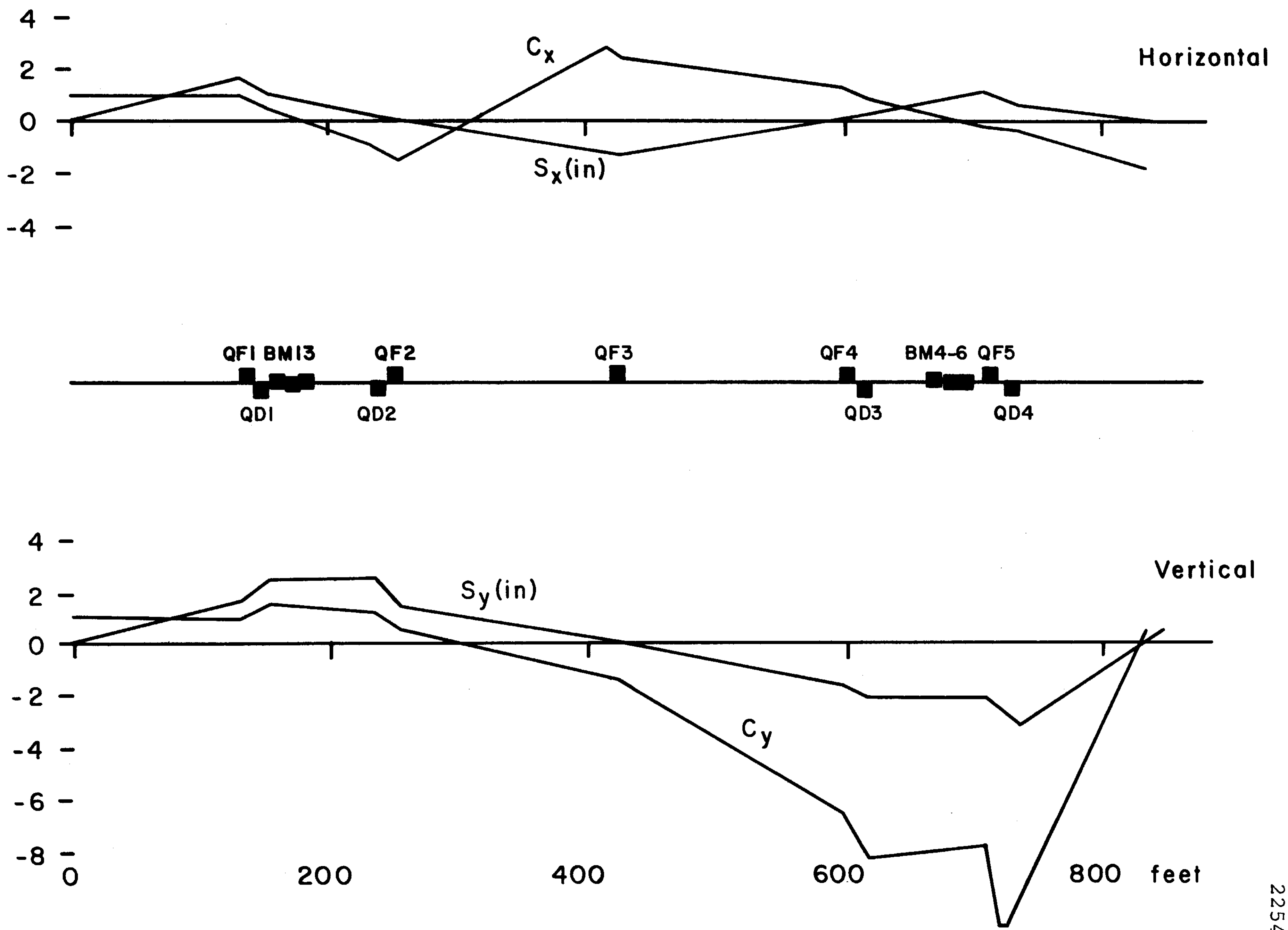


Fig. IV-4 7.5 mrad. Principal Trajectories - Tune 2

0.020 inch. The increase of effective source width due to non-zero production angle increases the horizontal emittance by nearly a factor of two and correspondingly degrades the resolution by the same factor. Thus, somewhat greater bending is needed in the 7.5 mrad beam than in the 2.5 mrad beam for example.

SUMMARY STATISTICS

Total quadrupole length	108.27'
Total bending magnet length	59.05'
Solid angle - tune 1	2 μster
- tune 2	3 μster
Total bend	8.06×10^{-2} rad
Positive yield @ 100 BeV/c (Hagedorn-Ranft) (no/3×10^{12} interacting protons/BeV/c)	2×10^{7}
Dispersion - tune 1	0.57"/%
- tune 2	1.27"/%
Resolution - tune 1	0.04%
- tune 2	0.1%
Maximum $\Delta p/p$	±1.5%

Resolution and second order effects: Second order envelope traces have been run for both tunes with $\beta = 0$, $\beta = 10^3$, and $\beta = 2\times10^4$ where β is defined by the mid-plane field expansion.

$$B_y(x) = B_0\left(1 - \frac{nx}{\rho} + \frac{\beta x^2}{2\rho^2} + \ldots\right),$$

n is the field index $\rho B_y'(0)/B_y(0)$, and ρ is the orbit radius of curvature. The horizontal half-width at the momentum slit including dispersion for these β values and $\Delta p/p = 1.5\%$ are

	Tune 1	Tune 2
$\beta = 0$:	$\sigma_x = 1.9067''$	$\sigma_x = 0.8646''$
$\beta = 10^3$:	$\sigma_x = 1.9075''$	$\sigma_x = 0.8646''$
$\beta = 2\times10^4$:	$\sigma_x = 2.2177''$	$\sigma_x = 1.022''$

Thus, for $\beta \sim 10^3$ no sextupole corrections are required. This β corresponds to $\Delta B \sim 0.05\% \ B_0$ at the edge of 5cm useful aperture, a factor of two larger than the ΔB specified for main ring magnets. Such precision in B appears within reason. When $\Delta p/p = \pm 1.5\%$, $\beta = 10^3$ gives a spot .17" wide by .29" high at the final focus for tune 1 and .63" wide by .22" high for tune 2. The focal plane tilt is 11 mrad for tune 1 and 6 mrad for tune 2.

Component misalignment: The effect of component misalignments is to put unintentional kinks in the optic axis and thus to lose some acceptance by vignetting. However, if the beam is used only to discriminate relative momentum values, the resolution is not degraded by alignment stable over the comparison interval. The assumptions that components can be positioned everywhere within about 10 mils of their ideal location and that the positioning errors are independent lead to horizontal uncertainty of the optic axis at the momentum slit of ±0.15" for tune 1 and ±0.33" for tune 2. Because the dispersions for these tunes are 1.27"/% and 0.57"/% respectively one sees that absolute momentum uncertainty is about 0.1% for tune 1 and 0.6% for tune 2.

For tune 1 aperture loss with such a tolerance is likely to be a few percent according to a TRANSPORT misalignment run. In tune 2, however, the chosen polarity of the doublets puts three vertically defocussing quads in tandem. Each one of these works to magnify previous vertical errors. Thus, in tune 2 vertical errors of order 10 mils can lead to greater than 50% aperture loss according to the TRANSPORT result.

Particle yield: The particle yield for both tunes has been calculated from Hagedorn-Ranft production curves produced by the program SPUKJ[14]. The solid angle is 2 μster for tune 1 and 3 μster for tune 2 respectively. A momentum bite of $\Delta p/p = 1\%$ was used and 3×10^{12} protons were assumed to interact in a lead target in accordance with the conventions of the beams group of the 1969 Summer Study. Kaon yields have been corrected for decay according to the length for each tune. A tabulation is given in Table IV-3 and the tune 2 results are plotted in Figure IV-5.

Operating power: The power required to run the medium energy high resolution beam at 120 BeV/c is calculated assuming high power "front-end" quads for the first doublet and septum type magnets for the three bending magnets of the first section. For the other dipoles a power conserving proposal of Billinge is used and for the other quads a scaling up to four inches of a Brobeck designed two-inch quad is used.

TABLE IV-3 PARTICLE YIELDS (in. 10^6)
(lead target, 3×10^{12} interacting protons, $\Delta p/p = 1\%$)

Tune 1 ($\Delta\Omega$ = 2 μster)

Momentum	p	π^+	π^-	k^+	k^-	$\bar{p}$
20	4.6	24	22	.32	.18	.26
40	9.8	29	24	1.3	.56	.41
60	14	23	16	1.4	.38	.23
80	16	11	7.7	1.2	.18	.086
100	14	3.3	2.4	.90	.060	.025
120	9.4	.94	.68	.28	.014	.0045

Tune 2 ($\Delta\Omega$ = 3 μster)

Momentum	p	π^+	π^-	k^+	k^-	$\bar{p}$
20	6.8	36	32	.57	.32	.40
40	15	43	36	2.2	1.0	.61
60	22	34	24	2.1	.59	.34
80	24	17	12	1.8	.28	.13
100	21	5.0	3.6	1.4	.043	.037
120	14	1.4	1.0	.43	.022	.0068

