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1. Introduction

This paper describes briefly, and mainly from an ion optical point of view, the beam transport system for the Berkeley 88-inch cyclotron. Particular attention will be paid to a bending system that has been designed to deflect the beam through an angle of 104 deg in order to guide it into the cave provided for high-intensity bombardments. It has, of course, been necessary to base the design parameters for the various elements of the system on theoretical information about, e.g., the extracted beam. It is likely that modifications and changes will have to be made in the near future when enough experience has been gained regarding the performance of the magnetic lenses. In general, the beam-transport system has been designed with as much flexibility as possible, to allow for such changes.

2. General Layout

Figure 1 shows a schematic layout of the beam-transport system. The beam emerging from the cyclotron is focused by a quadrupole doublet Q_1, and directed into a switching magnet M_S, which bends it into any one of several

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[†] Work done under the auspices of the U.S. Atomic Energy Commission.

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experimental caves. For further focusing outside the cyclotron vault, quadrupole lenses (Q_3 to Q_6) will be provided. These lenses will probably be arranged as doublets, but they can, if it becomes desirable, also be arranged as triplets. (For slight adjustments of the orientation of the beam before it enters M_S, a steering magnet between Q_1 and M_S has been contemplated.)

To reach the cave provided for high-intensity bombardments the beam has to be bent through 104 deg. This is accomplished by means of the switching magnet M_S and a 47-deg sector magnet M_B. A quadrupole doublet downstream from M_B will focus the beam onto the target T. When calculating the optical properties of this bending system, two alternate positions of the downstream quadrupole lens have been considered (Q_2 and Q_2^*).

3. The Magnetic Lenses

All quadrupoles shown in the layout (fig. 1) have an aperture of 4 in. and are of a standard type designed at Lawrence Radiation Laboratory. The standard doublets are assembled from 8-in. long units. Some 16-in. units will be available for possible triplets.

The switching magnet M_S is of the circular-pole type, with a uniform field. The physical pole diameter is 40 in., and the gap is 3 in. The pole tips consist of demountable pole disks, and this makes it possible to change the gap if desirable (it can be increased to a maximum of 4 in.). The total weight of the switching magnet is about 27 metric tons. With a 3-in. gap, a field of about 19.5 kG can be attained. The field needed to bend 66-MeV deuterons through an angle of 57 deg. is roughly 16 kG. The exact field value will depend on the effect of the fringe field.

The design parameters for the bending magnet M_B had to be chosen so as to fit the dimensions of the switching magnet, which was already designed mentioned here that bending systems can be designed which have (to the first order) no dispersion in the final beam. Penner$^{2)}$ has discussed such an arrangement for 90 deg deflection, as suggested to him in a private communication with K. L. Brown. In the present case a system of two bending magnets combined with a downstream quadrupole doublet seemed to represent a simple and adequate solution. According to first-order calculations it will be possible to obtain a rather narrow beam spot at the target. In particular, the calculations show that it is possible in this way to make the radial size of the beam at the target only slightly dependent on the momentum dispersion caused by the bending magnets. If later it becomes necessary to modify this system, the insertion of a single quadrupole between the two magnets might be considered.

Figure 3 illustrates the principal arrangement of the 104-deg bending system. In the first-order study of this arrangement, the switching magnet M_S has been considered as a 57-deg sector with straight pole edges. (This assumption is, of course, very nearly true as long as only a narrow region on each side of the optic axis is considered. However, the possibility of making empirical corrections by shaping the pole edges has been kept in mind.)

As already mentioned, both M_S and M_B are of the uniform-field type. The optic axis of the system is the central trajectory of ions with the momentum p_0 (the average momentum). For this trajectory the entry into, and exit from, the magnets are assumed to be perpendicular to the pole boundaries.

Basically, the arrangement has been designed in such a way that a beam (of ions of a given momentum) that is initially parallel in the radial plane will be transformed to a finally parallel or almost-parallel beam. We assume (see fig. 3) that a ray of ions with various momenta enters M_S parallel with the optic axis. If we suppose that the two magnets both have a focal plane at F (for ions of the average momentum p_0), the outgoing ray R of ions with momentum p_0 will, of course, also be parallel with the optic axis. A ray R_1 of momentum $p_0 + \Delta p$ will leave M_B displaced with respect to R and also, in general, with a slope to this ray. If we suppose that both R and R_1 could be made parallel with the optic axis, then it is easy to realize that a quadrupole doublet downstream from M_B could focus both rays to approximately the same point on the optic axis (taking into account that the quadrupole does not give rise to any first-order dispersion).

