SLAC TN-65-40
Luke Mo
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20 BeV/c SPECTROMETER

I. INTRODUCTION

As it has been stated in the spectrometer proposal of Group A,[1] the 20-BeV/c spectrometer is the most flexible instrument available for performing initial secondary beam surveys at small angles as a function of the linear accelerator energy. Also it is a very useful instrument for doing elastic or inelastic electron and positron scattering experiments, investigating the mechanism of photoproduction processes, and checking the limit of validity of quantum electrodynamics.

Because of the kinematics of high energy processes, the 20 BeV/c spectrometer does not have to cover a large angular range. The angular range from 0° to about 25° would be adequate. At small angles, the cross sections of scattering processes and peripheral processes are large so that a solid angle of about 10^{-4} steradian is acceptable. As in the case of the 8 BeV/c spectrometer, a momentum resolution of about 0.1% is desired in order to distinguish processes different by one-pion production. A θ-resolution of about 0.3 mr in the production angle is sought in order to insure the wanted momentum resolution. The following parameters have been used as input specifications:

1. Target length $x_o = \pm 3$ cm
2. Production angle $\theta_o = \pm 4.5$ mr
3. Target height $y_o = \pm 0.15$ cm
4. Azimuthal angle $\varphi_o = \pm 8$ mr
5. Momentum band $\pm 2\%$

[1] Panofsky, *et al*, Group A Proposal of SLAC, 1964, written in collaboration with physicists from Group C, MIT and CIT.

The desired optical features are as follows:

1.	Momentum resolution	$\delta_r < \pm 0.05\%$
2.	Angular resolution	$\theta_r \leqq \pm 0.15$ mr
3.	Solid Angle of acceptance	$\Omega \geqq 10^{-4}$ sr
4.	Momentum acceptance	$\delta = \pm 2\%$
5.	Angular dispersion	$D_\theta \leqq 2$ cm/mr
6.	Momentum dispersion	$D_\delta \geqq 3$ cm/%

II. THE ROTATED QUADRUPOLE SPECTROMETER

A very ingenious solution to this problem, due to Panofsky et al,[2] is to generate the momentum dispersion in the horizontal plane and the θ-dispersion in the vertical plane. The beam is kept within the easy reach of the floor thus simplifying the mechanical problems encountered in construction. The concept of the design is shown in Fig. 1. In the horizontal plane, the quadrupole Q1 focuses a line target to a point image in the center of the quadrupole Q2. This intermediate image is then focused by the quadrupole Q3 onto the image plane. The final image size is linearly proportional to both production angle and momentum. The horizontal position of the focus in Q2 depends only on the production angle. The defocusing quadrupole Q2 does not affect the final image in the horizontal plane to first-order. If the quadrupole Q2 is rotated about the beam axis by an angle α, a component of magnetic field increasing linearly from the axis will exist in the horizontal plane and it will deflect the beam vertically by an amount proportionally to the angle θ. By the mean time the beam originally in the vertical plane will receive a horizontal impulse. The strengths of the quadrupoles Q1 and Q2 can be adjusted to create a point-to-point focus in the vertical plane and line-to-point focus in the horizontal plane. The angle of rotation of the quadrupole Q2 is adjusted to generate the desired θ-dispersion at the vertical focal plane.

The salient feature of the above design is characterized by the rotation of the quadrupole Q2. The rest of the system could be any member of different combinations of elements.

[2]Panofsky, et al, SLAC TN-64-39, 1964.

The first-order transformation matrix from the target to the focal plane of a typical design with a Q2 rotation angle $\alpha = 7.05^{\circ}$ is given as below:

TABLE I

First-Order Matrix Element at Focal Plane

	x_o	θ_o	y_o	φ_o	z	δ
x	-0.000	0.000	0.878	0.000	0.000	3.025
θ	0.787	-0.617	-1.216	-1.139	0.000	2.424
y	-0.001	1.697	-1.172	0.000	0.000	-0.000
φ	-0.590	1.430	-0.668	0.000	0.000	- 0.202
z	0.238	-0.152	-0.179	-0.345	1.000	0.076
δ	0.000	0.000	0.000	0.000	0.000	1.000

In the above table, the angles are in mr, the lengths are in cm, and the momentum δ in percent. The first-order dispersions and resolutions are:

$$
\begin{aligned}
D_\delta &\simeq 3 \text{ cm/\%} \\
D_\theta &\simeq 1.7 \text{ cm/mr} \\
\delta_r &\leq 0.1\% \\
\delta_\theta &\leq 0.3 \text{ mr}
\end{aligned}
$$

These results appeared to be very satisfactory. However, K. L. Brown investigated the second-order aberrations of this system and found that their values are larger than the limits set by the required resolutions. It appeared to be too laborious to reduce the aberrations by higher multipole magnets. Even if appropriate corrections were found, trouble shooting and adjustment of the final system appeared difficult. The system was therefore abandonded. We have, therefore, investigated designs which bend the beam in the vertical plane.

III. THE UPWARD S-BEND SPECTROMETER

The final choice of the 20 BeV/c spectrometer was the upward S-Bend configuration suggested by B. Richter and K. L. Brown. The magnet configuration in the vertical plane was chosen to be BS-B+S+B-SB as shown in Fig. 2. The notation is that B represents a 5.2° bending magnet, S a sextupole, and (+ and -) focussing and defocussing quadrupoles in the horizontal plane. As it is shown by K. L. Brown,[3] the momentum dispersion in the focal plane for a system which focuses a point object to a point image in the vertical plane is given by

$$D_y(z) = -C_y(z) \int_0^z h(z') \, S_y(z') \, dz'$$

where z is the distance from the target along the central trajectory, $h(z) = 1/\rho(z)$ is the curvature of the central ray at z. The cosine-like and sine-like functions, $C_y(z)$ and $S_y(z)$, are the first-order coefficients in the Taylor's series expansion for the particle trajectory with respect to the central ray,

$$y(z) = C_y(z) y_o + S_y(z) y_o' + D_y(z) \, \delta$$

Since we want to have a double cross-over point in the vertical plane at the middle of the spectrometer, so that a slit system could be placed there to clean up the beam. The sine-like function $S_y(z)$, will change sign after passing the middle section of the spectrometer. In order to obtain the desired momentum dispersion, the corresponding sign of the curvature h(z) has to be changed to make the definite integral positive (or negative) definite. Therefore, the beam is first being bent upward. After passing through the middle section of the spectrometer, it is being bent downward and kept parallel to the floor. The offset of the central trajectory at the image from the main beam line is 10'4" (17'2" from the floor). The wall opening of the End Station A has to be raised in order to swing the spectrometer up to angles of 35° with respect to the forward

[3] K. L. Brown, SLAC TN-64-18, 1964

direction of the main beam. However, it avoids a split level floor which would be necessary for a downward S-bend configuration.

Because there is no mixing between the horizontal and vertical planes, this choice is much simpler optically than the rotated quadrupole configuration. Most of the second-order chromatic aberrations can be reduced by the three sextupoles to values within the limits set by the required resolutions. The term $(y|\varphi_o\delta)$ can be reduced further by tipping the momentum-measuring counter array to an angle of 43^{o} with respect to the optical axis of the spectrometer. The first order transformation matrix from the target to the momentum-measuring counter array is given in Table 2:

TABLE 2

First-Order Transformation Matrix of the S-Bend Spectrometer in the Momentum Measuring Focal Plane (Units: Length in cm, Angle in mr.)

	x_o	θ_o	y_o	φ_o	z_o	δ_o
x	0.033	1.531	0.000	0.000	0.000	0.000
θ	-0.652	-0.066	0.000	0.000	0.000	0.000
y	0.000	0.000	0.927	-0.000	0.000	2.826
Φ	0.000	0.000	3.410	1.078	0.000	5.061
z	0.000	0.000	0.495	0.305	1.000	0.291
δ	0.000	0.000	0.000	0.000	0.000	1.000

The counter array which measures the production angle θ is located 50 cm upstream from the momentum-measuring hodoscope, and is perpendicular to the optical axis of the spectrometer. The first-order transformation matrix from the target to the θ-measuring hodoscope is given in Table 3:

TABLE 3

First Order Transformation Matrix of the S-Bend Spectrometer

in the Production Angle Measuring Focal Plane

(Units: Length in cm, Angle in mr)

	x_0	θ_0	y_0	φ_0	z_0	δ_0
x	0.000	1.534	0.000	0.000	0.000	0.000
θ	-0.652	-0.066	0.000	0.000	0.000	0.000
y	0.000	0.000	0.757	-0.054	0.000	2.573
φ	0.000	0.000	3.410	1.078	0.000	5.061
z	0.000	0.000	0.495	0.305	1.000	0.291
δ	0.000	0.000	0.000	0.000	0.000	1.000