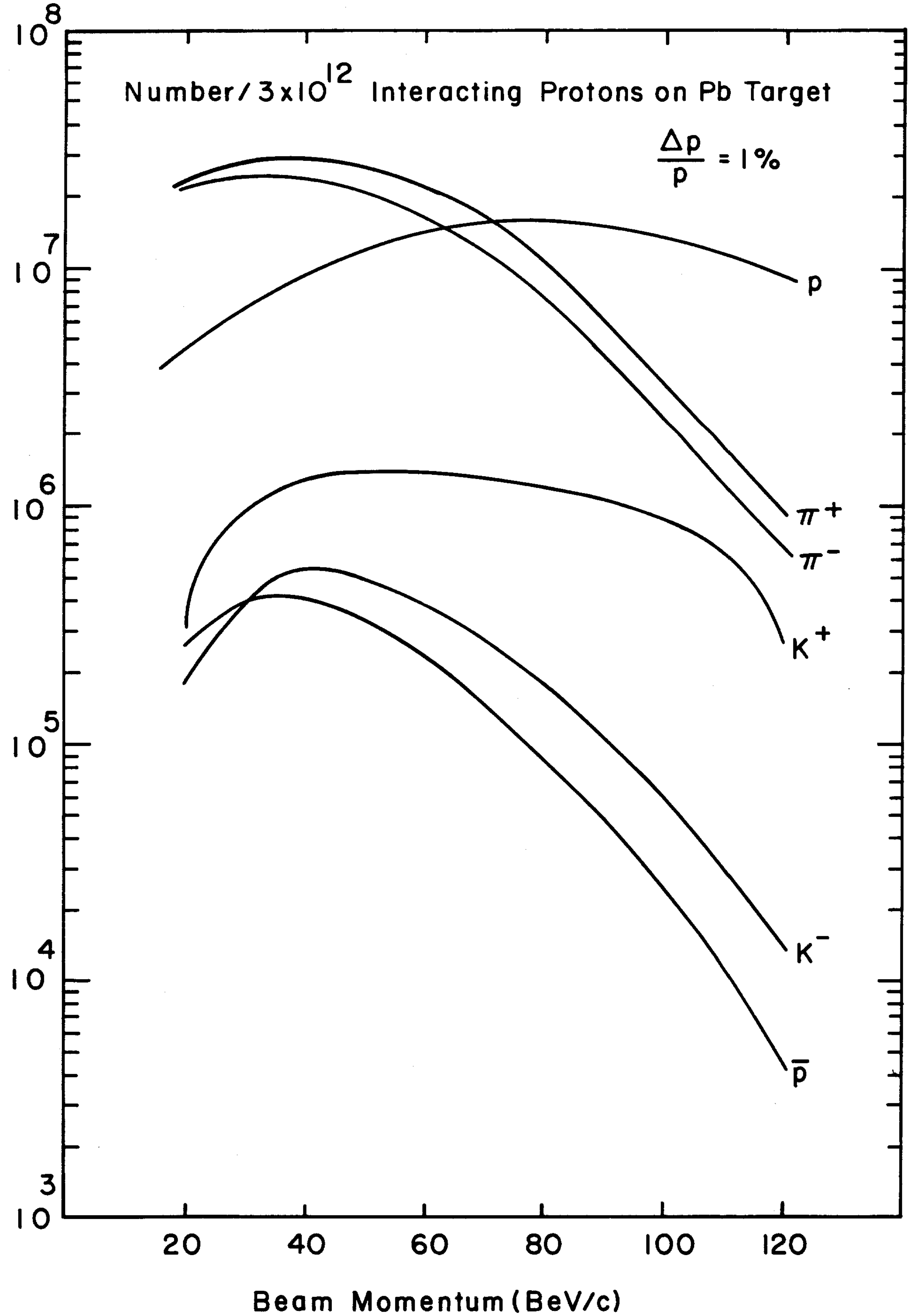


Fig. IV-5: Particle Yield 7.5 MRAD-Tune 2

The power for tune 1 is 1.5 Mw and for tune 2 is 1.7 Mw. The power to run at any other momentum is reduced by a factor of the ratio squared of the momentum to 120 BeV/c.

Concluding remarks: Certain design decisions were made in the medium energy high resolution beam for the sake of illustrating what length savings could be made in comparison to the design used for the high energy high resolution (2.5 mrad) beam. Because no thorough costing has been done the value of these savings of ∿300' is not known. For reasons of acceptance and alignment tolerance it would be preferable to run tune 2 with the DFFD polarities and lengthen the sections by about 100' each. Furthermore, it would be somewhat advantageous to increase the final doublet focal length to reduce divergence. If the cost savings from reduced beam length appear attractive the same changes of polarity could shorten the high energy beam even more.

V. HIGH INTENSITY - HIGH MOMENTUM BEAM

The 1969 Aspen Summer Study Report (SS-37) proposed a high intensity, unseparated charged beam. This beam is designated as the 3.5 mrad beam in SS-37. It was designed to be capable of transporting 200-BeV/c particles. It maximizes intensity by having a solid angle of 3.8μster and a momentum band pass of $\frac{\Delta P}{P} = \pm 5\%$. (It should be noted that the momentum of a particular particle may be determined to $\frac{\Delta P}{P} = \pm 0.2\%$ by using tagging counters. This includes second order effects.) In accordance with the design criteria of SS-37, an attempt was made to provide two experimental areas. Because of the large band pass desired, it was not feasible to put a Y in the beam as was done with the high resolution beams. Instead, it was proposed that the beam have two experimental areas in series with a set of quadrupoles between the areas to refocus the beam after it passes through the first area into the second. During the Summer Study the beam was designed using only thin lens optics. Since then first and second order TRANSPORT runs (including the effects of dipole fringe fields and finite entrance and exit for the dipole angles) have been made and a detailed design based on the Summer Study design has been completed. Because of the large momentum band pass desired, chromatic aberration in the lenses is quite important. For example, the angle between the horizontal focal plane and the beam direction at the first focus is only 3.3 mrad. This design should, therefore, be considered as only a first pass at the design of a high intensity beam.

Table V-1 lists the elements in the beam (including the dipole fields and quadrupole gradients required for transporting 200 BeV/c positive particles. Table V-2 lists the beam envelope for first order $\frac{\Delta P}{P} = 0\%$, and second order $\frac{\Delta P}{P} = \pm 5\%$, assuming a beam acceptance of ±0.03" X ±0.8mrad. horizontally, ±0.02" X ±1.2mrad. vertically. (This assumes a proton beam spot 0.04" in diameter and a 3.5mrad production angle with a 4" long target. In accordance with advice from R. Billinge, the quads are not completely filled. It is assumed that the angular acceptance of the beam is more nearly rectangular than ellipsoidal. That is, the quad field near the coils is not used, but that near the iron pole tips is assumed to be good. From inspection of the principle rays shown in Fig. V-2, one sees that by completely filling the quads it is possible to accept a solid angle of $\pi * \sim 1.0$mrad (horizontal) $* \sim 1.6$mrad vertical = 5.0μster).

Table V-2 also lists the first order transfer matrix elements (also known as the principle rays) and the only important second order matrix elements, T_{126} and T_{346}, which contain chromatic aberrations. These elements enable one to trace any ray through the system to second order. For example, a particle that left the target on the horizontal axis ($\Delta Y = 0$) but from $\Delta X = -0.01"$, with horizontal and

TABLE I

NAME	ELEMENT	Length of element in ft.	Field or gradient for 200 BeV/c positive particles	Horizontal focal length or bend	Total length (ft.)
Target	Beam spot .04"dia, acceptance ±.8 mr H ±1.2 mr V	0.33			0
	Drift	103.5'	kG/in		103.5
T1Q1	Narrow quad horizontally defocusing	10'	+6.711 kG/in	-25.58ft	113.5
	Drift	1'			114.5
T1Q2	Narrow quad horizontally focusing	10'	-6.088 kG/in	31.69ft	124.5
	Drift	1'			125.5
T1Q3	Narrow quad horizontally focusing	10'	-6.088 kG/in	31.69ft	135.5
	Drift	1'			136.5
T1Q4	Narrow quad hori.defocusing	10'	6.711 kG/in	-25.58ft.	146.5
	Drift	10'			156.5
B1	Septum dipole	10'	20.0 kG	9.14mr	166.5
	Drift	1'			167.5
B2	Septum dipole	10'	20. kG	9.14mr	177.5
	Drift	1'			178.5
B3	Septum dipole	10'	20. kG	9.14mr	188.5
	Drift	56.5			245.0
Field Lens	Low power quad	10'	-4.918 kG/in	75ft	255.0
	Drift	56.5			311.5
B4	Dipole	10'	20. kG	9.14mr	321.5
	Drift	1.			322.5
B5	Dipole	10.	20. kG	9.14mr	332.5
	Drift	1.			333.5
B6	Dipole	10.	20. kG	9.14mr	343.5
	Drift	10.			353.5
T2Q1	Quad horizontally focusing	10.	6.711	-25.58ft	363.5
	Drift	1.			364.5
T2Q2	Quad horizontally focusing	10.	-6.088 kG/in	31.69ft	374.5
	Drift	1.			375.5
T2Q3	Quad horizontally focusing	10.	-6.088	31.69ft	385.5
	Drift	1.			386.5
T2Q4	Quad horizontally defocus.	10	6.711	-25.58ft	396.5
	Drift	103.5			500.
	Drift	100.			600.
	TUNE I CONTINUATION				
T3Q1	Quad horizontally defoc.	10	+6.853 kG/in	-25.02ft	610
	Drift	1			611
T3Q2	Quad horizontally focus.	10	-6.192	31.19ft	621
	Drift	1			622
T3Q3	Quad horizontally focus.	10	-6.192	31.19ft	632
	Drift	1			633
T3Q4	Quad horizontally defoc.	10	6.853	-25.02ft	643
	Drift	100			743

TUNE II CONTINUATION

T3Q1	Quad horizontally defocus.	10	5.821	-29.73ft	610
	Drift	1			611
T3Q2	Quad horizontally focus.	10	-5.399	35.51ft	621
	Drift	1			622
T3Q3	Quad horizontally focus.	10	-5.399	35.51ft	632
	Drift	1			633
T3Q4	Quad horizontally defocus.	10	5.821	29.73ft	643
	Drift	200			843
	Drift	100			943
T4Q1	Quad horizontally defocus.	10	6.185	-27.89ft	953
	Drift	1			954
T4Q2	Quad horizontally focus.	10	-5.686	33.81	964
	Drift	1			965
T4Q3	Quad horizontally focus.	10	-5.686	33.81	975
	Drift	1			976
T4Q4	Quad horizontally defocus.	10	6.185	-27.89	986
	Drift	150			1136

