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A 45° INFLECTION SYSTEM FOR THE STANFORD TWO-MILE ACCELERATOR*

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Summary

A 45° inflector for the off-axis injectors is described. The system features second-order isochronous corrections to preserve accelerator bunch length. The correction is made with a combination sextupole-quadrupole, the design for which is also included.

Introduction

The design of the two-mile linear accelerator includes the provision for two off-axis injectors located at the ends of the tenth and twentieth sectors of the thirty-sector machine. These extra injectors will greatly increase the reliability and the versatility of the accelerator. In addition, by using the auxiliary beam take-off provisions that are located just ahead of each off-axis injector, the accelerator can be operated as two, or even three, separate accelerators.

Probably the most important need for the off-axis injectors is to increase the reliability of the whole accelerator. Virtually no other single active component except the main injector is essential to operating the accelerator. By using one of the off-axis injectors when the main injector requires service, it may be possible to operate satisfactorily for all experiments except those requiring either the maximum energy or requiring a positron beam. The reason for the latter restriction is that the positron source for the accelerator is located immediately downstream from the first off-axis injector.

One of the most valuable features of the two-mile accelerator is the multiple beam provision. As many as six different "beams" can be accelerated on consecutive pulses. The different beams can be directed to one of the experimental areas by magnets in the beam switchyard. The off-axis injectors will greatly enhance these multiple-beam features by allowing the experimenter a much wider choice of parameters from which to specify beam requirements.

Each off-axis injector will be basically identical to the 30-MeV main injector which is located at the beginning of the accelerator.[1] The essential difference is that the off-axis injector is positioned at a 45° angle to the main accelerator axis, and this requires a magnetic inflection system to transport the beam and bend it on the axis.

Inflection System

The principal requirement for the inflection system is that it must bend the beam onto the main axis without degrading the beam parameters significantly. The secondary requirement is that the main beam is not affected so that multiple beam operations using two or more injectors are possible. The beam parameters which pertain to the inflection problem are the transverse momentum, the spot size, the energy, the momentum spread, and the bunch length. These parameters are summarized in Table I.

TABLE I

Input Beam Parameters

Horizontal spot	Δx	± 0.5 cm
Horizontal deviation	$\Delta\theta$	$\pm 3.3 \times 10^{-4}$ radian
Vertical spot	Δy	± 0.5 cm
Vertical deviation	$\Delta\varphi$	$\pm 3.3 \times 10^{-4}$ radian
Bunch length	Δz	± 0.8 mm
Momentum spread	$\Delta p/p$	$\pm 5.0\%$
Energy	E	30 MeV

To preserve the bunch length, the inflection system must be isochronous even though the total momentum spread is 10%. The term "isochronous" describes a system for which the transit time is a constant for all trajectories. The bunch length is important because it is the characteristic of the beam which determines the final energy spread in the accelerator. One can visualize a bunch of electrons riding the traveling wave through the disk-loaded waveguide. If the accelerator is properly phased, the bunch will be near the crest of the wave. The longer the bunch, however, the more some electrons will be spread out away from the crest, thus being accelerated less than the electrons nearer the crest.

A variety of systems was considered for the inflector. The simplest system, and the one which gives the best results, consists of a pair of 22.5° bending magnets separated by a horizontal focusing quadrupole lens. To avoid defocusing the beam vertically, the rays are focused vertically to a horizontal line at the center of the quadrupole by rotating the inner faces of the bending magnets. The function of the quadrupole is to refocus rays of various momenta as they spread from the first bending magnet. The focal length of the quadrupole is set for the nominal distance between centers of the bending magents. This system is shown in Fig. 1.

The analysis of the inflector was made by using the IBM 7090 computer with the program TRANSPORT.[2] Table II shows the results for the first- and second-order calculations using TRANSPORT.

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First-order calculations use only single powers of the beam parameters, e.g., Δx; second-order calculations include terms in $\Delta x \Delta \theta$, etc. The table is based on a 30 MeV beam.