The first order transformation from the target parameters $(x_0 \theta_0 y_0 \Phi_0 \delta)$ to a point in the focal plane (x, y), is of the form

$$x = B\theta_0$$

$$y = My_0 + D\delta$$

To first order, the angular resolution is perfect, whereas, a perfect measurement of y gives the momentum resolution

$$\delta_r = \left|\frac{M}{D}\right| y_0 = \pm \frac{0.927}{2.826} \times 0.15 = \pm 0.0492\%$$

Including second-order aberrations, the transformation from the target to the θ-measuring hodoscope is

$$\begin{aligned} x = [&1.534\ \theta_0 + 0.0177\ \theta_0 \delta_0] \\ &-0.0139\ x_0\ \varphi_0 \quad (\pm\ 0.334\ \text{cm}) \\ &+0.0048\ \theta_0\ \varphi_0 \quad (\pm\ 0.173\ \text{cm}) \\ &-\ 0.105\ \theta_0\ y_0 \quad (\pm\ 0.0708\ \text{cm}) \\ &-\ 0.0878\ x_0\ y_0 \quad (\pm\ 0.0395\ \text{cm}) \\ &-\ 0.00254\ x_0 \delta_0 \quad (\pm\ 0.0153\ \text{cm}) \end{aligned}$$

and the transformation from the target to the tipped momentum-measuring hodoscope is

$$
\begin{aligned}
y = \; & [2.826\ \delta_o - 0.0421\ \delta_o^2 - 0.0167\ \theta_o^2] \\
& + 0.927\ y_o & (\pm\ 0.139\ \text{cm}) \\
& - 0.000836\ \varphi_o^2 & (-\ 0.0535\ \text{cm}) \\
& + 0.0407\ y_o\varphi_o & (\pm\ 0.0488\ \text{cm}) \\
& - 0.0029\ x_o\theta_o & (\pm\ 0.0391\ \text{cm}) \\
& + 0.0042\ x_o^2 & (\ \ 0.0378\ \text{cm}) \\
& + 0.0291\ y_o\delta_o & (\pm\ 0.00873\ \text{cm}) \\
& + 0.0653\ y_o^2 & (\ \ 0.00147\ \text{cm}) \\
& + 8.99 \times 10^{-5}\Phi_o\delta_o & (\pm\ 0.00144\ \text{cm})
\end{aligned}
$$

The numbers in the parenthesis following the terms whose values cannot be known by a measurement of x and y at the focal plane were calculated for the following beam parameters:

$$
\begin{aligned}
x_o &= \pm\ 3\ \text{cm} \\
\theta_o &= \pm\ 4.5\ \text{mr} \\
y_o &= \pm\ 0.15\ \text{cm} \\
\Phi_o &= \pm\ 8\ \text{mr} \\
\delta &= \pm\ 2\%
\end{aligned}
$$

Including the second-order terms (adding by mean square root law), the resolution became

$$\theta_r = \frac{0.385}{1.534} = \pm\ 0.251\ \text{mr}$$

$$\delta_r = \pm\ \frac{0.167}{2.826} = \pm\ 0.059\%$$

These numbers are actually the resolutions evaluated at the bases of the resolution curves of the spectrometer. At the half maxima of the resolution curves, the widths are smaller and the resolutions evaluated there are within the required limits of $\pm$ 0.05% and $\pm$ 0.15 mr respectively.

The situation can be seen clearly from two of the resolution curves shown in Figs. 3 and 4. The dispersions at the focal planes are

$$D_\delta = 2.826 \text{ cm}/\%$$

$$D_\theta = 1.534 \text{ cm/mr}$$

The overall size of the counter hodoscope required for the assumed input beam parameters is 5.44" × 4.45". The physical parameters of the magnetic elements are given in Table 4.

TABLE 4

Element	Length (meters)	Pole-Tip Field kG	x-aperture (cm)	y-aperture (cm)
B1	4.04	14.85	± 5.79	± 8.81
S1	0.50	2.178	± 6.18	± 9.65
Q1	2.08	- 8.836	± 8.71	± 9.49
B2	3.08	19.48	±16.24	± 4.38
Q2	1.40	8.546	±19.08	± 2.28
S2	0.50	- 3.60	±19.15	± 2.19
Q3	1.40	8.546	±17.98	± 4.63
B3	3.08	19.48	±10.93	±10.02
Q4	2.08	- 9.110	± 7.49	±11.39
S3	0.50	2.253	± 7.43	±10.23
B4	3.04	19.74	± 7.21	± 6.19

In the above table, the negative value of the field strength of S2 indicates that its scalar magnetic potential takes the form

$$\Phi = -\frac{1}{3} k_3 r^3 \sin 3\theta$$

where k_3 is a constant to be explained in the Appendix. For S1 and S2, there is no minus sign on the right-hand side of the above expression.

Actually, the magnetic elements are going to be built with the apertures given in Table 5 for design compatibility with the 8 BeV/c spectrometer where possible.

TABLE 5

Element	x-aperture (inch)	y-aperture (inch)
B1	5.6	24
B2, B3	14.6	11.4
B4	6.75	11.4
Q1, Q4	11.0	11.0
Q2, Q3	15.25	15.25
S1, S3	10.25	10.25
S2	$\geq$ 15.25	$\geq$ 15.25

Figure 5 shows the unit sine-like, cosine-like, and the unit dispersion rays of the 20 BeV/c spectrometer. Figures 6 and 7 give the first-order focusing properties of the instrument. It can be seen that the beam spreads out very much in the middle horizontal plane of the system. Assuming the wall thickness of the vacuum chamber is 0.9 cm and that the vacuum chambers between the magnetic elements will not restrict the beam, the θ_o- and Φ_o-acceptance of the spectrometer are shown in Figs. 8 and 9. The solid angle of acceptance of the spectrometer is then calculated by the formula $\Omega = \pi\theta_o\Phi_o$. The solid angle as a function of the projected length of the target in the horizontal direction, x_o , is shown in Fig. 10. Figure 11 shows the solid angle as a function of the momentum δ .

IV. TOLERANCES OF THE 20 BeV/c UPWARD S-BEND SPECTROMETER

The tolerances of the quadrupoles and bending magnets of the 20 BeV/c spectrometer are calculated by the same method as for the 8 BeV/c vertical deflection spectrometer.[4] The approximation method for calculating the tolerances of the sextupoles is given in the Appendix. The

[4] L. Mo and C. Peck, SLAC TN-65-29, 1965.

criterion used for calculating the tolerances is that a given perturbation must not cause any ray to deviate from its proper position by 20% of the resolution. That is, for the 20 BeV/c spectrometer, the image position should not change more than $\pm$ 0.079 cm in the horizontal direction and $\pm$ 0.033 cm in the vertical direction. The resultant tolerances are given in Table 6. Since a given perturbation to the spectrometer will in general displace the image position in both the horizontal and the vertical directions, the tighter tolerance is binding.

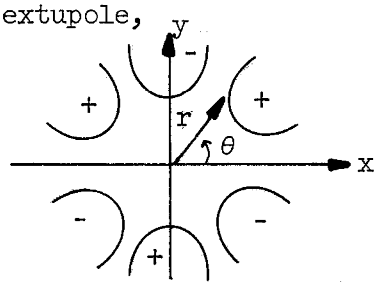
Table 7 gives the maximum deviations of the image position in terms of the perturbations to the magnetic elements. It is useful in calculating the correlated tolerances.

Acknowledgment

This report is a description of the 20 BeV/c spectrometer designed by Group A in collaboration with physicists from Group C, MIT and CIT, and Dr. K. L. Brown. I wish to thank Professor W.K.H. Panofsky, Drs. R. E. Taylor, H. DeStaebler and D. H. Coward for their helpful discussions on various aspects of the 8-BeV/c and the 20 BeV/c spectrometers, and also their generous aids in preparing those reports.

APPENDIX

In this appendix, formulas for the tolerances on the geometrical location, orientation, and as well as the magnetic field of a sextupole magnet will be derived. The derivation is based upon the following assumed polarity of the sextupole,



The scalar potential takes the form

$$\Phi = \frac{1}{3} K_3 r^3 \sin 3 \theta$$

where

$$K_3 = \frac{B(a)}{a^2} = \text{sextupole gradient}$$

$B(a)$ = field on poletips

a = radius of circular aperture.

The magnetic field may then be defined by

$$B_x = - 2K_3 xy$$

$$B_y = - K_3(x^2-y^2) .$$

where x is in the horizontal direction; and y, in the vertical direction. And the equations of motions are

$$\frac{d^2x}{dz^2} + K(x^2-y^2) = 0$$

$$\frac{d^2y}{dz^2} - 2Kxy = 0$$

in which

$$K = 3 \times 10^{-7} \frac{B(a)}{p\ a^2} \quad cm^{-3}$$

if

B(a)	in gauss
a	in cm
p	in BeV/c .