TABLE II

ℓ	Beam Envelope 1st Order $\frac{\Delta P}{P} = 0\%$ x	y	2nd Order $\frac{\Delta P}{P} = \pm 5\%$ x	y	Pinciple Rays Horizontal cos R_{11}	sin R_{12}	Vertical cos R_{33}	sin R_{34}	Dis-per-sion R_{16}	Second Order T_{126}	T_{346}
0	.03	.02	.03	.02	1	0	1	0	0	0	0
103.5	.99	1.55			1	1.24	1	1.24	0	0	0
113.5	1.28	1.42	Same		1.19	1.61	.82	1.13	-	-.003	+.002
124.5	1.59	1.17	as		1.40	2.00	.56	.94	-	-.005	+.006
135.5	1.34	1.38	1st order		1.11	1.67	.50	1.10	-	+.002	+.008
146.5	.99	1.55	except		.74	1.24	.46	1.24	-	+.010	+.010
156.5	.90	1.40	for		.57	1.12	.32	1.12	.00	+.017	+.013
166.5	.80	1.26	effect of momentum		.41	1.00	.18	1.00	+.01	+.024	+.015
177.5	.70	1.09	dispersion		.22	.87	.02	.87	+.02	+.031	+.018
188.5	.59	.93	.67	.93	.04	.74	-.13	.74	+.05	+.039	+.021
245.0	.06	.08	1.23	.24	-.91	+.06	-.93	+.06	+.24	+.076	+.036
250.0	.03	.02	1.27	.24	-.97	.00	-1.02	.00	+.25	+.077	+.039
255.0	.06	.07	1.23	.28	-	-	-	-	+.24	-	-
311.5	.59	.91	.66	1.17	-.45	-.74	-3.58	-.72	+.05	-.006	+.118
321.5	.69	1.06	.72	1.34	-.36	-.86	-4.00	-.84	+.03	-.019	+.131
332.5	.79	1.22	.83	1.52	-.26	-.99	-4.47	-.97	+.01	-.035	+.145
343.5	.90	1.38	.94	1.71	-.16	-1.12	-4.93	-1.10	.00	-.050	+.160
353.5	1.00	1.53	1.05	1.88	-.07	-1.24	-5.35	-1.22	-	-.064	+.173
363.5	1.29	1.40	1.37	1.63	+.01	-1.61	-4.79	-1.12	-	-.088	+.152
374.5	1.60	1.16	1.70	1.33	+.09	-1.99	-3.84	-.92	-	-.114	+.117
385.5	1.34	1.36	1.44	1.53	+.14	-1.67	-4.35	-1.08	-	-.106	+.131
396.5	1.00	1.53	1.09	1.78	+.19	-1.24	-4.80	-1.22	-	-.095	+.142
500.	.03	.02	.64	.46	+1.00	.00	+1.01	.00	-	-.160	-.074
600.	.96	1.48	1.33	2.30	1.78	1.20	6.62	1.18	-	-.223	-.284

TABLE II. TUNE I CONTINUATION

ℓ	x	y	x	y	R_{11}	R_{12}	R_{33}	R_{34}	T_{126}	T_{346}
600	.96	1.48	1.33	2.30	1.78	1.20	6.62	1.18	-.223	-.284
610	1.25	1.35	1.69	2.00	2.21	1.56	5.95	1.08	-.275	-.250
621	1.56	1.12	2.07	1.58	2.68	1.94	4.78	.89	-.331	-.193
632	1.30	1.31	1.69	1.80	2.17	1.62	5.46	1.05	-.261	-.214
643	.96	1.48	1.20	2.00	1.52	1.20	6.05	1.18	-.170	-.232
654	.86	1.32	1.01	1.73	1.24	1.07	5.28	1.05	-.125	-.194
743	.03	.02	.95	.66	-1.00	.00	-1.01	.00	+.238	+.110

TUNE II CONTINUATION

ℓ	x	y	x	y	R_{11}	R_{12}	R_{33}	R_{34}	T_{126}	T_{346}
600	.96	1.47	1.33	2.30	1.78	1.20	6.62	1.18	-.223	-.284
610	1.22	1.38	1.65	2.12	2.16	1.52	6.08	1.10	-.268	-.257
621	1.49	1.22	1.99	1.81	2.56	1.86	5.24	.97	-.317	-.214
632	1.29	1.46	1.68	2.12	2.16	1.61	6.15	1.16	-.259	-.246
643	1.03	1.69	1.29	2.41	1.63	1.29	6.99	1.34	-.185	-.276
654	.97	1.59	1.17	2.24	1.44	1.21	6.51	1.27	-.153	-.251
843	.06	.04	1.62	1.16	-1.87	.00	-1.78	.00	+.405	+.185
943	.53	.85	2.85	2.737	-3.62	-.64	-6.18	-.67	+.701	+.416
953	.67	.77	3.49	2.43	-4.43	-.82	-5.57	-.62	+.855	+.368
964	.83	.68	4.18	1.95	-5.31	-1.01	-4.58	-.54	+1.02	+.292
975	.707	.811	3.457	2.167	-4.42	-.87	-5.21	-.64	+.845	+.321
986	.55	.93	2.529	2.369	-3.27	-.67	-5.78	-.74	+.616	+.348
1136	.080	.049	2.521	1.745	+2.67	.00	+2.44	.00	-.630	-.279

vertical angles of +0.5 and -0.3mrad, with 1% less than nominal momentum, will, at 500 ft from the target, pass through the point

$$X = X_oR_{11} + X_o'R_{12} + X_o' \delta(= \frac{\Delta P}{P}) \; T_{126} = (-0.01).(1.0)$$

$$+(0.15).(.00) + (0.5).(-0.1)(-0.160) = +0.07";$$

$$Y = Y_oR_{33} + Y_o'R_{33} + Y_o'R_{34} + Y_o' \; \delta T_{346} = -0.02".$$

Figures V-1 and V-2 illustrate the elements, the beam envelope and the principle rays. Note that both vertical and horizontal cos rays have been scaled down by a factor of 2. The drift distance from the target to the first quadrupole was minimized within the constraint of physically fitting the beams of SS-37 around a single target. The first four quadrupoles are operated as a symmetric triplet; that is, the first and fourth have equal gradients and are horizontally diverging, the second and third have equal gradients and are horizontally converging. If one tries to replace this triplet of four quads with a doublet of two quads, achieving the necessary focusing requires separating the quads by ∿10 feet which results in approximately a ∿25% loss in solid angle. This may not be desirable in a beam that is trying to maximize intensity.

Note that operating four quads as a symmetric triplet with the outer two and the inner two in series requires only two power supplies, each having twice the capacity of single quad power supplies. This mode of operation