A first-order study of this system has shown that conditions can be found that not only make R parallel or almost parallel with the optic axis, but also make the slope of R_1 with respect to R, due to the momentum spread Δp, negligibly small. If, under such circumstances, a quadrupole doublet downstream from M_B (Q_2 of Q_2^* in fig. 1) is made to focus the beam to the target (T, fig. 1), the radial beam size at the target will only be affected very slightly by the momentum dispersion caused by the bending magnets.

For the first-order calculations referred to here, the matrix method[2, 3]) has been used. The following discussion deals mainly with the beam properties in the radial plane. The coordinates that describe a particle trajectory in this plane are the radial displacement x with respect to the central ray, the slope α, and the momentum spread, which is given by the ratio $\Delta p/p_0$. It is assumed that x is small compared to the bending radii ρ_1 and ρ_2, that α is small (maximum is a few degrees), and also that Δp is small compared to p_0. If M_x is the radial plane transfer matrix for the total system $M_S - M_B$, we have

$$M_x = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{pmatrix}, \qquad (1)$$

where

and ordered. The first-order numerical calculations used as a basis for these parameters will be discussed below. The space available for M_B was relatively limited. We found that the distance between the centers of M_S and M_B ought to be somewhere in the range 110 to 115 in. This distance was one of the parameters determining the choice of bending radius for M_B. The pole-sector parameters finally chosen are shown in fig. 2. As seen from this figure, the radius of curvature for the central arc is 45 in. The width of the pole sector has been made as large as 14 in. in order to insure as uniform a field as possible within the region occupied by the beam. The bending magnet has a gap of 3 in. and weighs about 6 metric tons. A field of about 18 kilogauss can be produced. The field needed to bend 66-MeV deuterons through 47 deg will be about 15 kG.

When determining the pole-face dimensions for M_S and M_B, the concept of a virtual (effective) field boundary[1]) has been used to account for the effect of the fringe field, as illustrated in fig. 2. If d is the separation between this boundary and the physical field boundary, one has $d = k \times g$, where g is the magnet gap and k is a factor that magnet designers often put equal to 1. Available field curves for magnets of a design similar to the ones described here indicated, however, that $k = 0.7$ could be assumed to be a reasonable average value.

4. Ion Optical Properties of the 105-deg Bending System

As previously mentioned, the purpose of this bending system is to bend the beam to the target in the high intensity cave with, if possible, no intensity losses. The area of the target is limited by a circle of 1 in. diam. The main goal in designing this system has been to eliminate, or decrease as much as possible, the momentum dispersion caused by the bending magnets. It may be

$$a_{11} = \cos\theta_1 \cos\theta_2 - \frac{\sin\theta_1}{\rho_1} (L \cos\theta_2 + \rho_2 \sin\theta_2) ,$$

$$a_{12} = \rho_1 \sin\theta_1 \cos\theta_2 + (L \cos\theta_2 + \rho_2 \sin\theta_2) \cos\theta_1 ,$$

$$a_{13} = \rho_1 (1 - \cos\theta_1) \cos\theta_2 + (L \cos\theta_2 + \rho_2 \sin\theta_2) \sin\theta_1 + \rho_2 (1 - \cos\theta_2) ,$$

$$a_{21} = \frac{L}{\rho_1 \rho_2} \sin\theta_1 \sin\theta_2 - \frac{1}{\rho_1} \sin\theta_1 \cos\theta_2 - \frac{1}{\rho_2} \cos\theta_1 \sin\theta_2 ,$$

$$a_{22} = \cos\theta_1 \cos\theta_2 - \frac{1}{\rho_2} (\rho_1 \sin\theta_1 + L \cos\theta_1) \sin\theta_2 ,$$

$$a_{23} = \sin\theta_1 \cos\theta_2 + \sin\theta_2 - \frac{1}{\rho_2} [\rho_1 (1 - \cos\theta_1) \sin\theta_2 + L \sin\theta_1 \sin\theta_2] .$$

We denote with x_0 and a_0 the particle coordinates at entry to M_S, and with x_e and a_e the coordinates at exit from M_B. Then we have, from the transfer matrix (1):

$$x_e = a_{11} x_0 + a_{12} a_0 + a_{13} (\Delta p / p_0) , \tag{2}$$

$$a_e = a_{21} x_0 + a_{22} a_0 + a_{23} (\Delta p / p_0) \tag{3}$$

If $a_{21} = 0$, ions of momentum p_0 entering M_S as a parallel beam will also leave M_B as a parallel beam. The dispersion caused by the system is determined by the matrix elements a_{13} and a_{23}.