In the 20 BeV/c spectrometer, the sextupoles are oriented at an angle of 90^o with respect to the direction shown in the diagram. Changing the variables,

$$x \rightarrow y$$
$$y \rightarrow -x ,$$

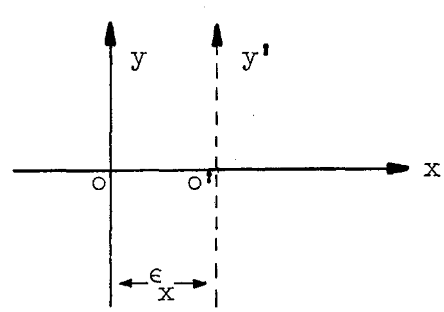
the equations of motion in the sextupoles become

$$\frac{d^2x}{dz^2} - 2Kxy = 0$$

$$\frac{d^2y}{dz^2} - K(x^2-y^2) = 0$$

For S1 and S3, K takes positive values; for S2, K is negative.

1. Horizontal Displacement of the Sextupole



$x' = x-\epsilon_x$

$y' = y$

To first order, the equations of motion become,

$$\frac{d^2x}{dz^2} - 2Kxy = - 2Ky\ \epsilon_x$$

$$\frac{d^2y}{dz^2} - K\ (x^2-y^2) = - 2Kx\ \epsilon_x$$

In the perturbation forces, x and y can be approximated by their values in the middle section of the sextupole. Using the Taylor's series expansions about the center of the sextupole,

$$C(z) = C_o + \left(\frac{dC}{dz}\right)_o (z-z_o) + \frac{1}{2}\left(\frac{d^2C}{dz^2}\right)_o (z-z_o)^2 + \ldots$$

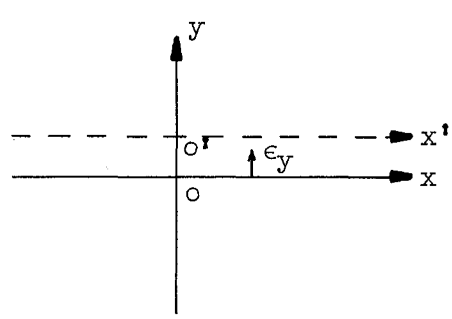
$$S(z) = C_o + \left(\frac{dC}{dz}\right)_o (z-z_o) + \frac{1}{2}\left(\frac{d^2C}{dz^2}\right)_o (z-z_o)^2 + \ldots$$

and also the general theorem due to K. L. Brown, the deviations of the image position at the focal plane are given by the expressions:

$$\Delta x = - 2KLS_x(z)\ C_{xo} y_o \epsilon_x$$

$$\Delta y = 2KLC_y(z)\ S_{yo} x_o \epsilon_x$$

2. <u>Vertical Displacement of a Sextupole</u>



$$x' = x$$
$$y' = y - \epsilon_y$$

The equations of motion become

$$\frac{d^2x}{dz^2} - 2Kxy = - 2Kx\ \epsilon_y$$

$$\frac{d^2y}{dz^2} - K(x^2y^2) = 2Ky\ \epsilon_y$$

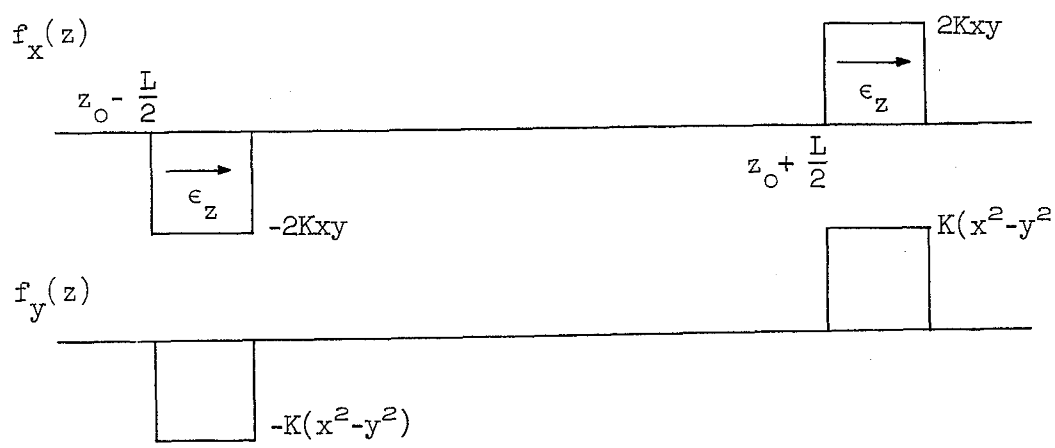
The deviations of the beam position are given by

$$\Delta x = -2KLS_x(z)\ C_{xo} x_o \epsilon_y$$

$$\Delta y = -2KLC_y(z)\ S_{xo} y_o \epsilon_y$$

3. Z-Displacement of a Sextupole

The perturbation forces due to the longitudinal displacement of a sextupole are shown in the following:



Using the Taylor's series expansions,

$$C(z) = C_o + \left(\frac{dC}{dz}\right)_o (z-z_o) + \frac{1}{2}\left(\frac{d^2C}{dz^2}\right)_o (z-z_o)^2 + \ldots$$

$$S(z) = S_o + \left(\frac{dS}{dz}\right)_o (z-z_o) + \frac{1}{2}\left(\frac{d^2S}{dz^2}\right)_o (z-z_o)^2 + \ldots$$

the following results were obtained,

$$\Delta x = 2KLS_x(z)\ C'_{xo}\ x_o y_o \epsilon_z$$

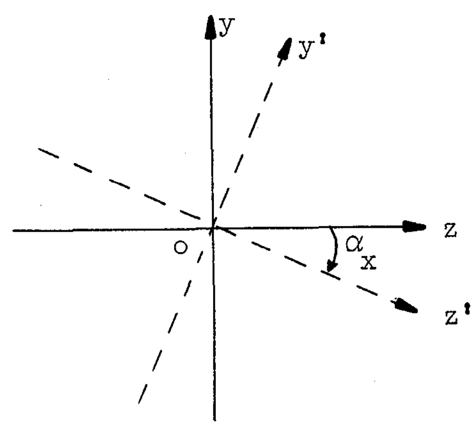
$$\Delta y = -KLC_y(z)\ S'_{yo}(x_o^2-y_o^2)\ \epsilon_z$$

where

$$C'_{xo} \equiv \left(\frac{dC_x}{dz}\right)_o$$

$$S'_{yo} \equiv \left(\frac{dS_y}{dz}\right)_o$$

4. <u>Rotation of a Sextupole about an Axis through the Center of the Element, and Parallel to the x-axis</u>



In the primed system of the sextupole, the magnetic field is given by

$$\vec{B} = K_3 \left[(x'^2-y'^2)\ \vec{i}' + 2x'y'\ \vec{j}'\right]$$

in which

$$x' = x$$
$$y' \simeq y + z\alpha_x$$
$$\vec{i}' = \vec{i}$$
$$\vec{j}' \simeq \vec{j} + \vec{k}\ \alpha_x$$

Viewed from the unprimed system, the magnetic field appeared like

$$\vec{B} = K_3 \left[\vec{i}\ (x^2-y^2-2yz\alpha_x) + \vec{j}\ (2xy+2xz\alpha_x) + \vec{k}\ 2xy\alpha_x \right]$$

The longitudinal field component can be neglected because the displacements it will produce are smaller by a factor of $v_{x,y}/v_z \sim 10^{-3}$ compared to the other perturbation terms caused by the transverse components. The equations of motion become

$$\frac{d^2x}{dz^2} - 2Kxy = 2Kxz\ \alpha_x$$

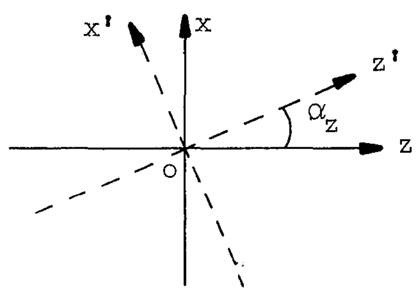
$$\frac{d^2y}{dz^2} - K(x^2-y^2) = -\ 2Kyz\ \alpha_x$$

and the deviations of the image position are given by

$$\Delta x = \frac{1}{6} KL^3\ S_x(z)\ C'_{xo}\ x_o\alpha_x$$

$$\Delta y = \frac{1}{6} KL^3\ C_y(z)\ S'_{yo}\ y_o\alpha_x$$

5. Rotation of a Sextupole about an Axis through the Center of the Element, and Parallel to the y-axis



The primed coordinate system is related to the unprimed system through the relationships,

$$x' = x - z\alpha_y$$
$$\vec{i}' = \vec{i} - \vec{k}\ \alpha_y$$
$$y' = y$$
$$\vec{j}' = \vec{j}$$

The magnetic field appears in the unprimed system like

$$\vec{B} = K_3 \left[(x^2-y^2-2xz\alpha_y)\ \vec{i} + 2(xy-yz\alpha_y)\ \vec{j} - (x^2-y^2)\ \alpha_y\ \vec{k} \right]$$