Beam Envelope Fortune I

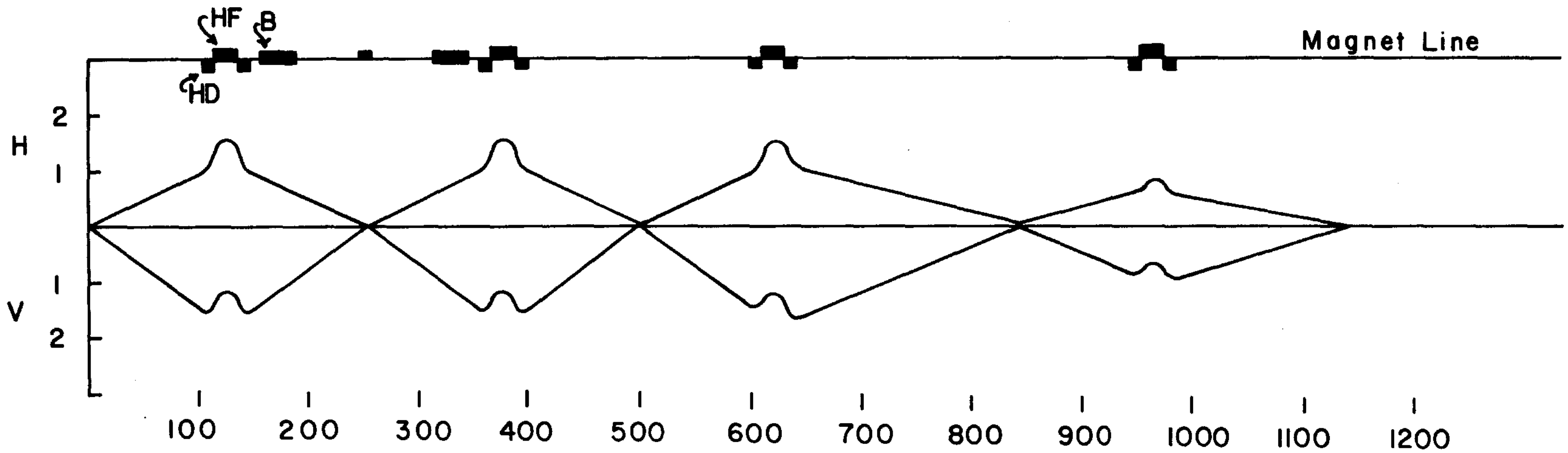


Fig. V-1 Magnet Line and Beam Envelope for Tunes I and II

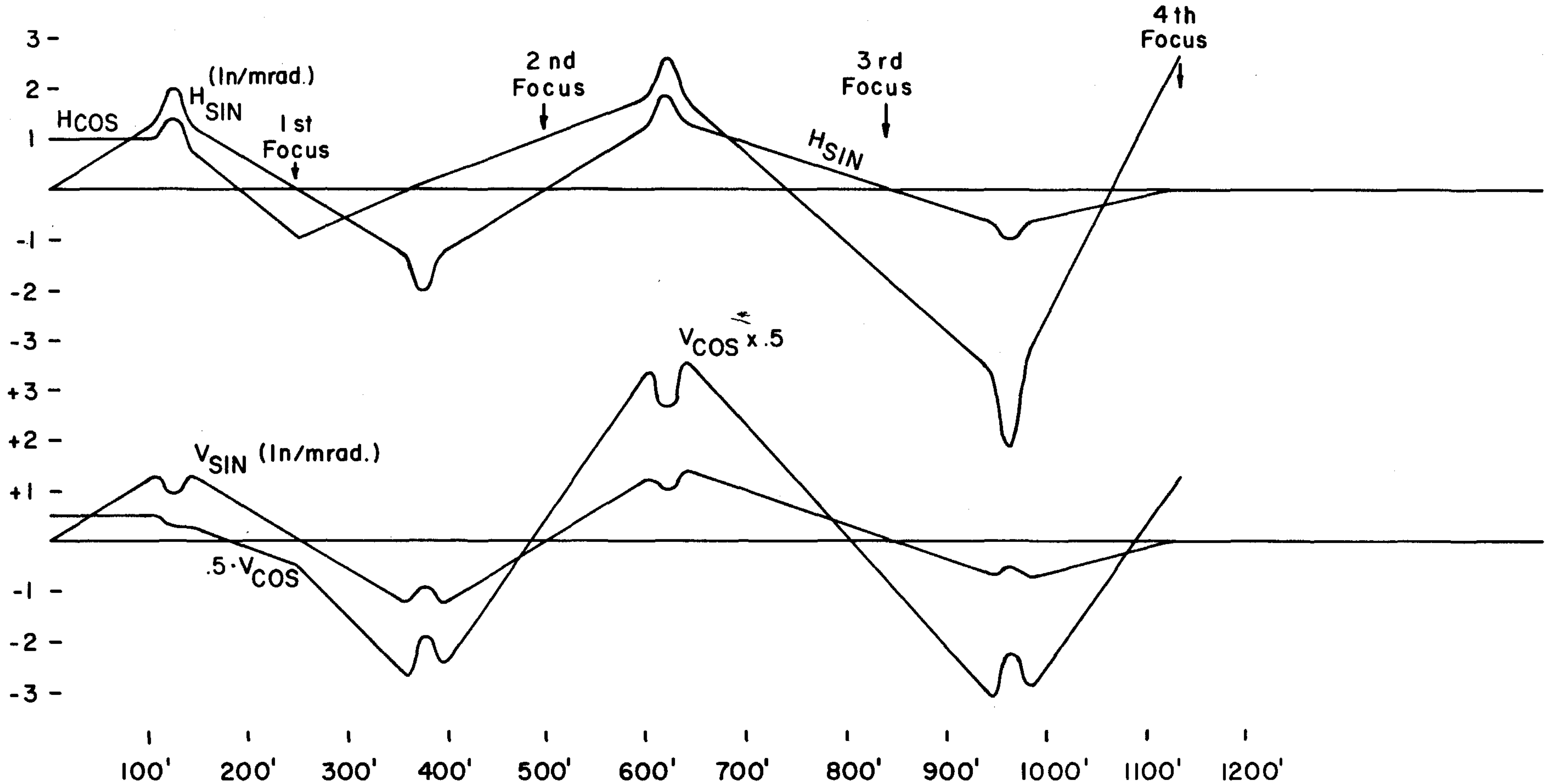


Fig. V- 2b Principle Rays for Tune II (Note: COS-like rays are scaled by a factor of .5) can effect a considerable ($\geq$25%) savings in cost for power supplies.

This first triplet produces point-to-point focusing in both the horizontal and vertical planes from the target to a momentum slit located 250' from the target.

Ten feet after the end of the triplet are three septum dipoles which bend the beam away from the area center-line and provide momentum dispersion. Thus 250' from the target there are horizontal and vertical foci with magnifications of 1. The horizontal dispersion at this point is 0.247"/%.

Centered about this point is a field lens which is horizontally converging. Because of the foci at its center it is very nearly decoupled from the geometric optics of the system and acts in momentum space to provide point-to-point focusing from the first set of bending magnets into a second identical set. Complete momentum recombination in both position and angle is provided in this way.

Beyond the second set of bending magnets is a second symmetric triplet which is optically identical to the first. (It does not need to consist of narrow quads, however). It provides point-to-point focusing from the momentum slit 250' from the target onto clean-up slits located 500' from the target. This second focus could be used as an experimental area for P, π^+, π^-, K^+, K^-, or $\bar{P}$ physics. Figures V-3 and

V-4 illustrate the flux possible with this beam. Following the procedure of D.Reeder, we find a flux of 2.0 × 10" diffracted 200 BeV/c protons, (assuming a 10cm target length.) Because of the high intensity of this beam, it would be difficult to use scintillation counters or threshold Cerenkov counters that count most of the beam. However, one should note that between the second and third quads of the second triplet, the horizontal divergence of the beam is ±0.241mrad, the vertical divergence is ±0.358mrad. (These numbers are second order with no sextupole elements). One could thus use a differential Cerenkov counter of the H. White design[15] to distinguish the K's in the beam from the π's and p's or $\bar{p}$'s at 100 BeV/c. The resolution of such a counter is good enough that the wide momentum band pass still leaves a 2mrad separation between π and K light rays in the worst case. That is, with the H. White design kaons have a Cerenkov angle of 10mrad with a half-width of 1mrad; pions have a Cerenkov angle of 14mrad, also with a half-width of 1mrad. These half-widths include the effects of beam divergence and momentum band pass.

From Fig. V-3 it can be seen that one can get $3.6 * 10^6$ K^-'s at 100 BeV/c. Including second order effects (mainly chromatic aberrations in the quads) one can get a spot at 500' from the target with a full horizontal width of 1.28" and a full height of 0.89" for a ±5% momentum bite.

3×10^{12} Interacting Protons on Pb, 3.8μster about 3.5m. $\Delta p/p = \pm 5\%$ ● $\bar{p}$, ◆ π^-, ■ K^-