When the studies of the 104-deg bending system were started, the switching magnet M_S was already designed and ordered. Due to this fact, ρ_1 was a fixed quantity. Taking into account that the above-mentioned factor k is not accurately known, and that it also will vary as the field is changed, ρ_1 has been estimated to fall in the range 38.5 to 42.5 in. (corresponding to a variation of k between 0.3 and 1); $\rho_1 = 41$ in. has been considered as a probable average value. The bending angles $\theta_1 = 57$ deg and $\theta_2 = 47$ deg were also given quantities. Furthermore, the distance between the centers of the two magnets was, as mentioned, relatively fixed. The first step of the calculations was now to find a value for ρ_2 that could make the system fulfill the conditions briefly discussed above. As a result of this, a ρ_2 value of 45 in. was chosen as a suitable average value. However, to make allowance for a variation of k between 0.3 and 1, it has been assumed that ρ_2 may fall in the range from 42 to 47 in.

Figure 4 shows the matrix elements a_{13} through a_{23} as functions of the separation L between M_S and M_B for various sets of values of ρ_1 and ρ_2. (For the values of the matrix elements given in fig. 4, the units for x and α in eqs. (2) and (3) are inches and radians, respectively.) With the geometry available, L has to be approximately 70 in. (plus or minus a few inches). The figure shows that for L = 70 inches, $\rho_1 = 41$ in., and $\rho_2 = 45$ in. the element a_{21} comes very close to zero, and a_{23} becomes so small that the term $a_{23}(\Delta p/p_0)$ in eq. (3) becomes almost negligible ($|\Delta p/p_0| \leq 0.002$). In this case, an initially parallel beam of particles with a given momentum will leave the system as an almost parallel beam. Due to the small value of a_{23} the slope of outgoing rays with respect to the optic axis will be only very slightly affected by $\Delta p/p_0$.

To determine the radial beam size at target and, in general, verify the behavior of the 104-deg bending arrangement, a number of rays have been traced from source to target for 64-MeV deuterons. For this purpose, the transformation matrices for the various steps have been calculated. The field-strength parameters for the quadrupole lenses have been derived on the basis of curves of the type described by Enge[4].

The position of the apparent (virtual) radial source and the beam coordinates at this source have been calculated from the radial transfer matrix[5] for the deflector channel and the fringe field to a distance of about 3 31.5 in. downstream from the end of the channel (to E - E in fig. 5). The space from E - E to the entrance of the first quadrupole (Q_1) has been assumed to be field-free. The coordinates x_s and a_s at the apparent source have been estimated by assuming an effective diffuse source to be at the entrance of the deflector channel. The radial width of the apparent source (for a given momentum) as calculated in this way is only about 0.016 in., which means that the source is almost a point source. The maximum slopes for the outgoing rays have been determined by assuming that the width of the deflector channel at exit has the value used in the calculation of the channel matrix (for 64-MeV deuterons). The location of the apparent source is about 8 in. upstream from the end of the deflector.

The relative momentum spread $\Delta p/p_0$ has been estimated to be ± 0.002. Due to the momentum dispersion, the centers of the sources corresponding to the maximum and minimum momenta, respectively, are separated a distance of about 0.16 in. (see fig. 5, S_1 and S_2).

Figure 5 shows the results of some of the beam calculations for 64-MeV deuterons. Two positions for the downstream quadrupole doublet have been considered (Q_2 and Q_2^*). The lens parameters for the quadrupole doublet Q_1 have been adjusted in such a way that outgoing rays of particles of a given momentum are very nearly parallel in the radial plane. Vertically, Q_1 produces a slightly converging beam. The parameters for the downstream quadrupole lens (Q_2 or Q_2^*) have been set to produce an image at the target, both in the radial plane and in the vertical plane. In both quadrupole doublets the upstream lens element has been made to focus radially and to defocus vertically. Two rays A and B from the sources S_1 and S_2 (defined above) have been traced to the target. The rays leaving the downstream quadrupole doublet are marked

A, B and A^*, B^*, respectively, for the two alternate positions of this quadrupole lens. Due to symmetry, the image points which the rays C and D produce at the target will be mirror images of the image points produced by A, B and A^*, B^*, respectively, (the reflection being made about the optic axis).