Neglecting the longitudinal field component, the equations of motion become

$$\frac{d^2x}{dz^2} - 2Kxy = - 2Kyz\ \alpha_y$$

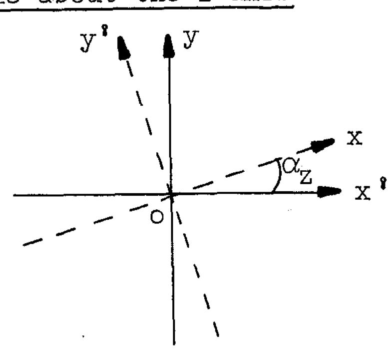
$$\frac{d^2y}{dz^2} - K(x^2-y^2) = - 2Kxz\ \alpha_y$$

The deviations of the image position are given by

$$\Delta x = - \frac{1}{6} KL^3 S_x(z)\ C'_{xo}\ y_o \alpha_y$$

$$\Delta y = \frac{1}{6} KL^3\ C_y(z)\ S'_{yo}\ x_o \alpha_y$$

6. Rotation of a Sextupole about the z-axis



The coordinate transformations are

$$x' \simeq x + y\alpha_z$$

$$y' \simeq y - x\alpha_z$$

$$\vec{i}' \simeq \vec{i} + \vec{j}\alpha_z$$

$$\vec{j}' \simeq -\vec{i}\alpha_x + \vec{j}$$

In the unprimed system, the magnetic field appears like

$$\vec{B} = K_3 \left[\vec{i}\ (x^2-y^2+2xy\alpha_z) + \vec{j}\ (2xy-x^2\alpha_z+y^2\alpha_z) \right]$$

The equations of motion become

$$\frac{d^2x}{dz^2} - 2Kxy = -K(x^2-y^2)\ \alpha_z$$

$$\frac{d^2y}{dz^2} - K(x^2-y^2) = 2Kxy\ \alpha_z$$

The deviations of the image position are given approximately by

$$\Delta x = -KLS_x(z)\ C_{xo}(x_o^2-y_o^2)\ \alpha_z$$

$$\Delta x = -2KL\ C_y(z)\ S_{yo}\ x_o y_o \alpha_z$$

7. Magnetic Field Tolerances of a Sextupole

Suppose that the magnetic field of a sextupole is varied by a small percentage Δ of the ideal value, then the equations of motion become