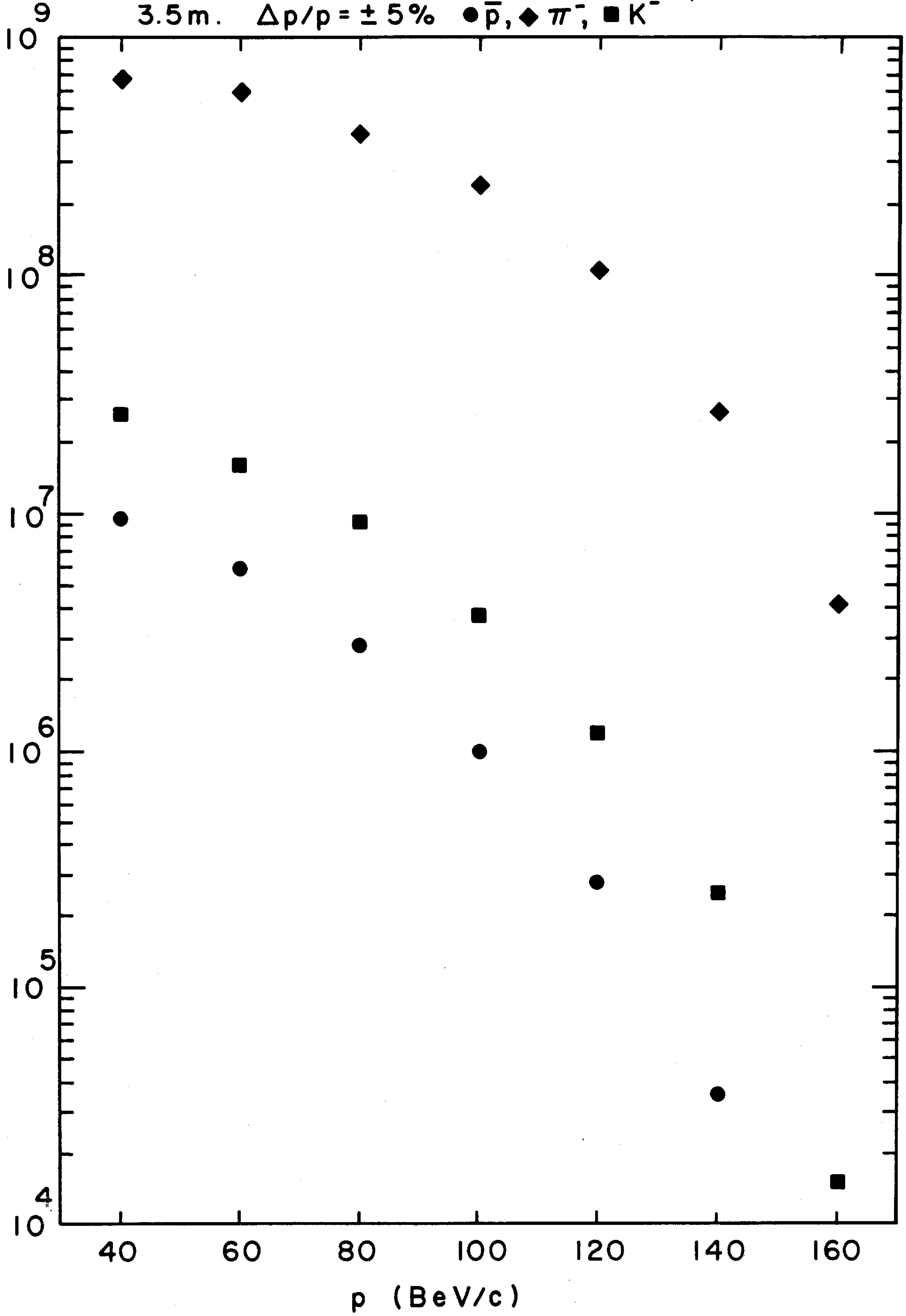


Fig. V-3

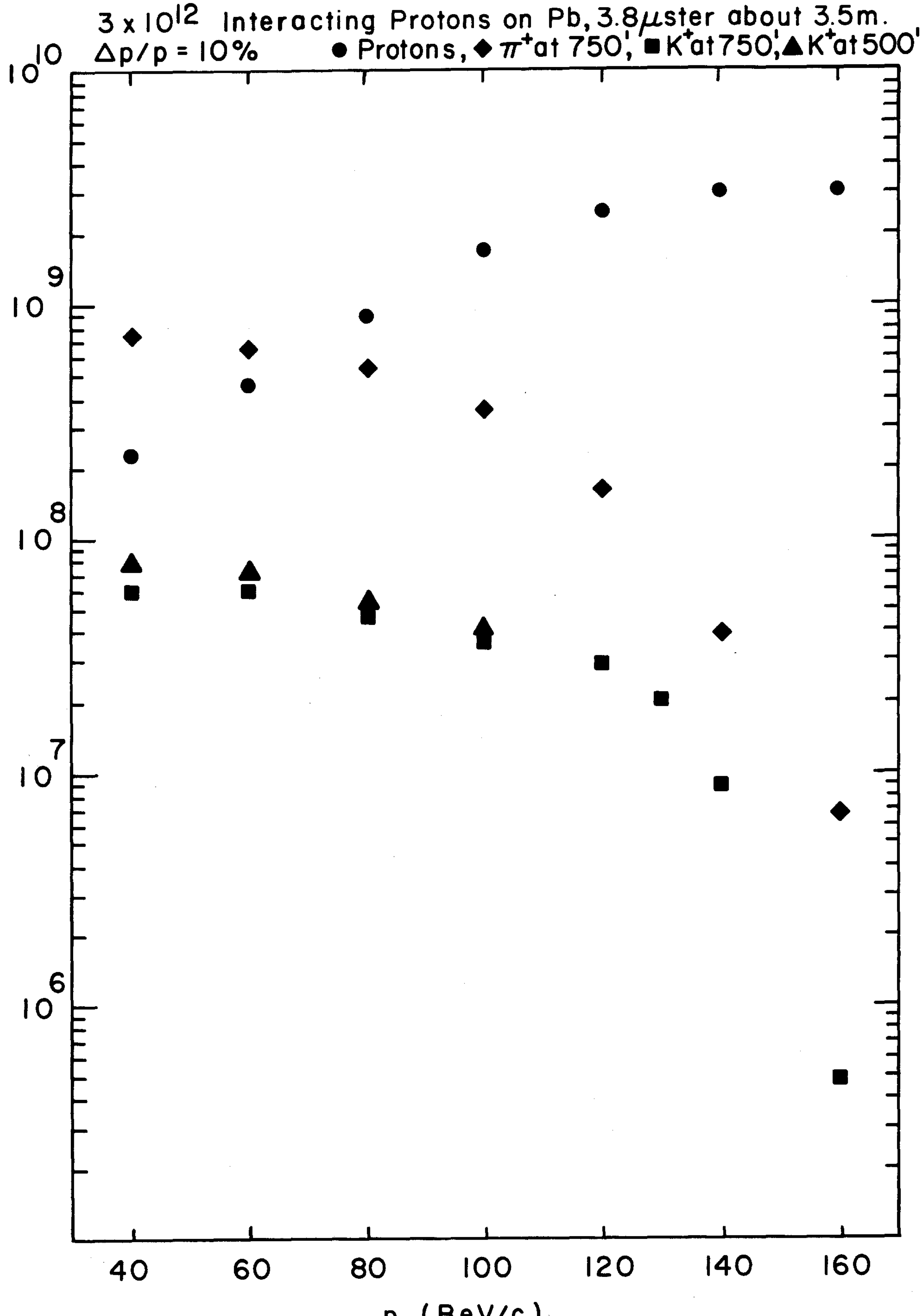

3 x 10^12 Interacting Protons on Pb, 3.8 μster about 3.5m.
Δp/p = 10%
● Protons, ◆ π+ at 750', ■ K+ at 750', ▲ K+ at 500'
10^10
10^9
10^8
10^7
10^6
40
60
80
100
120
140
160
p (BeV/c)

Fig. V-4

This spot size is almost entirely second order and goes to full widths of 0.06" horizontal * 0.04" vertical linearly as the momentum bite goes to 0.

For the more esoteric uses of this beam, such as for production of a K_L^o beam or as an electron beam, horizontal and vertical slits would be placed at this second focus to clean up the beam. Beyond this focus is another symmetric triplet of four quads which in Tune I produces a third vertical and horizontal focus at 743' from the target. This was considered to be the prime experimental area in SS-37. The first order magnifications are essentially 1 in both horizontal and vertical planes and the ±5% ΔP/P spot size including second order terms is ±0.95" horizontally, ±0.66" vertically.

The K_L^o beam[16] could be produced for use in this area from a 100 BeV/c negative beam by putting a high Z target (lead, for example) at this focus, and putting ∿20' of 20 kilogauss sweeping magnet just after the target.

At 30' (40") from the target the K^o beam would be inside a 9" (11") diameter circle and all charged particles would be outside a 17" (25") diameter circle. The K^o spectrum was calculated in SS-29. For the present design the total area under the curve should be 7000/pulse.

Note that in Barish's original design[17], K^o production target was placed between the middle two quads of the third triplet. The beam is parallel here but it is not clear how this helps. There is a clear problem in that the beam is large here and the last two quads, unless removed, would act as solid angle collimators, as well as forcing the sweeping magnet further downstream from the production target. The net result would appear to be placing the experimental target (or detection apparatus) at least twice as far from the K^o production target. The loss in total flux might be about a factor of 2 from decreased effective solid angle while the beam spot area would increase by a factor of 4. One should note that 10% of 100 BeV/c K_S^o remain at 40' while only 1% remain at 80'. Thus a larger distance from production target to experimental apparatus may be desirable if a particular experiment desires only K_L^o .)

An electron (or tagged photon) beam could be produced using this beam with the addition of a vertical sweeping magnet between the primary target (which one would like to be beryllium for an electron beam) and the first quad. One also requires a lead converter just before the first quad. Diebold and Hand[18] (SS-49) propose that this magnet have BL $\geq$20 kilogauss-meters. In their design it would be 10m × 2kG, would require $\simeq$50kW of power and water cooling. The electrons are produced in the lead converter by γ rays from π^o decays, the π^o's having been produced in the primary target. Because of the small momentum transfer in these processes, the electrons produced in the lead converter appear to come from the primary target, whereas mesons produced by neutrons appear to come from a target $\sim$50 times as large. Most of these can thus be eliminated in cleanup slits. Note that Diebold and Hand use only a ±2% momentum bite. Thus, chromatic aberrations lead to the spot at the second focus having a full height of 0.36". Diebold and Hand calculate that the size of the electron beam would be 0.36" full height in first order because of the increased effective target size, this, in turn, being due to the electron production process.

For Tune II the third triplet is retuned to produce horizontal and vertical foci at 843' from the target with a horizontal magnification of 1.87, a vertical magnification of 1.78. If desired, one could put cleanup slits at this point, but because of higher order effects the spot size will be so large (∿3.2" wide by 2.3" high for the full 10% momentum bite) that slits may not do much. A fourth triplet centered about a point 965' from the target produces a fourth double focus 1136' from the target with a horizontal magnification of 2.68, a vertical magnification of 2.44.

These magnifications can be changed continuously to magnifications of about 0.6 by moving the intermediate focus closer to the third triplet. (That is, by changing the quadrupole gradients but not their positions).

Table V-3 gives the power required for the beam when tuned to 200 BeV/c particles. The front end (up to the field lens) requires 2480 kilowatts, the second section (to the second focus) requires 515 kilowatts, the Tune I continuation requires

TABLE V-3

Element	200BeV/c Field or Gradient	Power kW	Type
T1Q1	6.7112	400	Danby
T1Q2	6.0879	330	"
T1Q3	6.0879	330	"
T1Q4	6.7112	400	"
B1	20	340	Septum
B2	20	340	"
B3	20	340	"
		2480	
FLD	4.918	43	Low Power
B4	20	60	"
B5	20	60	"
B6	20	60	"
T2Q1	6.7112	80	"
T2Q2	6.0879	66	"
T2Q3	6.0879	66	"
T2Q4	6.7112	80	"
		515	
Tune 1			
T3Q1	6.8533	84	Low Power
T3Q2	6.1919	68	"
T3Q3	6.1919	68	"
T3Q4	6.8533	84	"
		304	
Tune 2			
T3Q1	5.8205	60	Low Power
T3Q2	5.3989	52	"
T3Q3	5.3989	52	"
T3Q4	5.8205	60	"
T4Q1	6.1847	68	"
T4Q2	5.6855	57	"
T4Q3	5.6855	57	"
T4Q4	6.1847	68	"
		474	

an additional 304 kilowatts while the Tune II continuation requires 474 kilowatts. Thus in Tune I the beam requires 3.30 megawatts, as opposed to 3.47 for Tune II.

In conclusion, this beam design is certainly feasible but probably not optimal. In particular, this design provides no good place to put sextupole correcting elements. (They would do as much harm to one plane as good to the other). It also requires a large number (17) of quadrupoles.

It appears possible to design this beam using doublets instead of symmetric triplets. This could cut the number of quadrupoles needed almost in half while reducing the particle flux by about 25%. Also, at K. Brown's suggestion, it appears useful to have the first horizontal and vertical foci at different positions along the beam line. This would provide places where sextupoles could correct chromatic aberrations in one plane without coupling as strongly to the other plane.

VI. ABERRATIONS DUE TO QUADRUPOLES

In the case of bending magnets the next higher field correction beyond the dipole contribution, that is, the sextupole term, can be treated directly with a second order TRANSPORT run. This is not true, however, for quadrupoles. The next highest field term for a 4-pole magnet with reflection symmetry in the x = 0 and y = 0 planes is a dodecupole term, ϕ_6. Experience has shown that it is practical to maintain symmetry sufficient to suppress the octupole term, ϕ_4,which arises when there is a single symmetry plane. To determine the effect of the dodecupole term, it is necessary to expand the orbit equation and evaluate the contribution directly. In turn, this can be used to set a limit on field quality for quadrupoles. In particular, it is necessary to study this question when considering possible apertures for quadrupoles.

Deviations of a quadrupole system from first order optics may be classified as

1. Chromatic aberration
2. Field error or higher order multipole terms
3. Kinematic or geometric aberration

These aberrations are, in general, important in the order named. The leading terms of each type can be separated out by expanding the magnetic field in multipoles and orbit coordinates in power series as done below.[19]