TABLE II

Beam Opitcs for Inflection System

Parameter	Output First Order	Output Second Order
Δx	± 0.5 cm	± 0.93 cm
$\Delta \theta$	$\pm 3.3 \times 10^{-4}$ rad	$\pm 3.76 \times 10^{-4}$ rad
Δy	± 0.5 cm	± 0.56 cm
$\Delta \varphi$	$\pm 3.3 \times 10^{-4}$ rad	$\pm 3.31 \times 10^{-4}$ rad
Δz	± 0.8 mm	± 5.76 mm
$\Delta p/p$	± 5.0 %	± 5.0 %

From the table it is apparent that when second-order effects are included, the system is not satisfactory as it stands. The worst trouble is the debunching which is mostly due to chromatic aberration in the quadrupole. Chromatic aberration causes both high and low momenta rays to travel a longer path in the second bending magnet. The aberration can be corrected by adding a sextupole element to the quadrupole. Qualitatively the effect of the sextupole is to increase the strength of the quadrupole on the side toward which the higher energy rays are deflected and to decrease it on the other side. The sextupole correction is needed only in the horizontal plane of the quadrupole and can be added by suitably modifying the quadrupole. By actually over-correcting the quadrupole, the high and low momenta rays are allowed to make the final bend on the inside of the main trajectory; thus they take a shorter path through the second bending magnet and make up for the long path they took through the quadrupole. This recombination of the bunch is shown schematically in Fig. 2. Table III shows the calculated results of the sextupole-corrected system.

TABLE III

Sextupole-Corrected Rotated Pole Face System
(25 MeV and 68.0-cm radius)

Δx	± 0.92 cm
$\Delta \theta$	$\pm 3.75 \times 10^{-4}$ rad
Δy	± 0.56 cm
$\Delta \varphi$	$\pm 3.31 \times 10^{-4}$ rad
Δz	± 0.81 mm
$\Delta p/p$	± 5.0%

The choice of radius was made as a compromise between using the largest possible magnets to reduce the effects of fringing fields and the maximum dimensions available within the confines of the inflector housing.

Compensating System

The bending magnet at the end of the inflector must lie on the main beam axis. To avoid the problems inherent in attempting to pulse this magnet when the main and the off-axis injector beams are operating simultaneously, a compensating magnet system is required upstream to counter the effect of the last inflector magnet on the main beam. Three magnets, each identical to the last inflector magnet, are used to restore both the lateral position and the direction of the beam so that it is centered on, and parallel to, the accelerator axis. These magnets, mounted as shown in Fig. 3, have essentially no effect on the phase space of the high energy beam on the main axis.

The first of the three compensating magnets bends the beam in the same direction as the last of the inflector magnets. The two middle magnets then bend the beam by twice the angle for each of the others and in the opposite direction. The net result is that the beam is neither deflected nor translated by the system.

Sextupole-Quadrupole

The beam in the horizontally focusing quadrupole is at a point of vertical focus. Thus the fields above or below the horizontal plane of symmetry are of no specific interest. It is possible to modify a quadrupole to obtain a combination quadrupole and sextupole field along the horizontal or x axis. The desired field has the dependence

$$B_y = ax + bx^2, \quad B_x = 0 \ (y = 0, \text{ only}) \qquad (1)$$

where a and b are arbitrary constants.

It is conventional to consider the ordinary quadrupole field as derived from the scalar potential

$$V = axy. \qquad (2)$$

The location of the pole surfaces is then found from the ordinary equation for a set of hyperbolas,

$$xy = V/a \ , \qquad (3)$$

where 2V/a is the square of the radius of the bore hole. By differentiating Eq.(2) from $\vec{B} = -\vec{\nabla} V$, the usual linear field is found for both axes.

If we choose a similar potential function,

$$V = -(axy + bx^2y + cy^3), \qquad (4)$$

we find for the vertical field

$$B_y = -\frac{\partial V}{\partial y} = ax + bx^2 + 3cy^2 \qquad (5)$$

which agrees with the requirement of Eq. (1) at $y = 0$.

The horizontal field component is given by

$$B_x = -\frac{\partial V}{\partial x} = ay + 2bxy \ . \qquad (6)$$

From Maxwell's equation, $\vec{\nabla} \cdot \vec{B} = 0$,

$$\frac{\partial B_x}{\partial x} = 2by = - \frac{\partial B_y}{\partial y} = - 6cy, \qquad (7)$$

from which $c = - b/3$.