$$\frac{d^2x}{dz^2} - 2Kxy = 2Kxy\ \Delta$$

$$\frac{d^2y}{dz^2} - K(x^2-y^2) = K(x^2-y^2)\ \Delta$$

The deviations of the image positions are given approximately by

$$\Delta x = 2KLS_x(z)\ C_{xo}\ x_o y_o \Delta$$

$$\Delta y = -KLC_y(z)\ S_{yo}(x_o^2-y_o^2)\ \Delta$$

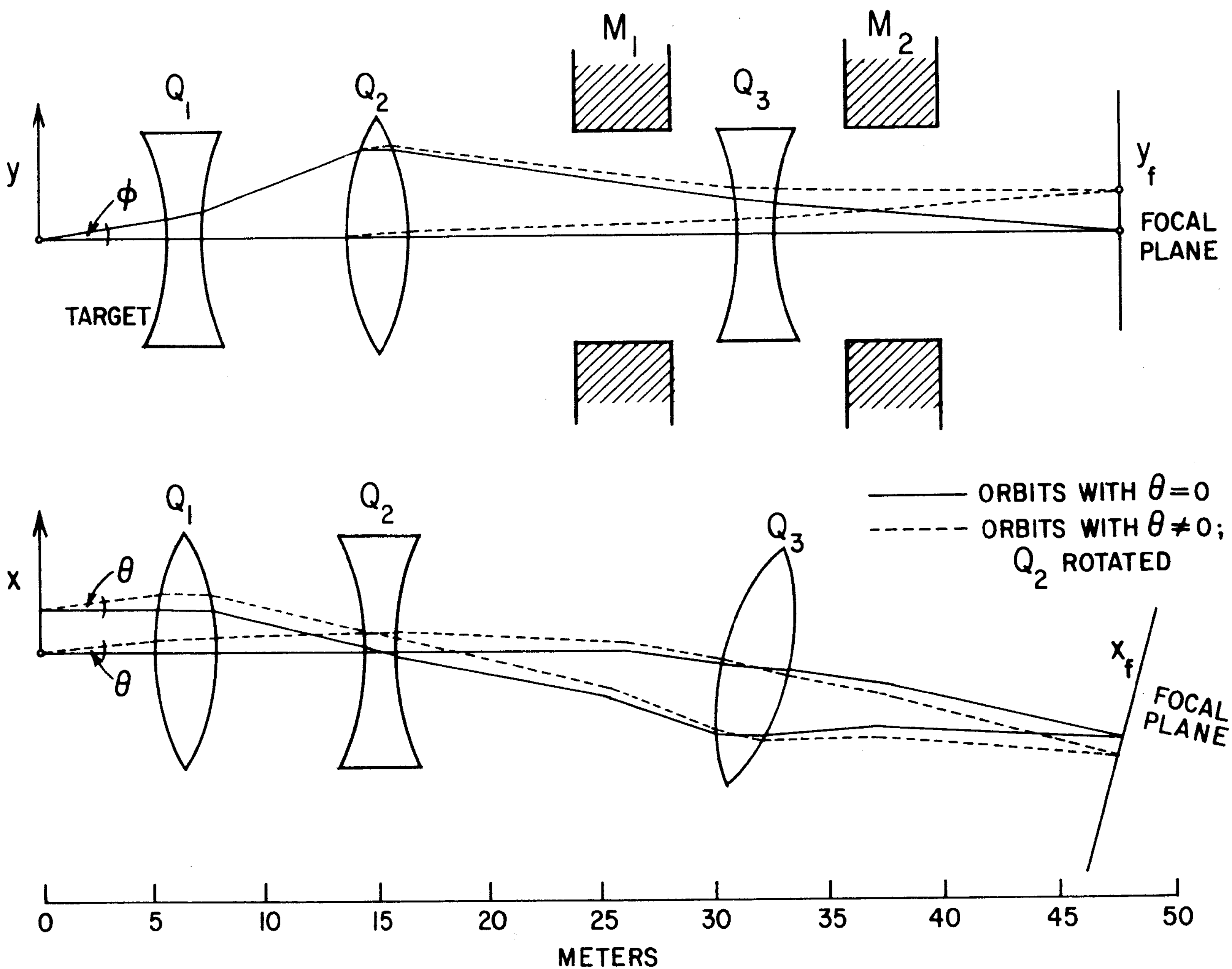


Fig.1 - ROTATED QUADRUPOLE SPECTROMETER

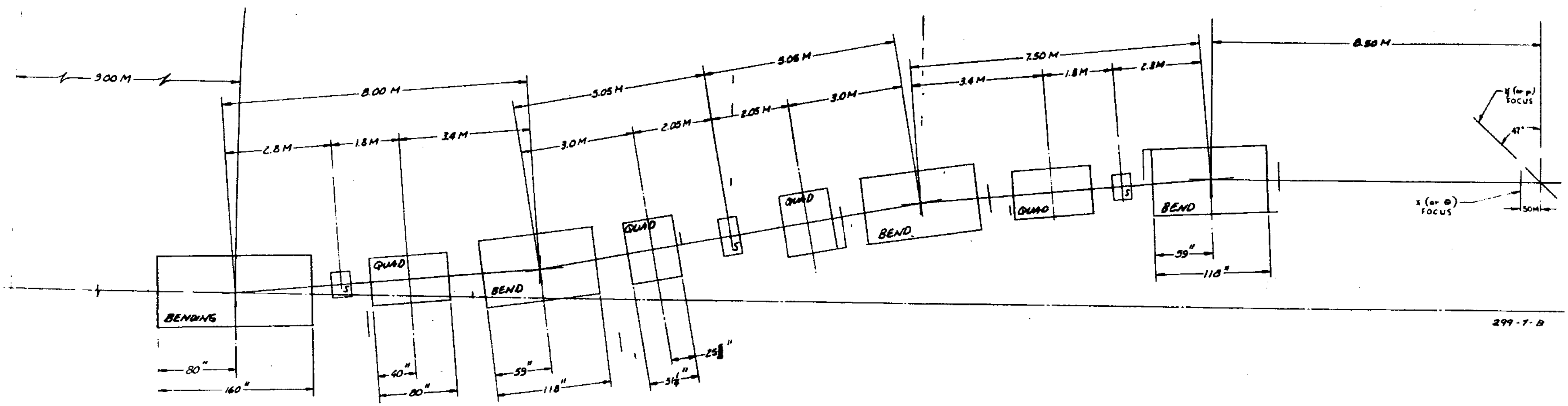


FIG. 2 - MAGNET ARRANGEMENT OF 20 BeV/c SPECTROMETER

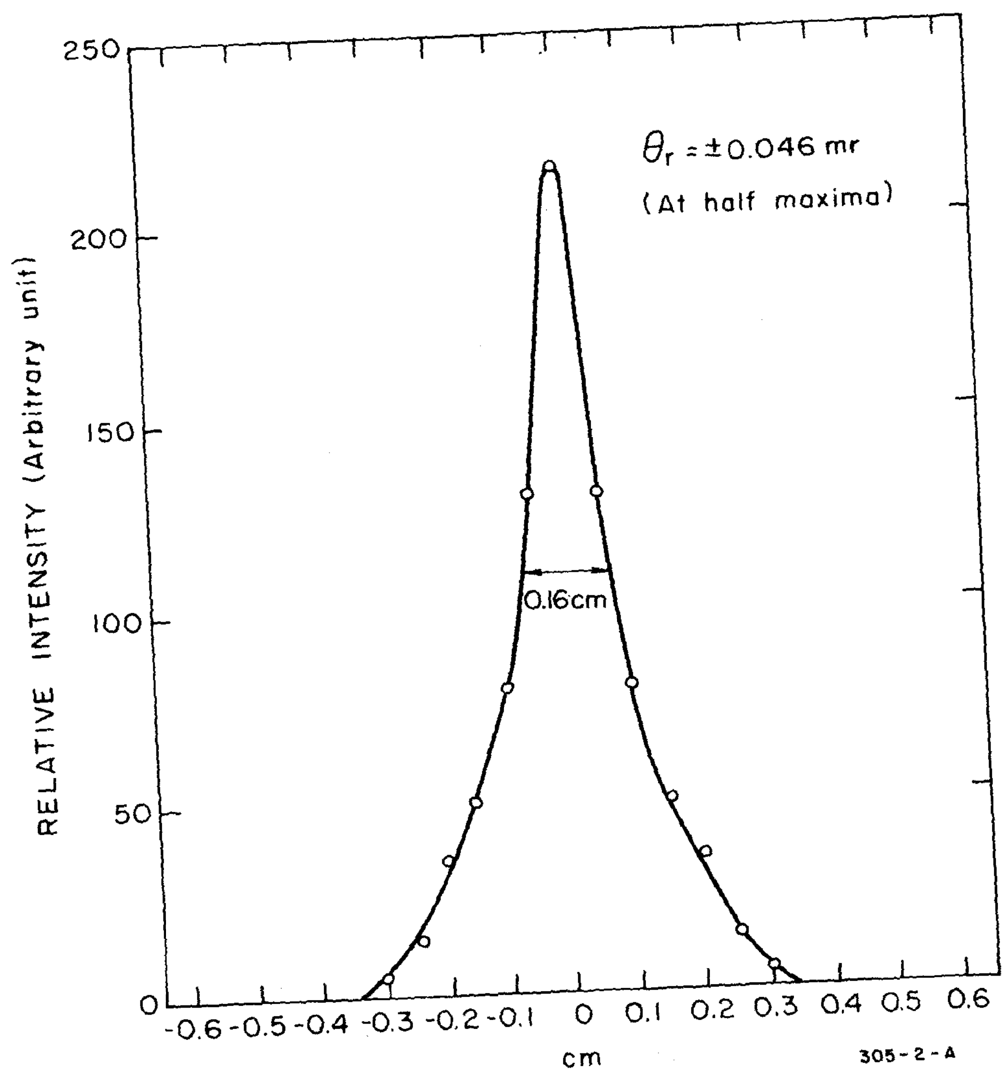


Fig. 3 - θ RESOLUTION CURVE OF THE 20-BeV/c SPECTROMETER FOR RAYS WITH $\delta = 0$ AND $\theta_o = 0$

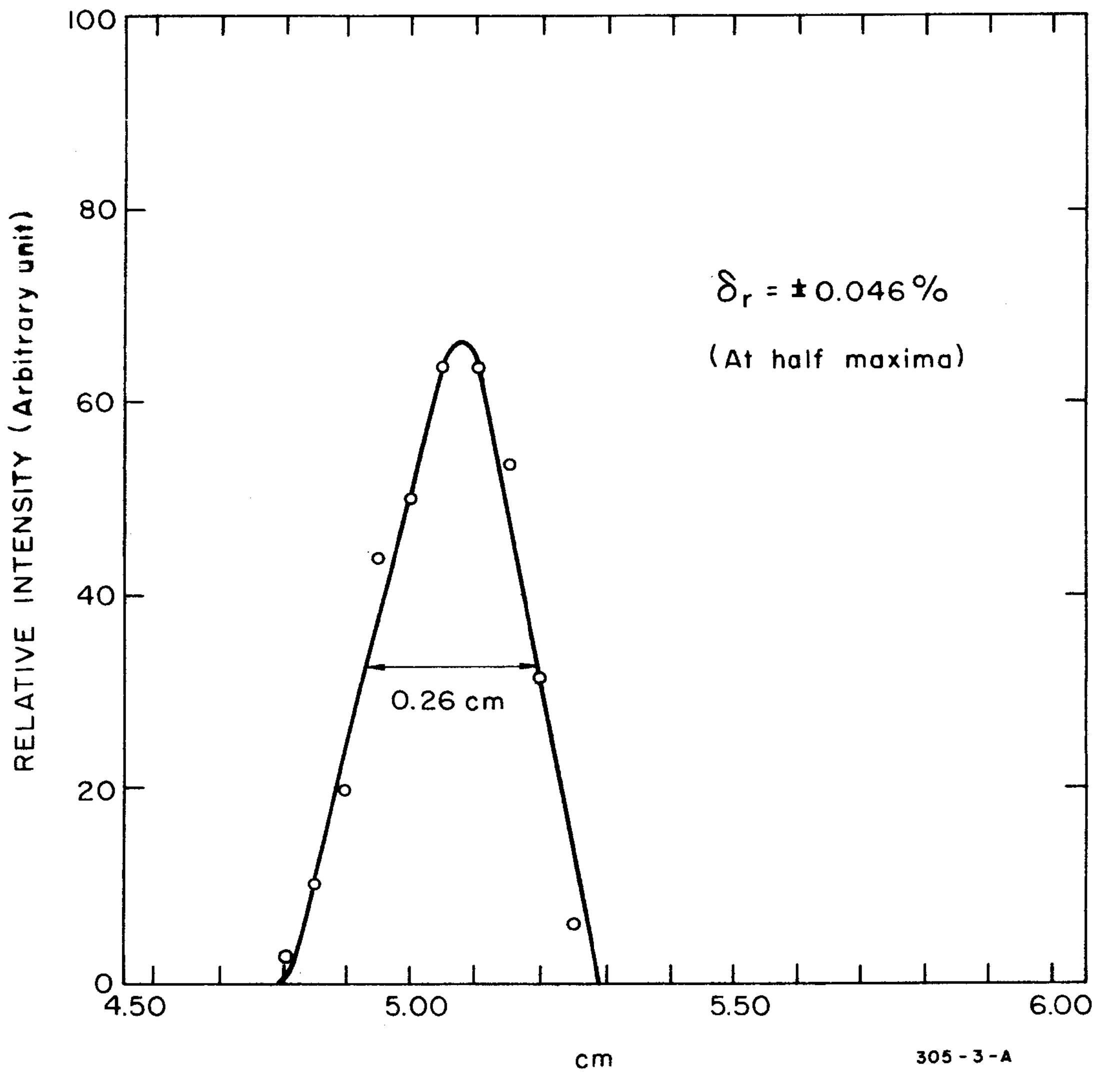


Fig. 4—MOMENTUM RESOLUTION CURVE OF THE 20-BeV/c SPECTROMETER FOR RAYS WITH $\delta_o = 2\%$ AND $\theta_o = 4.5$ mr