The orbit Lagrangian in the absence of bending magnets is

$$L = \sqrt{1 + x'^2 + y'^2} + \frac{e}{pc} A_z$$

where z = 0 is the optic axis, (x, y, z) is a cartesian coordinate system, x' = dx/dz, and A_z is the z component of the vector potential. The orbit equations may be written

$$(x' \cos\alpha)' + \frac{e}{pc} B_y = 0$$

$$(y' \cos\alpha)' - \frac{e}{pc} B_x = 0$$

where $\cos\alpha = dz/ds = 1/\sqrt{1 + x'^2 + y'^2}$ and α is the angle between the orbit and the optic axis. If one introduces a multipole expansion for B and expands cosα, the x equation becomes

$$x'' + 2\frac{e}{pc} \phi_2 x = \frac{e}{pc} \frac{\Delta p}{p} \left(1 - \frac{\Delta p}{p} + \ldots\right)(2\phi_2 x + 6\phi_6 X0 \ (x^5) + \ldots)$$

$$- \frac{e}{pc} (6\phi_6 .0 \ (x^5) + 10\phi_{10} .0 \ (x^9) + \ldots)$$

$$+ x' \left(\frac{1}{2} \alpha^2 - \frac{1}{24} \alpha^4 + \ldots\right)'$$

Perfect symmetry in the quadrupole magnet has been assumed to eliminate the ϕ_3, ϕ_4, and ϕ_5 field error terms. The term on the right-hand side on the first line contains the chromatic aberration, the second line the pure field error terms, and the third line the geometric aberrations. The two terms on the left-hand side are of the same order; if this order is defined as order = 1 the leading terms of each type have the order chromatic aberration $\Delta p/p$

dodecupole field error $\phi_6 \; x^4/\phi_2$

geometric aberration α^2

For the high resolution beams considered by NAL $\Delta p/p \gtrsim 10^{-4}$. Quadrupoles with $\phi_6/\phi_2 \simeq 10^{-7} cm^{-4}$ can be achieved with precision (but not extraordinary) machining techniques and shimming. This would require holding the circular iron pole tips to a transverse tolerance of $\simeq \pm$ 0.1 mil. This should be contrasted to stamping tolerances of $\pm$ 0.5 mil, copper conductor location tolerances of $\sim \pm$ 1 mil, and even poorer tolerances for superconductors current location due to flux jumping. In practice Argonne has achieved $\phi_6/\phi_2 \simeq 10^{-6}$ with machined poleface magnets. Because x = 2 to 4 cm is typical in secondary beams, aberrations from field error are $\lesssim 10^{-4}$. Thus, if the horizontal chromatic aberration is carefully corrected by sextupole elements one might wish to use considerable care in quadrupole design to push dodecupole contributions down to $\sim 10^{-5}$. Typical values for the angle α are 1 to perhaps 5 mrad at the most; therefore, geometric aberrations are $\sim 10^{-5}$. Then, if dodecupole errors are held to 10^{-5}, chromatic aberrations could be corrected by nearly a factor of ten before other aberrations become significant. When one is running with a large momentum bite and tagging momenta with counters, correcting sextupoles may be useful to eliminate linear chromatic aberration. In many beam designs, however, it is practical to set the tagging counters in the true focal plane to remove the first order $\Delta p/p$ term.

It appears mechanically practical to maintain the symmetry which suppresses lower multipole contributions. Quadrupole precision of the order discussed has, however, strong implications for area design. One cannot limit dodecupole error without devoting aperture to shimming and avoiding high pole tip fields. Thus, maximum gradients are somewhat limited and over-all magnet width must be increased to give the extra aperture. For example, a quad with a pole tip radius of two inches must have about 1.5 in. clearance between the coil and the useful field on each side. These 3 in. plus the copper for the excitation must be added to the magnet width. Furthermore, assymetric designs such as that suggested for the front end quadrupoles by the 1969 Summer Study have an octupole term to contend with. To shim this out over the desired excitation range of 10:1 is an extremely difficult task.

The dodecupole field error would appear to have profound implications for precision beams using superconducting quadrupoles where the field is determined primarily by the conductors. ϕ_6/ϕ_2 would rapidly approach the magnitude of the zero order solution. Measurements of the term might be quite difficult. Twelve pole correcting elements would be complicated to construct. The flux jump phenomena might require a measurement and correction each time the current was changed.

VII. BEAM TUNING AND INSTRUMENTATION

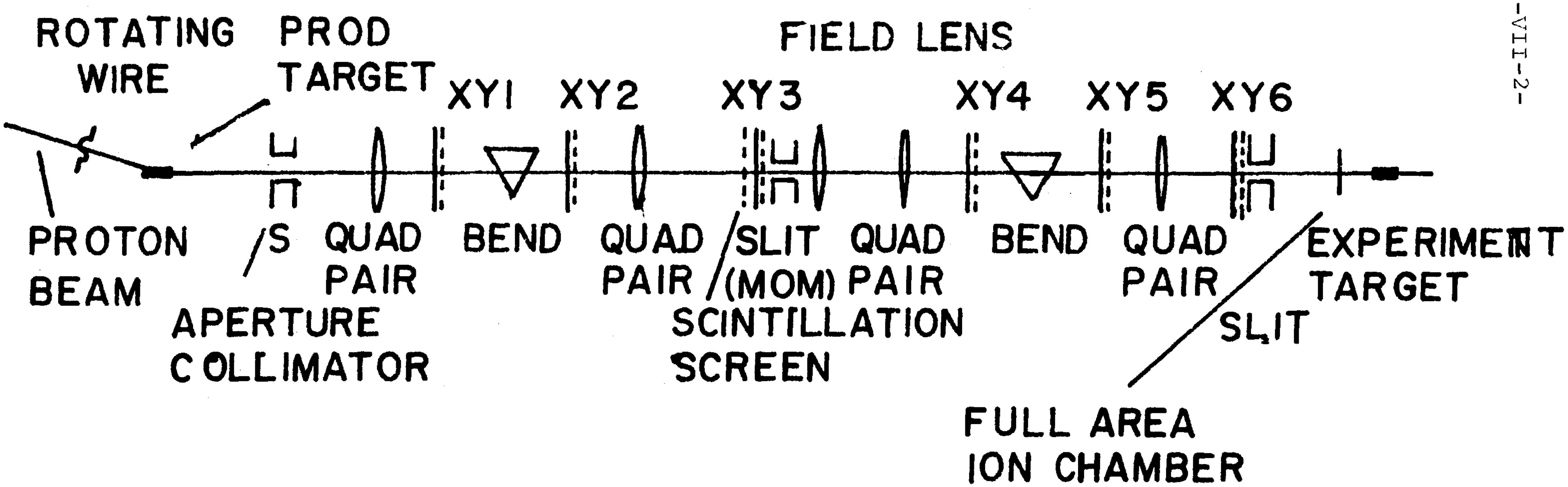
Introduction: The requirements for beam instrumentation fall into two somewhat distinct categories, beam tuning and beam operation. Beam tuning instrumentation includes devices such as scintillation screens to measure the beam properties, while operational devices might be instruments like Cerenkov counters. Beam tuning can be further broken down into actually tuning the beam and searching for sources of beam halos.

Intensity control for the beams can be provided by changing the target thickness (thus affecting other users), changing the aperture collimator, changing the momentum bite, or introducing multiple scattering. None of these is entirely satisfactory since each one also changes the beam envelope. Figure I-1 (prepared in cooperation with M. Atac and K. Pretzl) shows the instrumentation required in a typical beam. The x,y extent of the beam can be monitored using multi-element ion chambers. Typically x,y 1 might be 10 cm wide and have 20 elements. Measurements of the slope of the particle trajectories or xy correlations require either coincidence techniques or two dimensional screens (scintillation screens, polaroid film, etc.). There are several situations where such measurements will be extremely useful.

A rotating corkscrew wire upstream of the target can be used to monitor the primary beam size in both

FIG VII-1

BEAM INSTRUMENTATION
FOR HIGH RES. BEAM



XY ARE STRIP ION CHAMBERS

TM-223
2254

dimensions. At least one normal ion chamber intercepting the entire beam should be provided for absolution normalization.

In most cases, it is desirable for these devices to be remotely removable from the beam so that multiple scattering can be minimized. In addition, arrangements should be available to allow the introduction of polaroid film into the beam at a number of points.

The discussion that follows centers on the requirements for spatial resolution for tuning while generally ignoring the specific character of the elements.

The presence of a spectrum of beam momenta complicates the tuning process. Thus, the first section of a beam may be more difficult to tune. An illustration of this is the tune of the bending magnets. The dispersion of the 2.5 mrad beam is 4.6cm/1% momentum change. Thus a 0.1% current change will move the beam centroid 0.46cm at the focal plane. But actually the momentum slit will be illuminated with a very wide band of momenta so that there is no characteristic momentum except as established by the quadrupole tune. This problem is much less difficult in the second section. Certain features of the beam optics, such as chromatic aberration, can be used to ameliorate this problem.

Consider the tune of the initial quadrupole lens in the beam. A change of the gradient in this quadrupole changes the spot size after the quadrupole (a large spot), the parallelism of the rays after the quadrupole and the spot size at the focus (a small spot). However, the spot size at the focus is also changed by the second quadrupole pair so that it is not possible to directly understand which quadrupole is not properly set.

Near tune a 1% change in the current in the quadrupole will change the spot size directly after the quadrupole by approximately 1%, so that the spot size might increase from 10cm to 10.1cm. The slope of a characteristic ray which should be zero will also change. Figure VII-2 shows the change of the absolute value of the slope as a function of the gradient for the second quadrupole singlet. From this it is possible to infer that two spot measurements separated by 10m will show a size change of 0.3mm for a 1% gradient change. This is probably not possible to measure. Similarly, two scintillators 1mm wide and 10m apart in coincidence could only set the gradient to 3%. Also shown on the figure are the limitations on measuring slopes due to finite target size and multiple scattering.

A third technique is to observe the spot at the focal plane. Figure VII-3a shows the spot half size (zero target size) as a function of gradient (for the third quad singlet). Target spot size and measurement errors limit the measurements to about ±1mm. In turn, this means that the gradients can be set by this technique to about 1%. When