From the TRANSPORT program results it was learned that the correct ratio for sextupole field to quadrupole field was 0.1 at 8 cm. Then from Eq. (1), $8a = 64b \times 10$ and $b = a/80$. Thus Eq. (4) becomes

$$\frac{V}{a} = - xy - y \left(x^2 - \frac{y^2}{3}\right) / 80. \qquad (8)$$

Equation (8) shows, on inspection, that the sextupole modification is only a relatively small perturbation of the pure quadrupole. The shape of the quadrupole is shown in Fig. 4. Only the upper half of the quadrupole is shown because, by symmetry, the lower half is identical. Figure 4 is made from an automatic computer plot showing the family of equipotentials. Analysis of the computer solution for the potentials shows that the fields agree with the analytic solution within about 0.1% even though the poles are terminated at a finite distance.

List of References

1. This system is described in paper H-8 of the IEEE Particle Accelerator Conference, "The SLAC Injector," by Roger H. Miller, R. F. Koontz, and D. D. Tsang.

2. H. S. Butler, S. K. Howry, and C. H. Moore, "TRANSPORT: A Computer Program for Designing Beam Transport Systems." Internal Report, Stanford Linear Accelerator Center, Stanford University, Stanford, California (1963).

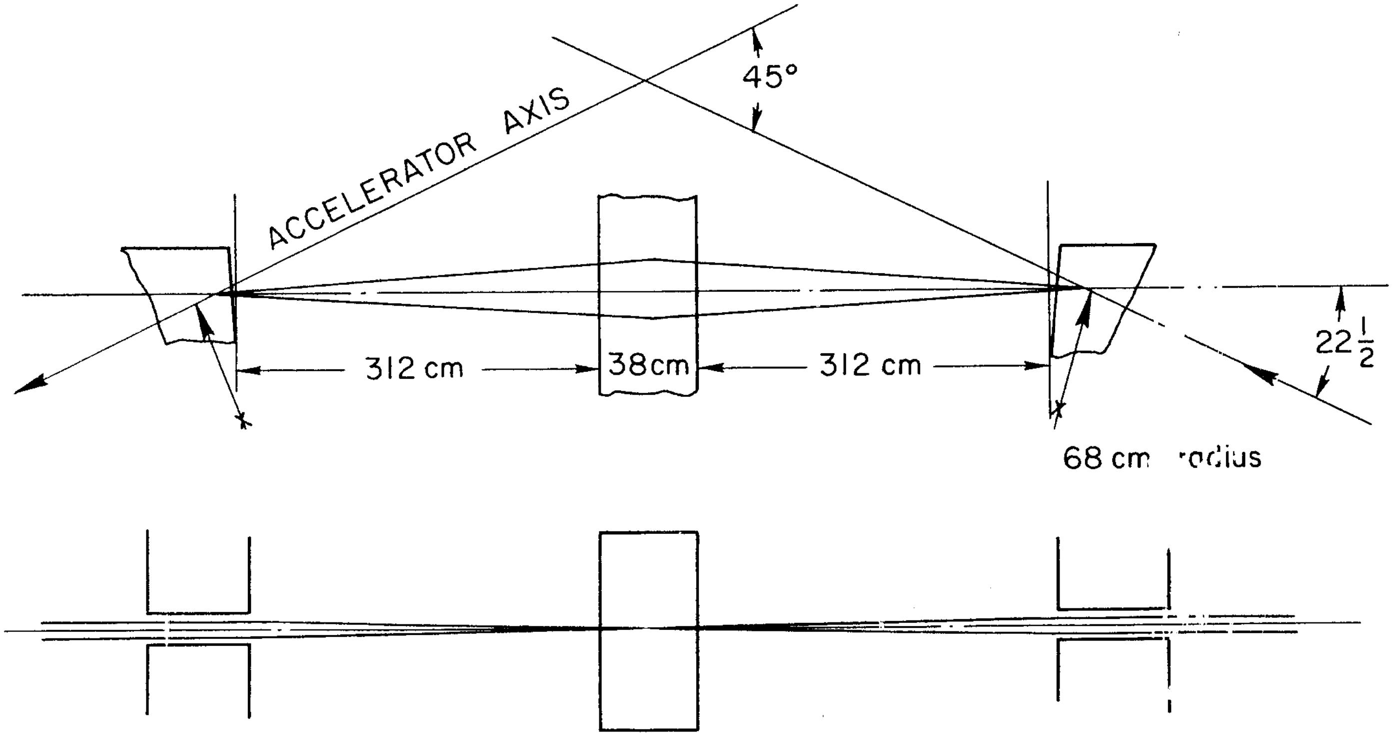


FIG. I 45° INFLECTION SYSTEM

232-1-A

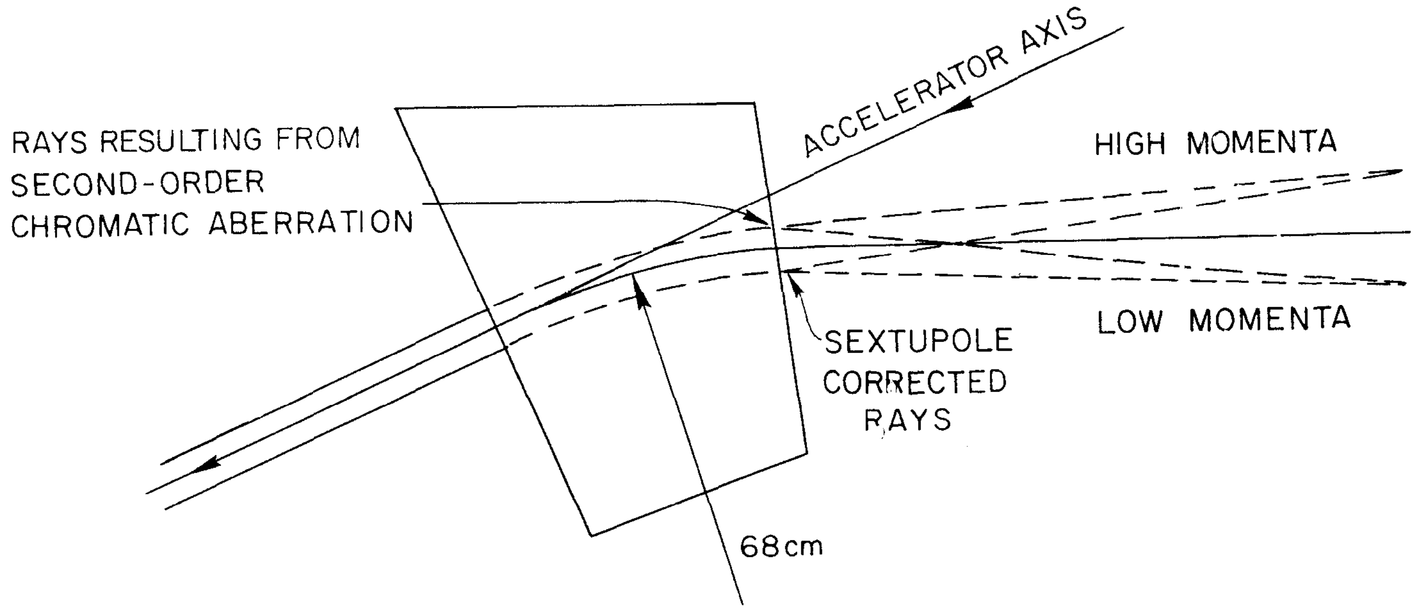
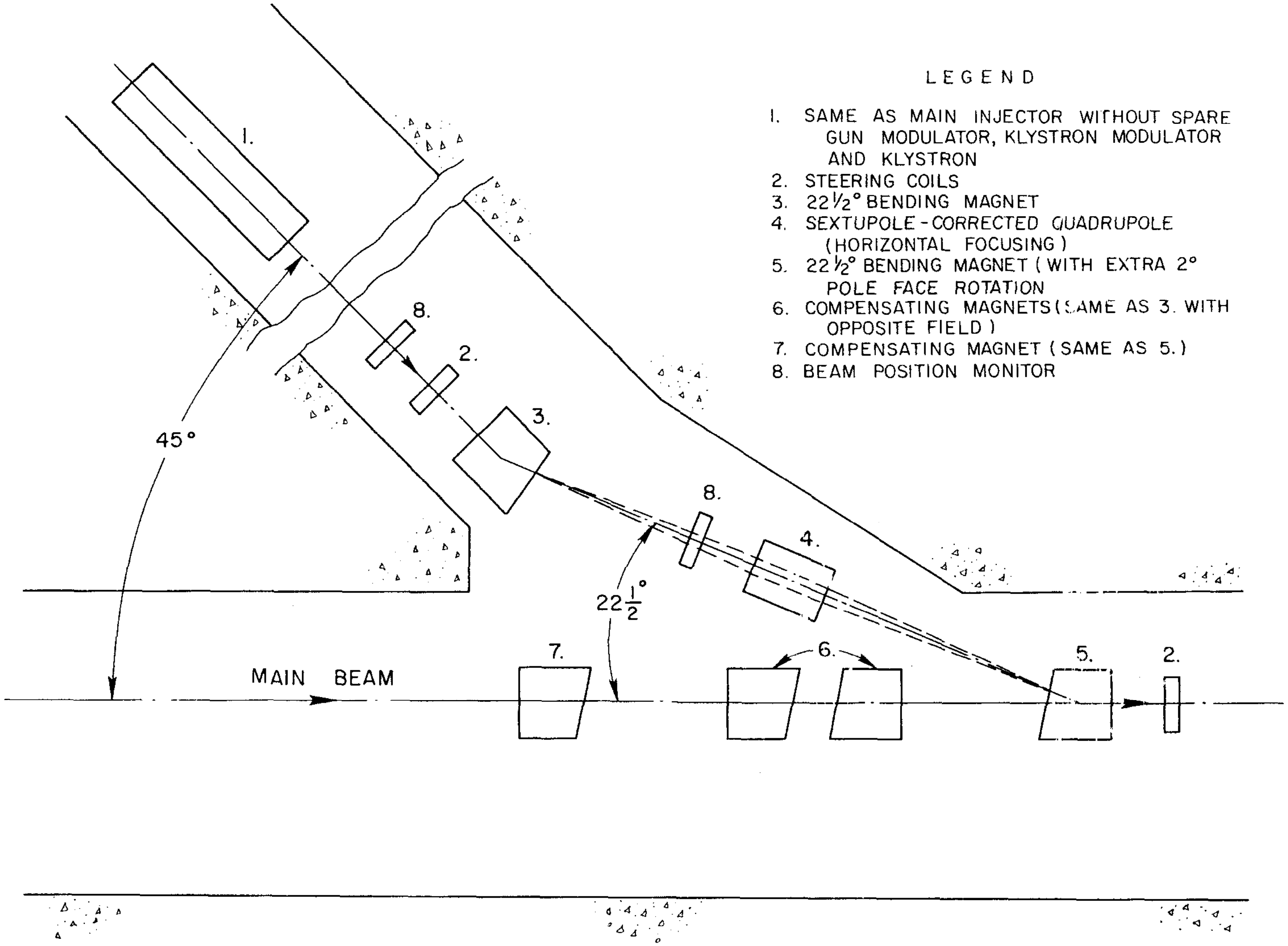


FIG. 2 THE EFFECT OF THE SEXTUPOLE CORRECTION

232 - 2 - A



LEGEND

1. SAME AS MAIN INJECTOR WITHOUT SPARE GUN MODULATOR, KLYSTRON MODULATOR AND KLYSTRON
2. STEERING COILS
3. 22½° BENDING MAGNET
4. SEXTUPOLE-CORRECTED QUADRUPOLE (HORIZONTAL FOCUSING)
5. 22½° BENDING MAGNET (WITH EXTRA 2° POLE FACE ROTATION
6. COMPENSATING MAGNETS (SAME AS 3. WITH OPPOSITE FIELD)
7. COMPENSATING MAGNET (SAME AS 5.)
8. BEAM POSITION MONITOR