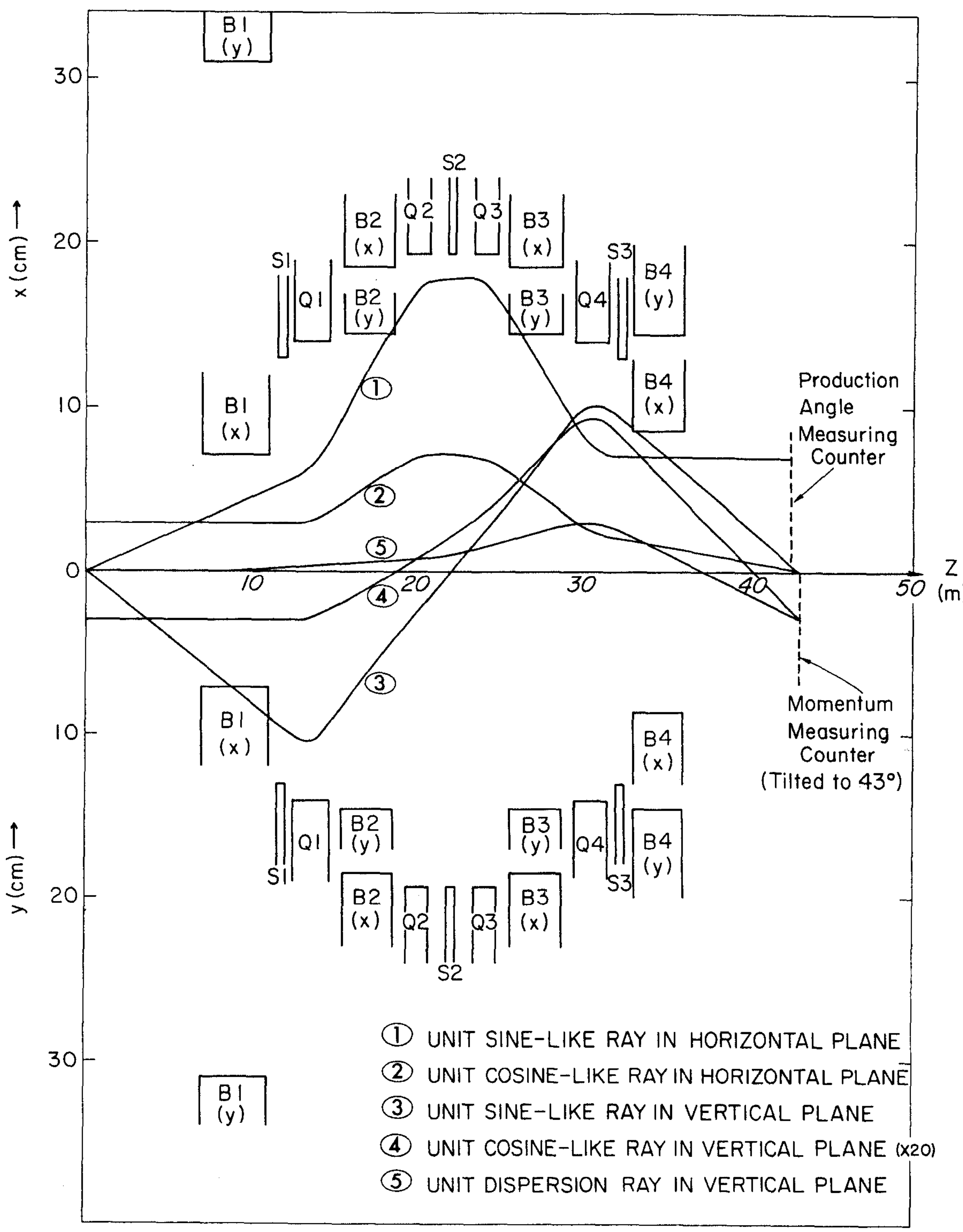


Fig. 5 - Unit sine-like, cosine-like, and dispersion rays of the 20 BeV/c spectrometer 299-2-C

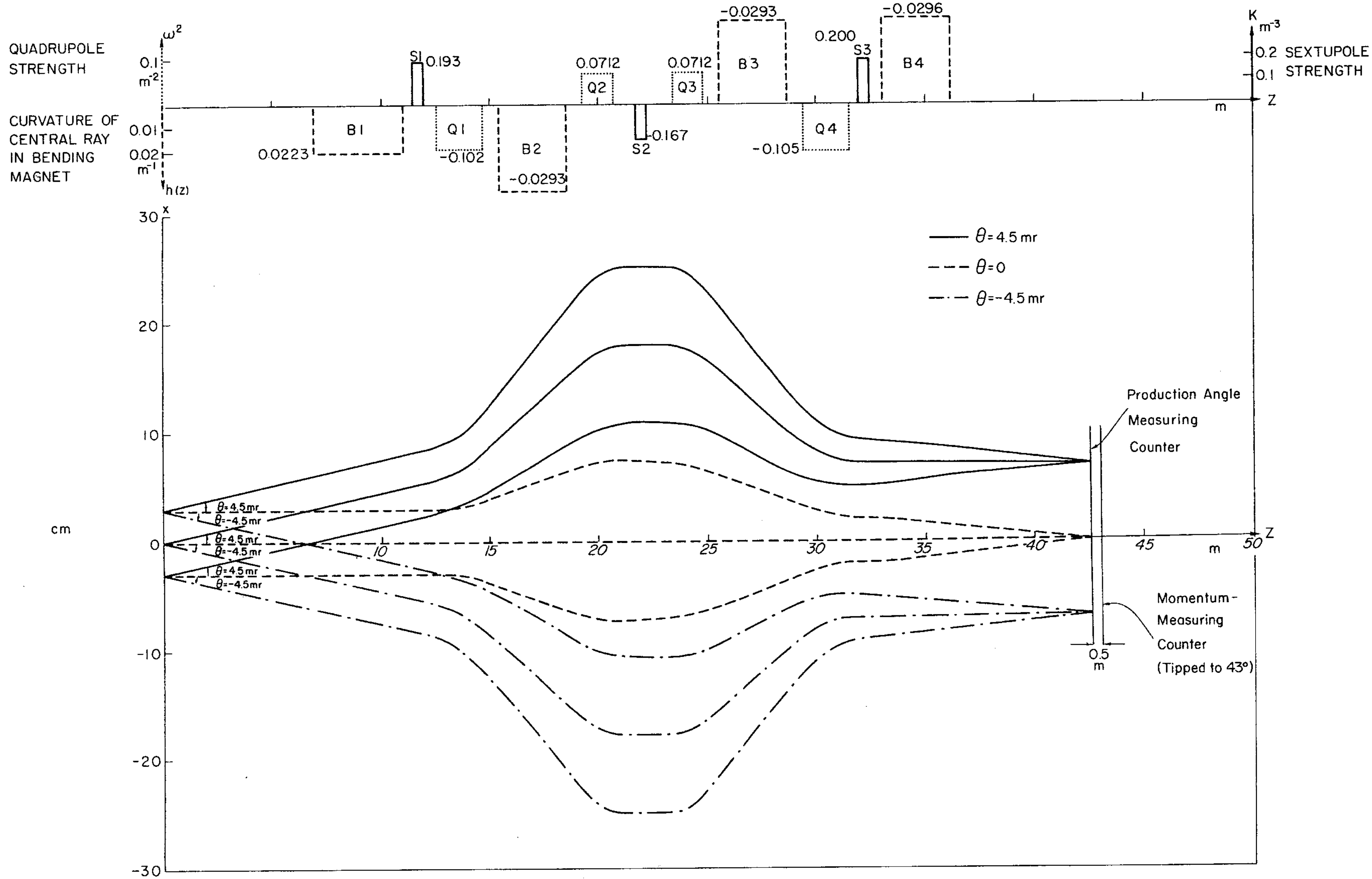
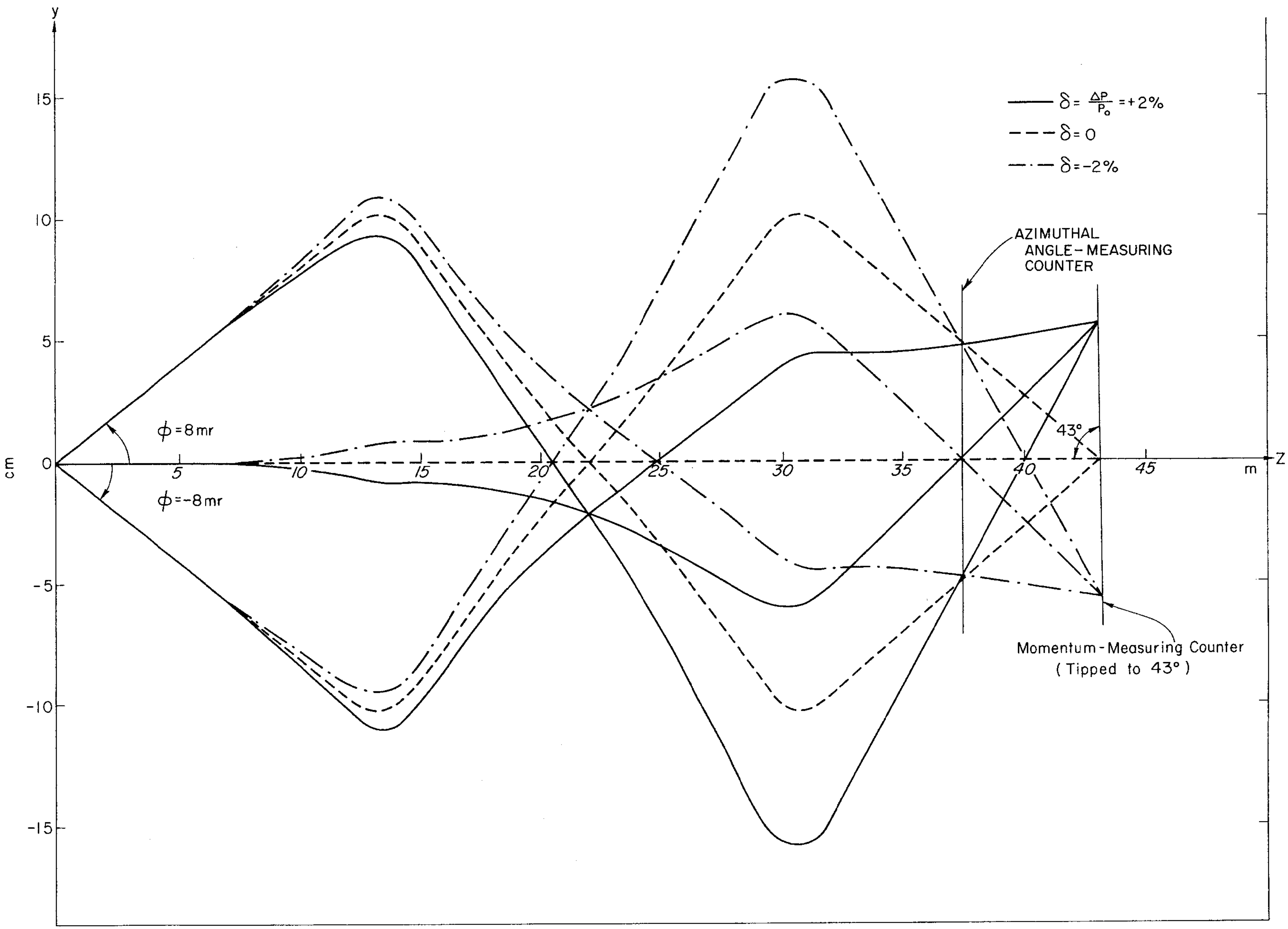