FIG VII-2 SLOPE VS GRADIENT
POINT TARGET - 2ND QUAD SINGLET

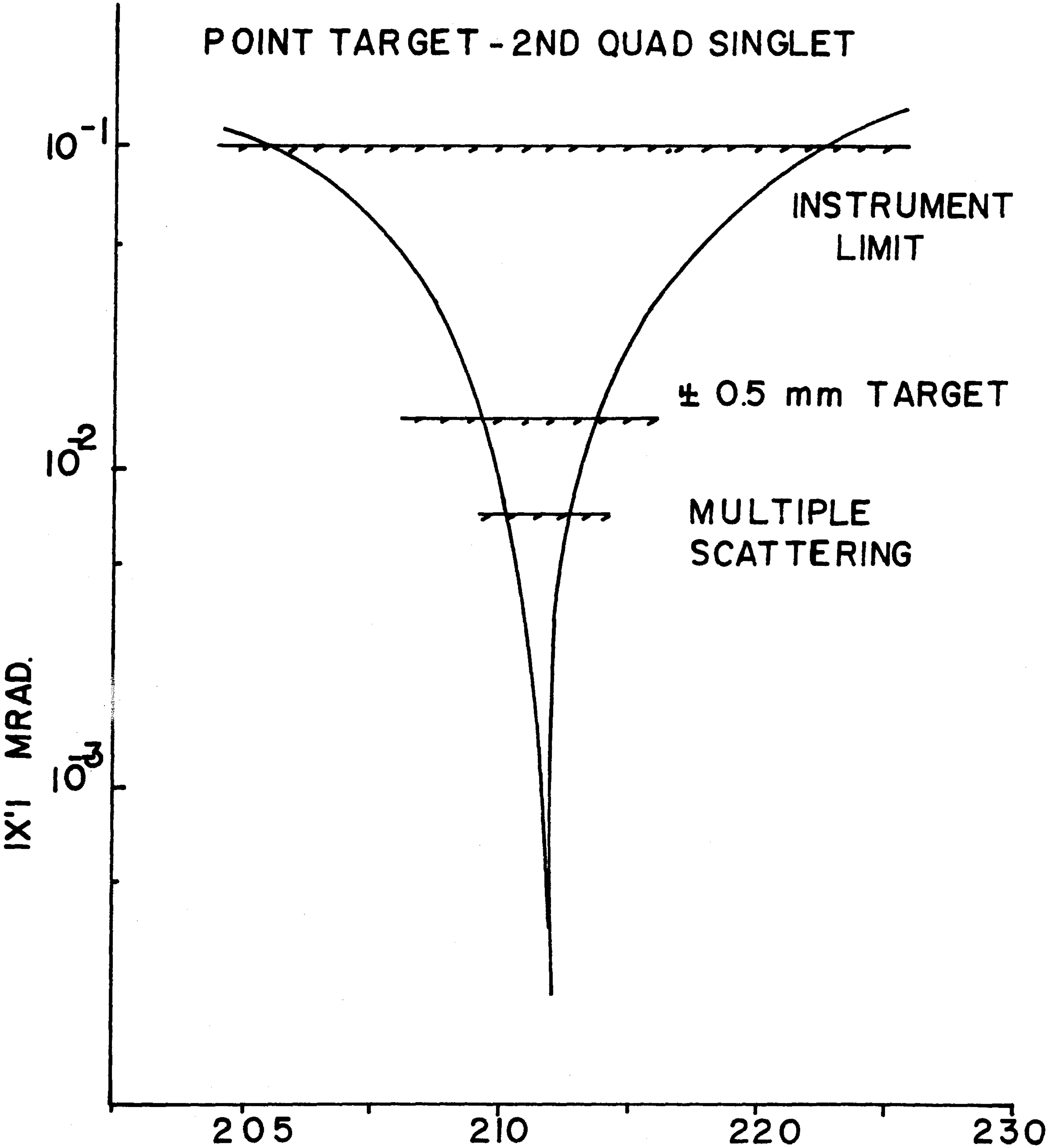


FIG VII-3a SPOT SIZE VS GRAD.
3RD QUAD SINGLET (2.5 MRAD)

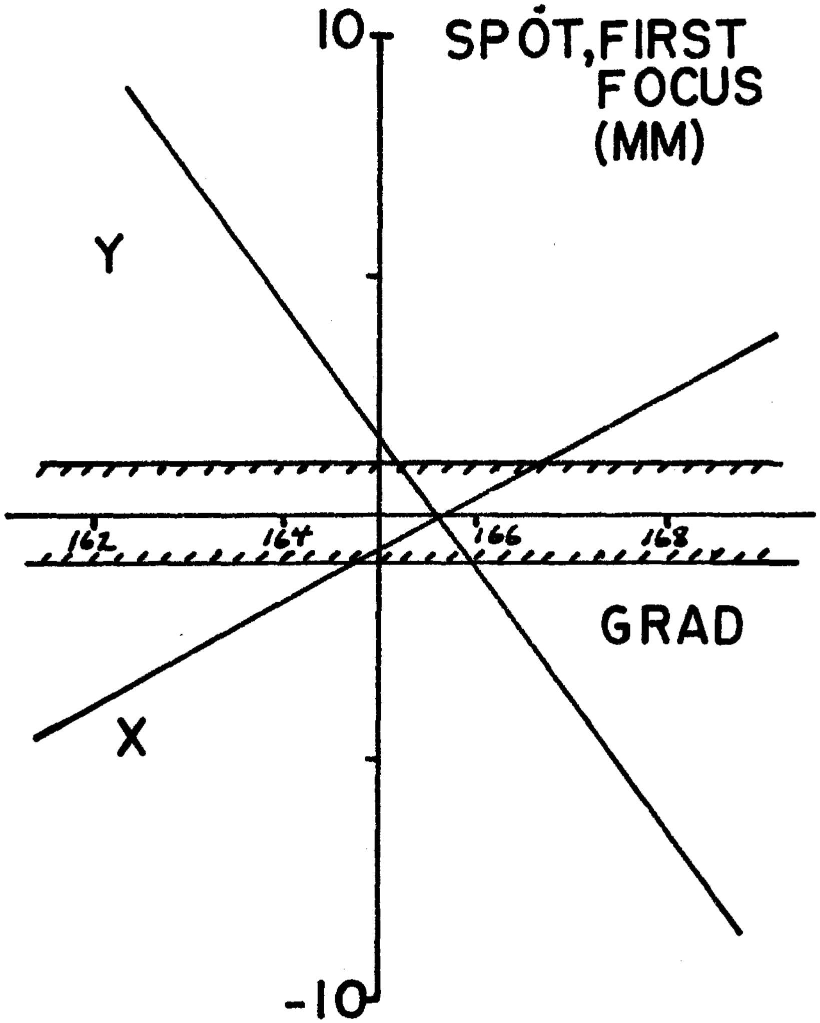
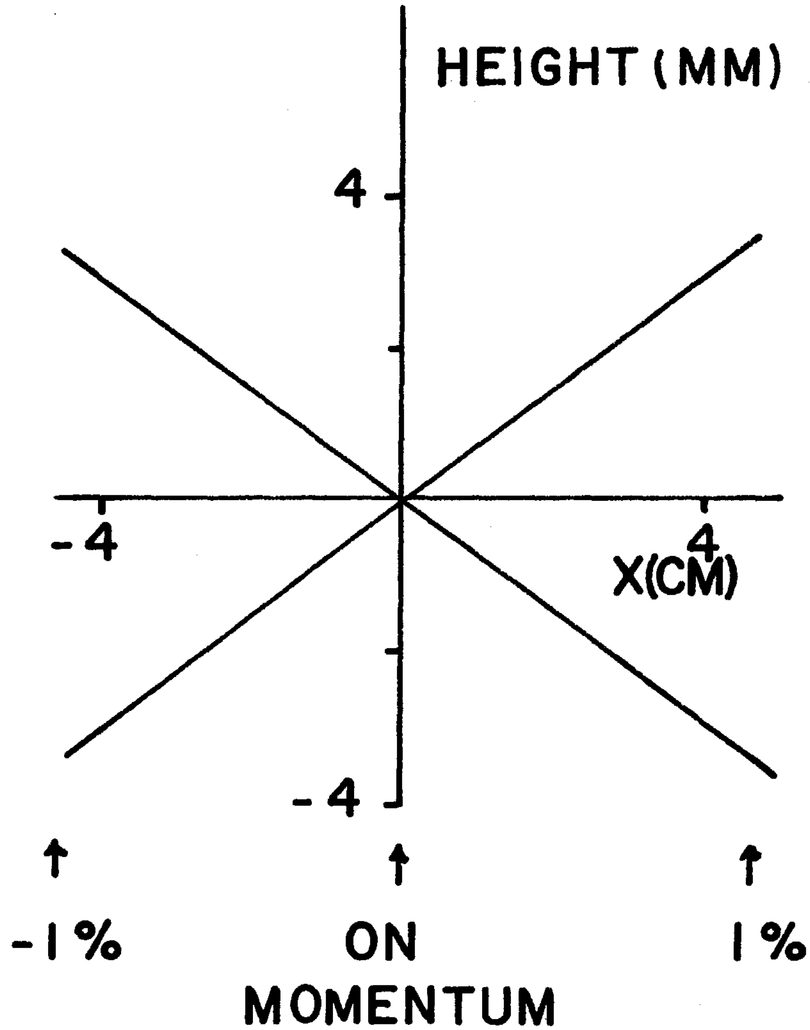


FIG VII-3b BEAM AT FOCAL PLANE



TM-223
2254

two or more elements are incorrectly set the problems become correspondingly more difficult. Note that the magnification varies differently for each element. It may be possible to factor out the effect of different elements using this fact.

The effect of momentum spread can be handled to some extent by using chromatic aberration. Figure VII-3b shows the beam distribution at the momentum slit for a zero size target. This forms a characteristic butterfly pattern because the off-momenta rays are focused at other positions and also dispersed in the horizontal plane. If the chromatic aberration is smaller, the vertical height of the pattern is compressed. To see this pattern it is necessary to use a device that maintains the xy correlation.

Ordinarily beam losses or obstructions are determined by either placing scintillation screens or polaroid film near the element in questions or extrapolating trajectories determined by wire plane detectors back to some source. These techniques can certainly be used to advantage.

A novel approach might be to place a scintillation screen at the focal plane then reset the last pair of quadrupoles to focus a particular aperture stop on the screen. For instance, to focus the first set of quadrupoles in the 2.5 mrad beam on to the first focal plane requires a gradient of 280kg/m as contrasted to the normal gradient of about 170 kg/m. This would imply that the quadrupoles be able to run at somewhat higher fields than their normal values, a condition that holds if a suitably low momentum is examined. Notice that the quadrupoles will also introduce some image distortion.