FIG. 3 OFF-AXIS INJECTOR LAYOUT

232-3-B

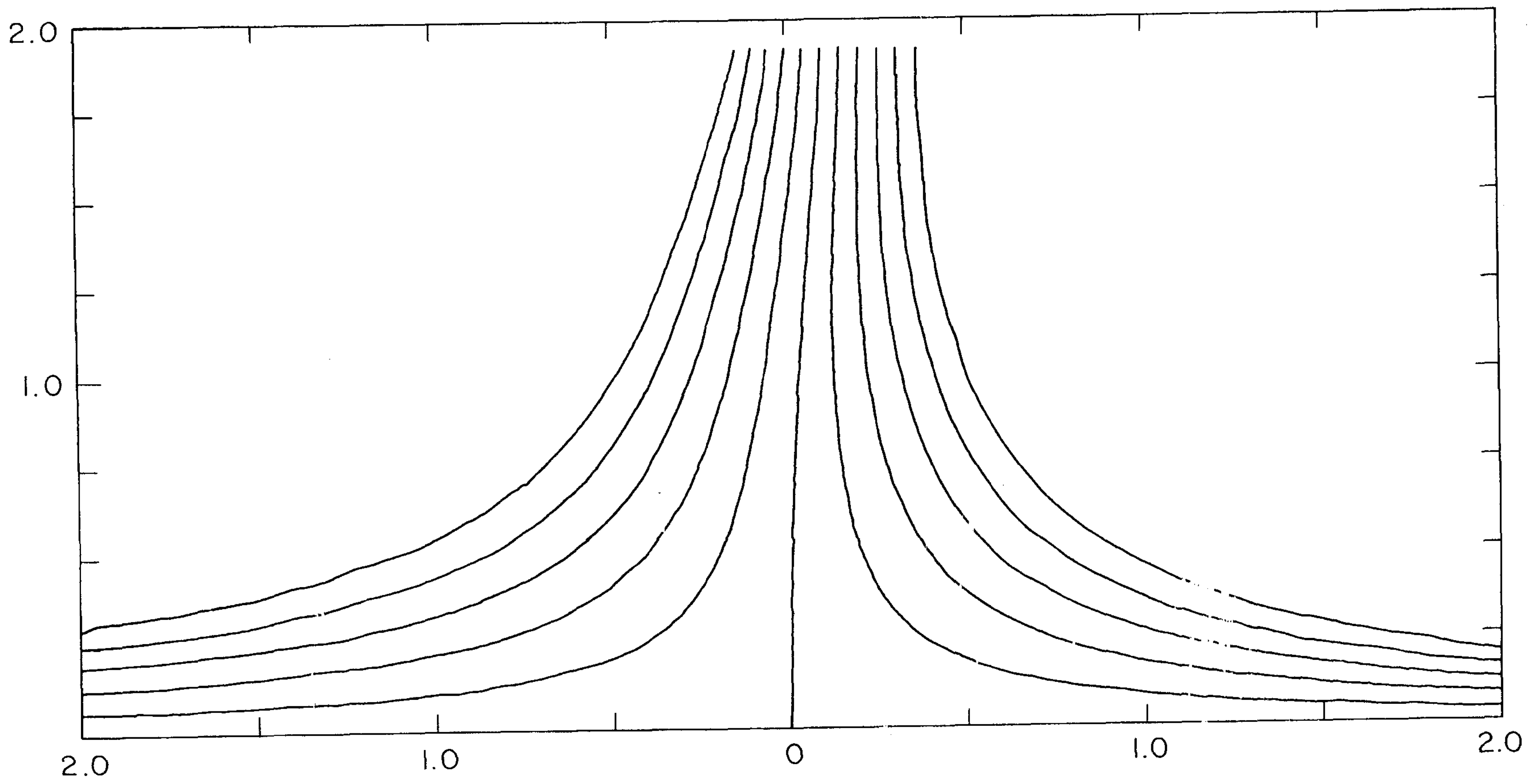


FIG. 4 SEXTUPOLE-QUADRUPOLE FOR OFF-AXIS INFLECTOR

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