FIG. 6 FIRST-ORDER FOCUSING PROPERTIES OF THE 20-BeV/c SPECTROMETER IN THE HORIZONTAL PLANE



299-6-D

FIG. 7 -- FOCUSING PROPERTIES OF THE 20-BeV/c SPECTROMETER IN THE VERTICAL PLANE

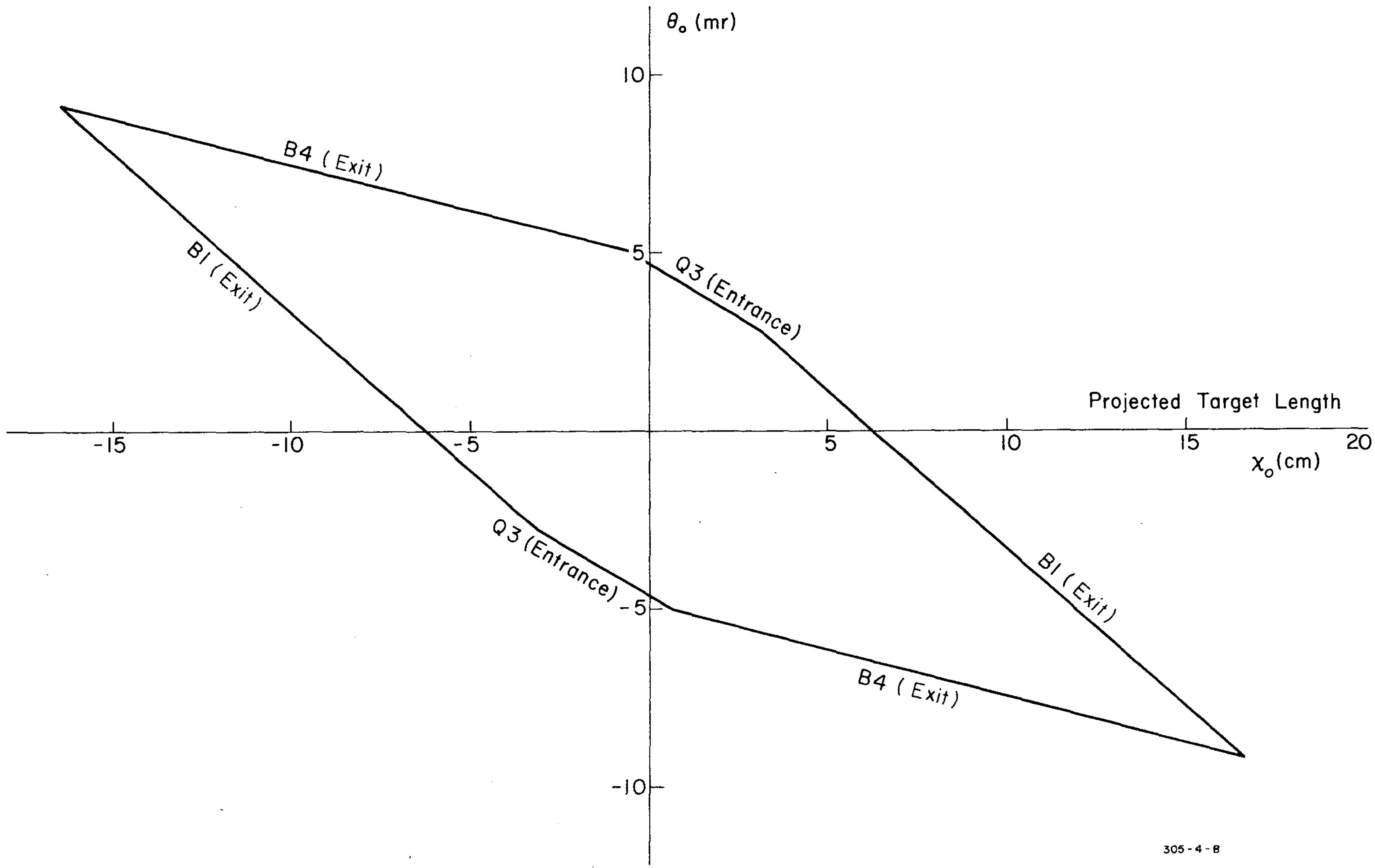


Fig.8 - θ_o ACCEPTANCE OF THE 20-BeV/c SPECTROMETER

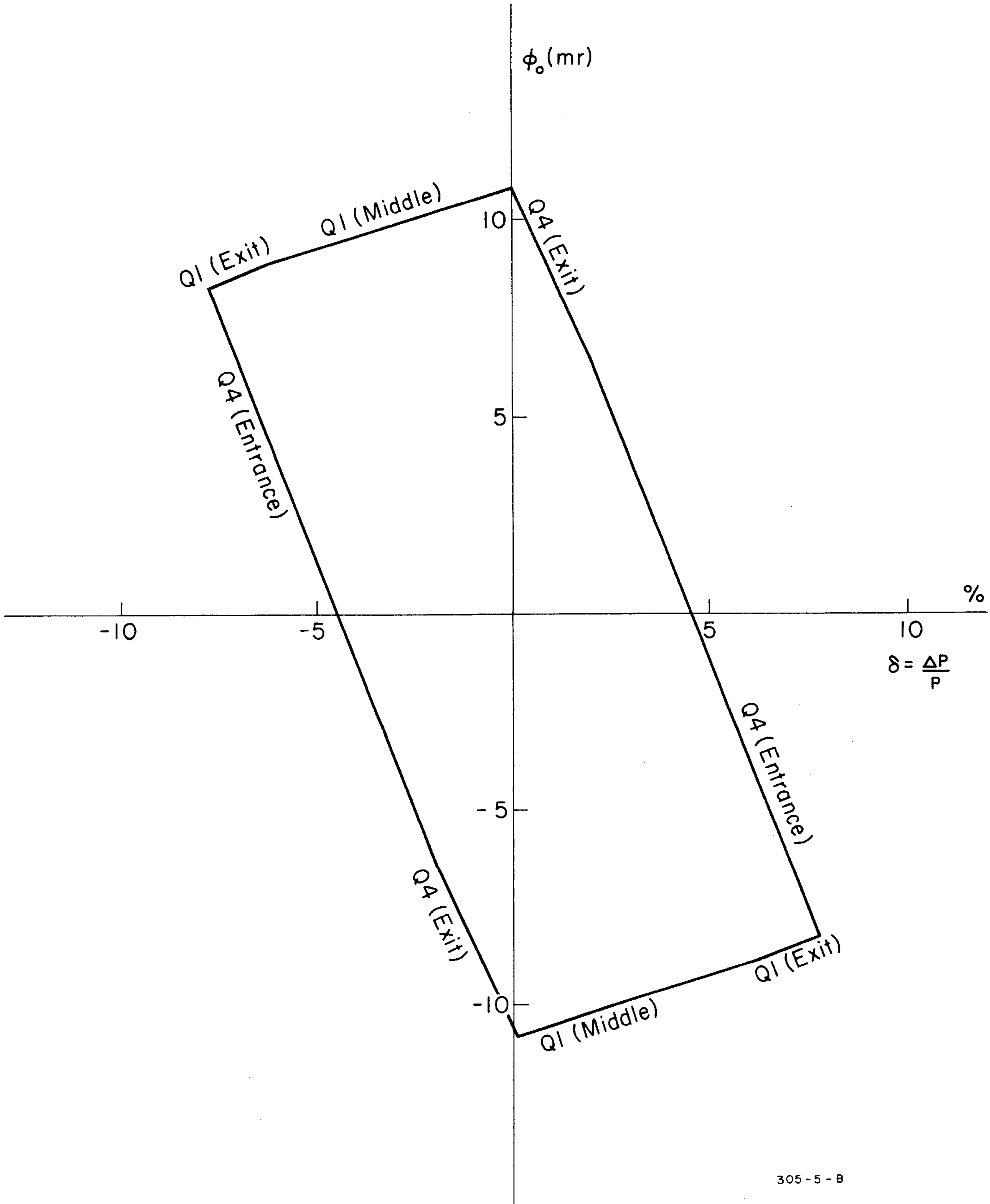