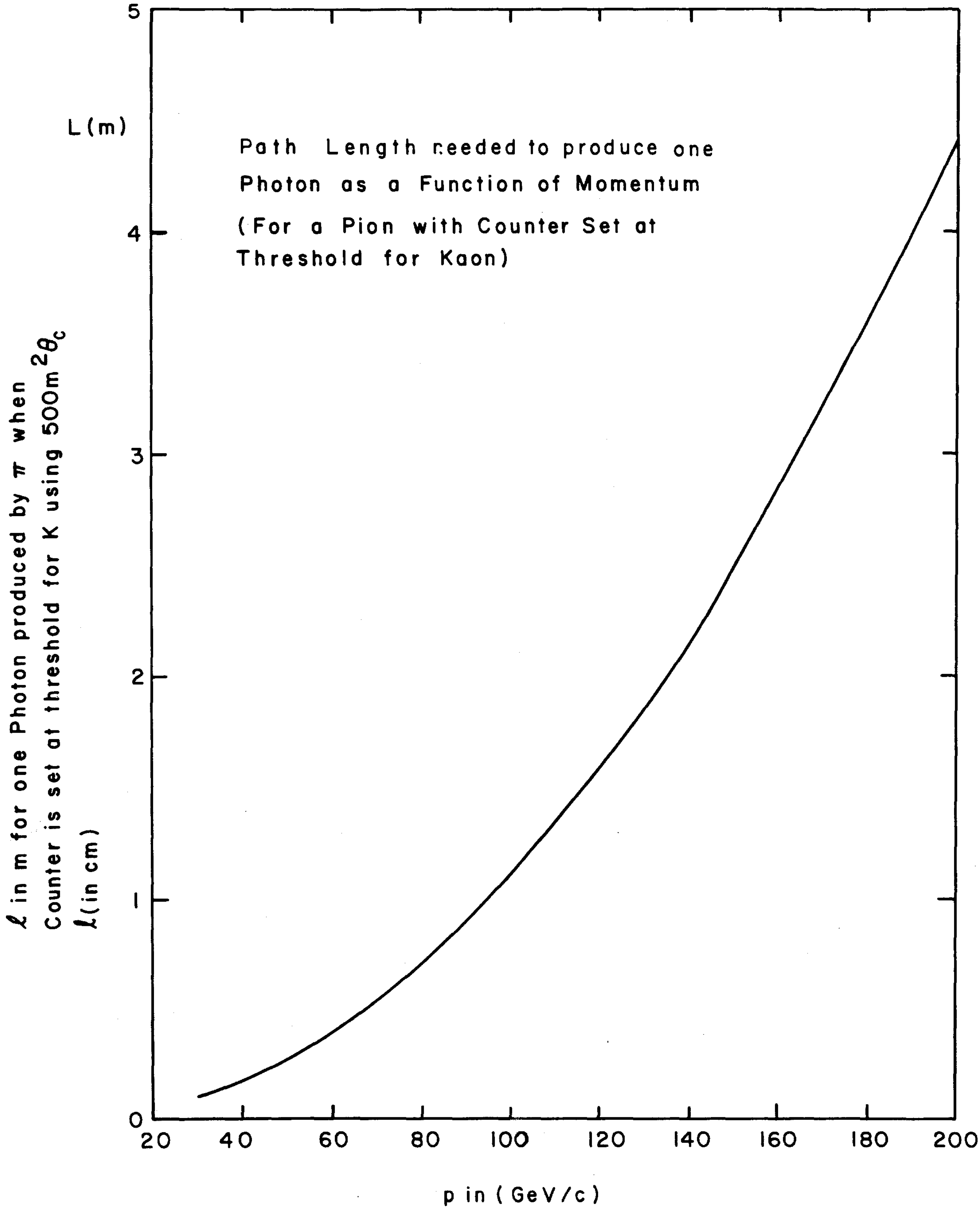
Experimental Apparatus: It has been noted in several places that one should, in theory, be able to open the momentum slits on many of these beams and still be able to tag a particular particle's momentum to the advertised accuracy of the beam. This seems quite reasonable for the high resolution beams run on negatives of any momentum, but for positives the number of particles going through the tagging counters probably exceeds reasonable counting rates ($\sim 10^7$/sec) above 120 BeV/c. Note that using very narrow (.6mm wide) scintillators allows one to have essentially the same resolution in Tune II of the high resolution beams as in Tune I, since the scintillator needs to be $\sim$1/4" long rather than a meter as for a slit. Therefore, it can be narrower than 1.5mm and still contain the entire beam emittance.

For the high intensity beam, it appears difficult to use the momentum tagging idea for a positive beam of any momentum or for negative beams of momentum less than approximately 100 BeV/c. This probl em recurs if one wishes to count the beam just in front of the experimental target, where the beam spot is presumably small. One can probably not open the high resolution beams up to more than about ten times their minimum momentum bite before the pulses from a scintillation counter counting the entire beam begin to overlap in time.

From several independent calculations, threshold Cerenkov counters will be of use up to some momentum above 100 BeV/c, the upper limit depends on the properties one assumes for phototubes. Figure VII-4 shows the length needed to produce one photon from a π when the threshold counter is set just below K threshold. Using tubes in existence today (RCA-C31025) one can easily separate π's and K's using a threshold counter 82 feet long at 100 BeV/c. Both of the high resolution beams and the high intensity beam have room for such a counter between the final quads and the experimental target. A recent note by R. Rubinstein[20] gives a focusing counter (DISC) design which will separate K's from π's and p's at 200 BeV/c and is only 4m long, but requires the beam divergence to be less than $\pm$ .05 mrad. It should be reemphasized that there is a serious problem in all of these beams that the available flux may be more than any counter which sees π's or p's can handle.

K. Pretzl has noted that the effect of multiple scattering on beam optics is proportional to the size of the sin-like ray at the point where the multiple scattering occurs. For these beams this counter should be placed where the beam is small. This indicates that DISC counters (which must be placed where the beam is parallel, therefore large) may cause multiple scattering problems.

Fig. VII - 4


L(m)
Path Length needed to produce one Photon as a Function of Momentum
(For a Pion with Counter Set at Threshold for Kaon)
ℓ in m for one Photon produced by π when Counter is set at threshold for K using 500m $^2\theta_c$
ℓ(in cm)
0
1
2
3
4
5
20
40
60
80
100
120
140
160
180
200
p in (GeV/c)

VIII. SUMMARY AND CONCLUSIONS

Three different beam lines suggested by the 1969 summer study have been developed in this memorandum. The studies for each one are largely complimentary. For instance, the high momentum, high resolution design has been used to study the effect of alignment errors and the use of a sextupole to correct chromatic aberration. The medium energy-high resolution beam illustrates some problems and features for a design in which the first quadrupole is focusing. It also studies the effect of target broadening from a larger production angle and compares second order effects to measured second order quantities in the main ring magnets. The high intensity beam illustrates the use of a symmetric triplet rather than a doublet.

In general, ±0.05% resolution is readily obtainable in the high resolution beams. Second order corrections have proved more difficult to treat than anticipated. They are not important for the high resolution beams but very significant for the high intensity beam.

Some more specific conclusions are:

Economic: Equipment costs are essentially linear with aperture when the beam elements are kept at the same distance. Thus there is no trouble in reducing costs if acceptance is sacrificed. The equipment costs could be reduced slightly at constant acceptance if the distance to the front quadrupole was shortened somewhat. Going to triplets could increase the acceptance by, at most, 25% in the case of the 3.5 mrad beam at the expense of doubling the quadrupole costs. Similarly making the first quadrupole focusing decreases the beam length slightly but gives rise to serious problems with beam element misalignments.

Finally, and perhaps most important, thin septum magnet elements and narrow quadrupoles have relatively heavy power demands.

Magnets: Field errors appear to be tractable in bending magnets and negligible in quadrupoles, except in the case of non-iron magnets. For these magnets field errors may be very serious in high resolution beams. Apertures of 4 inches or perhaps somewhat smaller appear suitable for the quadrupoles. Several field lens quadrupoles should be constructed with six inch or larger apertures and lengths shorter than ten feet. Roughly twenty percent of the bending magnets should have wide apertures to allow for left-right switching.

Alignment tolerances: Random element misalignments of ±10 mils result in fairly serious problems with absolute beam momentum but do not degrade the resolution or cause substantial aperture loss. However, if three successive quadrupoles have the same polarity very serious alignment problems occur.

Tuning: In general, the front section of a beam will be difficult to tune because many momenta are present. It may be quite difficult to construct beam monitors precise enough to tune quadrupoles to 1%. Tuning monitors should be removable to cut down multiple scattering.

Future work: Charged secondary beams still need a great deal of attention. After a beam mix is established, each group undertaking the commissioning of a beam should completely reexamine the design of their beam. However, there are a number of topics which should be investigated earlier:

1. A new design for the high intensity beam should be formulated which properly uses sextupoles and makes the resolution as good as possible consistent with high intensity. We feel this is the most important outstanding beam problem.

2. Beam purity studies now under way should be completed.

3. A study should be made of a superconducing beam when realistic tolerances are available.

4. A detailed beam tuning scenario should be completed. This should take into account recent beam tuning techniques at other laboratories.

5. The possibility of omitting vertical foci should be considered.[2] This might be more economical.

6. An alternate tune should be devised for the existing high resolution beam in which the final beam is more parallel rather than focused.

7. Quadrupole aberrations should be studied using a ray trace program.

REFERENCES AND NOTES

[1]M. Longo, UCID-10124, p. 137 (1966).

[2]G. Petrucci, ECFA-6716, V. II, p. 19 (1967).

[3]D. Reeder and J. MacLachlan, NAL Summer Study-41, V. 1, p. 41 (1969).

[4]D. H. White and others, NAL Summer Study-37, V. 1, p. 33 (1969).

[5]E. W. Anderson et.al., Phys. Rev. Letters 16, 855 (1966).

[6]K. Brown et.al., SLAC-91 (1969).

[7]Since the equipment cost per DC kilowatt capacity goes down with a bigger power supply, it is more efficient to run magnets in series where possible.

[8]"Cost Estimate of Experimental Equipment", William M. Brobeck & Associates Report No. 200 - 1 - R7, January 1969.

[9]Design Study "p - p Colliding Beam Storage Rings for the National Accelerator Laboratory", 1968.

[10]One inch sagitta corresponds roughly to ten feet of 20 kilogauss field and a 30 GeV/c momentum.

[11]The figures of 30" over-all width and 5" coil width correspond to a septum dipole with copper coils that is equivalent to the septum dipole in Figure II-1, which is meant to be superferric.

[12]NAL FN-145, "Quads and Bending Magnets for NAL", G. Danby and M. Good, May 7, 1968.

[13]K. L. Brown, SLAC-75 (1967).

[14]M. Awshalom and T. White, NAL FN-191 (1969).

[15]D. H. White, NAL Summer Study-9, V.3, p. 11 (1969).

[16]R. A. Zdanis, NAL Summer Study-29, V.1, p. 187 (1969).

[17]B. C. Barish, NAL Summer Study-30, V.1, p.55 (1969).

[18]R. Diebold and L. Hand, NAL Summer Study-49, V.1, p. 153 (1969).