To get the actual radial width of the beam at the target, one has to add to the width obtained from fig. 5 a term $0.016 \times M$, where M is the total radial magnification of the system. This term becomes almost negligibly small (about 0.07 in. when Q_2 is placed 62 in. downstream from M_B). Taking this into account, the total radial width in the two cases becomes 0.93 and 0.65 in. respectively. It turns out that less than 0.1 in. is due to dispersion caused by the system $M_S - M_B$. The vertical size at target has been calculated by assuming that an effective diffuse source is at the entrance to the deflector channel and has a height of 0.5 in. Under these assumptions the vertical size of the beam at target in the two cases considered becomes approximately 0.5 and 0.2 in., respectively.

It should be emphasized that the cases illustrated in fig. 5 do not necessarily represent optimum conditions. These will, of course, be found in practice by proper adjustment of the quadrupole excitations.

5. Beam-Analyzing System

For a few years the switching magnet will be used to produce an analyzed beam along the 57-deg direction. Later an analyzing system will be available for the direct beam from Q_1.

A first-order calculation has been made of the momentum resolution for the case in which the system $Q_1 - M_S$ is set to produce a radial image on a slit 120 in. downstream from M_S (inside the vault, close to the shielding wall; compare fig. 1). If we assume that the properties of the apparent radial source are those discussed above, it seems feasible to obtain an analyzed beam of 64-MeV deuterons with a momentum resolution of approximately 0.05%.

Acknowledgments

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REFERENCES

1) See, e.g., K. T. Bainbridge's article in *Experimental Nuclear Physics*, Vol. 1, ed. by Emilio Segrè (John Wiley & Sons, Inc., New York, 1953), p. 585.

2) S. Penner, Rev. Sci. Instr. **32** (1961) 150. This paper discusses the matrix method for calculating properties of magnetic deflection systems.

3) D. L. Judd, Study of Ion Optical Theory and Design, University of Colorado Report UCOL P-502, July 1960 (unpublished). This report presents a general first-order theory, including a discussion of the matrix method, as well as a detailed second-order theory.

4) H. A. Enge, Rev. Sci. Instr. **30** (1959) 248.

5) These matrices were calculated by Dr. A. A. Garren and Mr. H. C. Owens. For details on the deflector calculations see A. A. Garren, D. L. Judd, Lloyd Smith, and H. A. Willax, Electrostatic Deflector Calculations for the Berkeley 88-inch Cyclotron, Lawrence Radiation Laboratory Report UCRL-10067, May 1962, Nucl. Instr. and Meth. (to be published).

FIGURE CAPTIONS

Fig. 1. General layout of the beam transport system. The deflector is indicated by D. Q_1 through Q_6 indicate quadrupole lenses (Q_2 and Q_2^* are alternate positions of the quadrupole doublet downstream from M_B); M_S is a switching magnet; and M_B is a 47-deg bending magnet.

Fig. 2. The pole sector of the 47 deg bending magnet. The dashed lines parallel with the pole edges indicate the virtual field boundaries. The geometry shown is based on the assumption that the intersection between the virtual field boundaries includes as a point the center of curvature for the sector arcs. In this case d is about 2.1 in.

Fig. 3. Principal arrangement of the 104 deg bending system M_S-M_B. The switching magnet M_S is here regarded as a sector magnet with straight pole edges. In the actual case, the sector angles are: $\theta_1 = 57$ deg, $\theta_2 = 47$ deg. With regard to the values of ρ_1 and ρ_2, see the text. The distance L is the separation between the virtual field boundaries.

Fig. 4. The matrix elements a_{11} through a_{23} of the radial-plane transfer matrix for the 104 deg bending system vs the magnet separation L (see fig. 3). Three cases have been considered, corresponding to different values for ρ_1 and ρ_2 (compare fig. 3): I, $\rho_1 = 42.5$ in., $\rho_2 = 47.0$ in. ; II, $\rho_1 = 41.0$ in., $\rho_2 = 45.0$ in.; III, $\rho_1 = 38.5$ in., $\rho_2 = 42.0$ in.