Fig. 9 - ϕ_o ACCEPTANCE OF THE 20-BeV/c SPECTROMETER

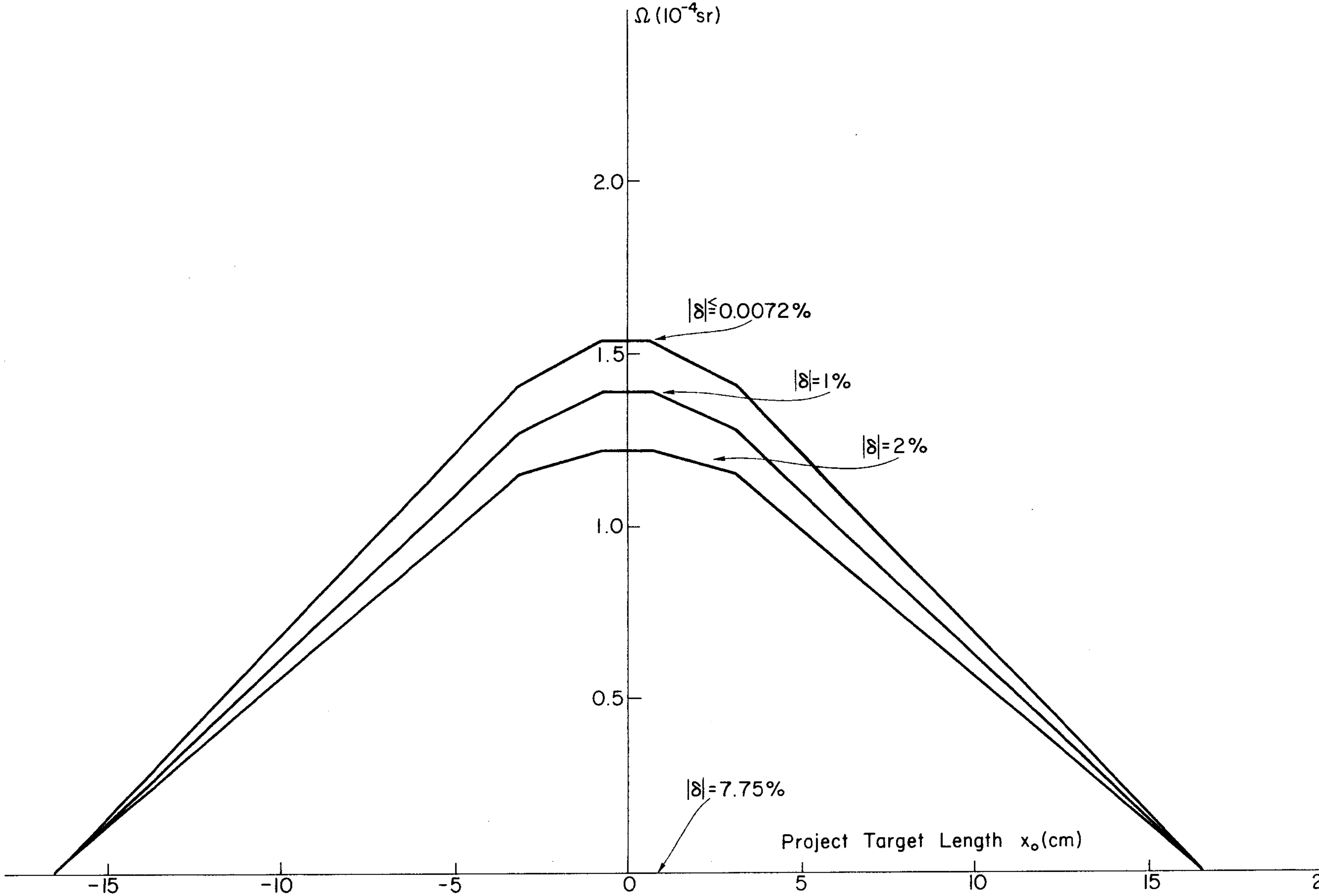


Fig.10--SOLID ANGLE OF ACCEPTANCE OF THE 20-BeV/c SPECTROMETER

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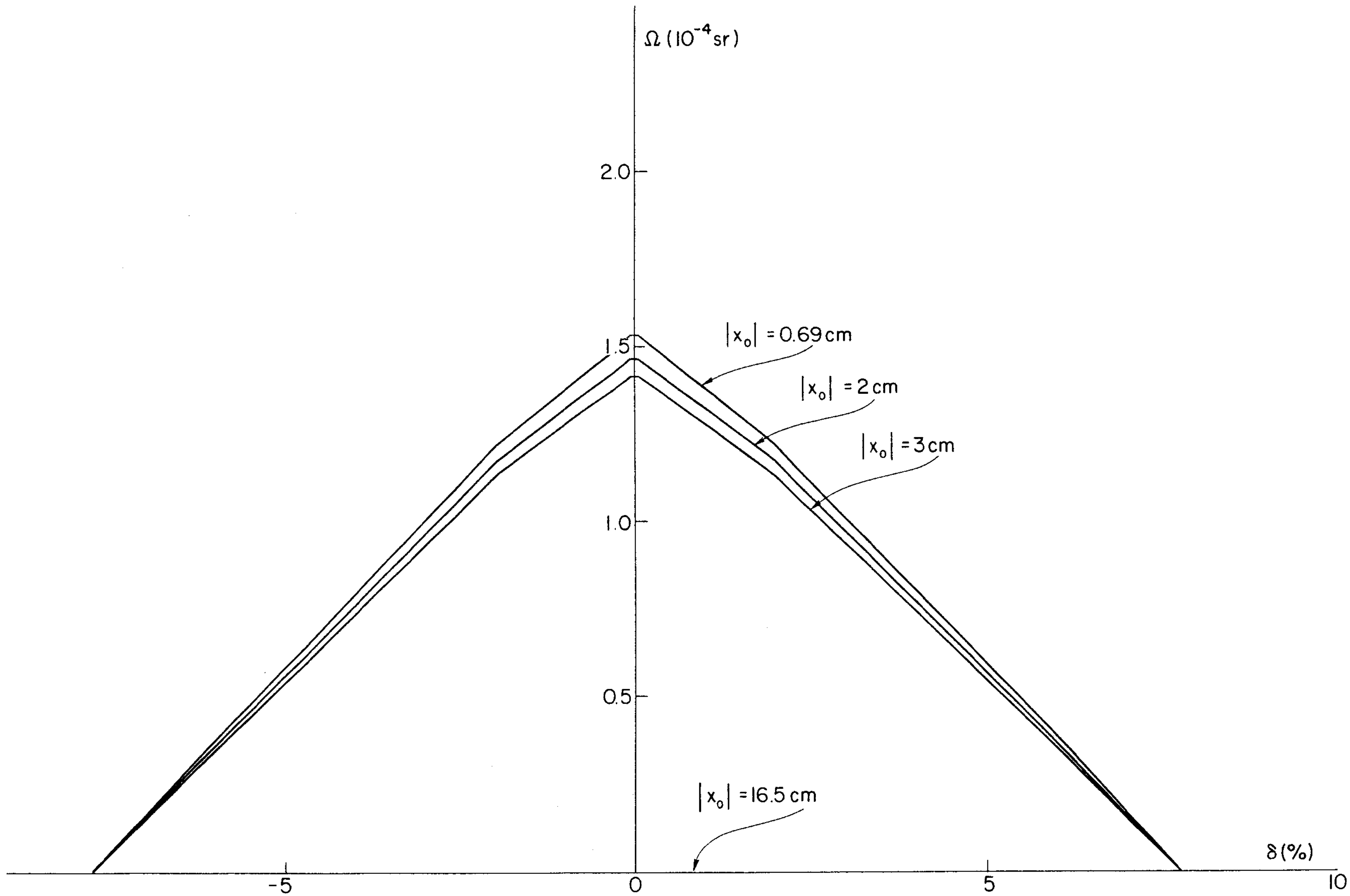

Fig. 11--SOLID ANGLE OF ACCEPTANCE OF THE 20-BeV/c SPECTROMETER

305-7-B