Fig. 5. Particle trajectories in the radial plane through the 104 deg bending system. In the calculations M_S has been considered a 57 deg sector magnet with straight pole edges (see fig. 3). The fringe-field has been assumed to end at E-E. Two positions of the downstream quadrupole doublet have been considered (Q_2 and Q_2^*; the corresponding

outgoing rays are A, B and A^*, B^*, respectively). The parameters used for the system $M_S - M_B$ are those represented by case II, fig. 4, with $L = 70$ in.

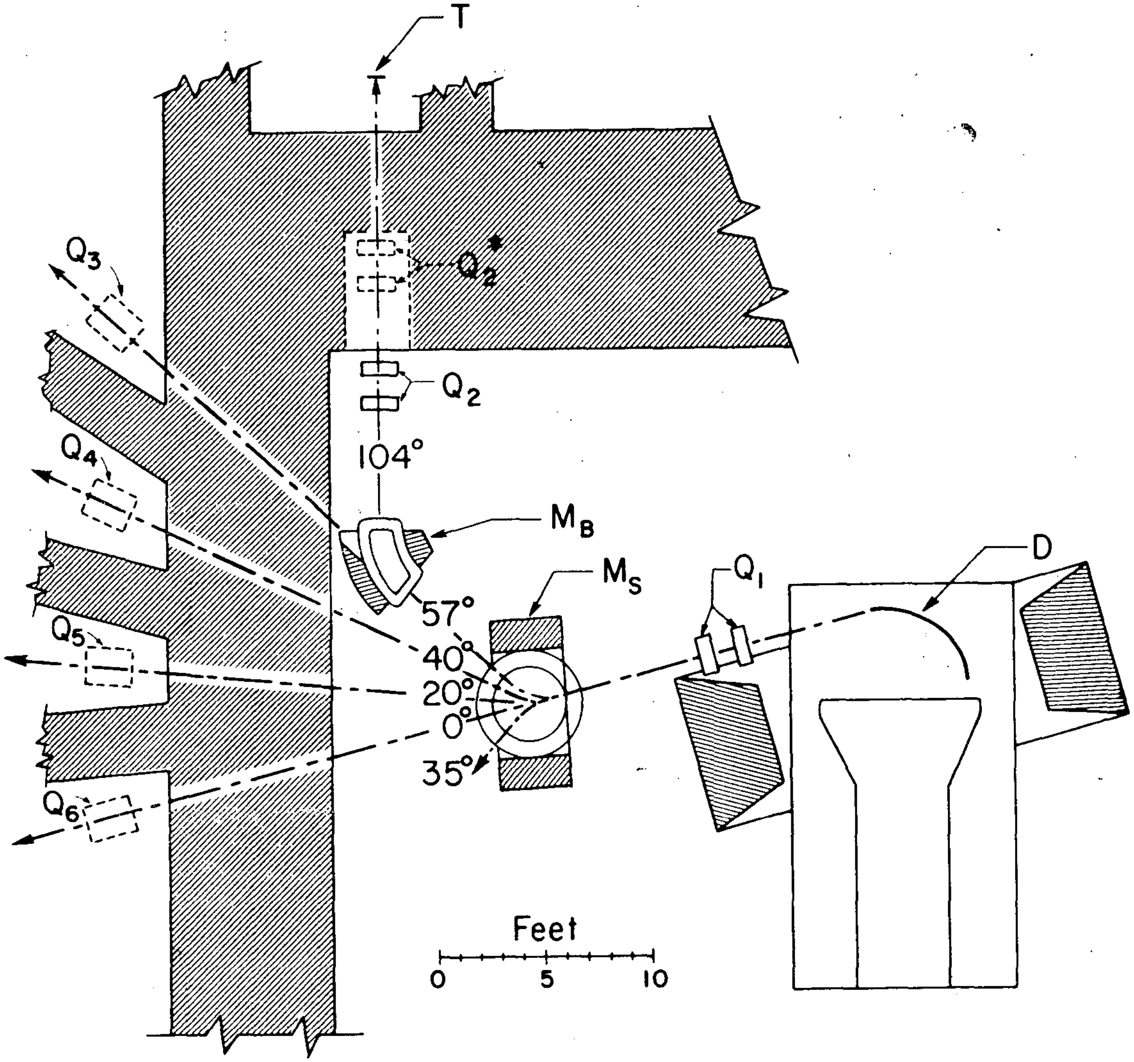

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Fig. 1

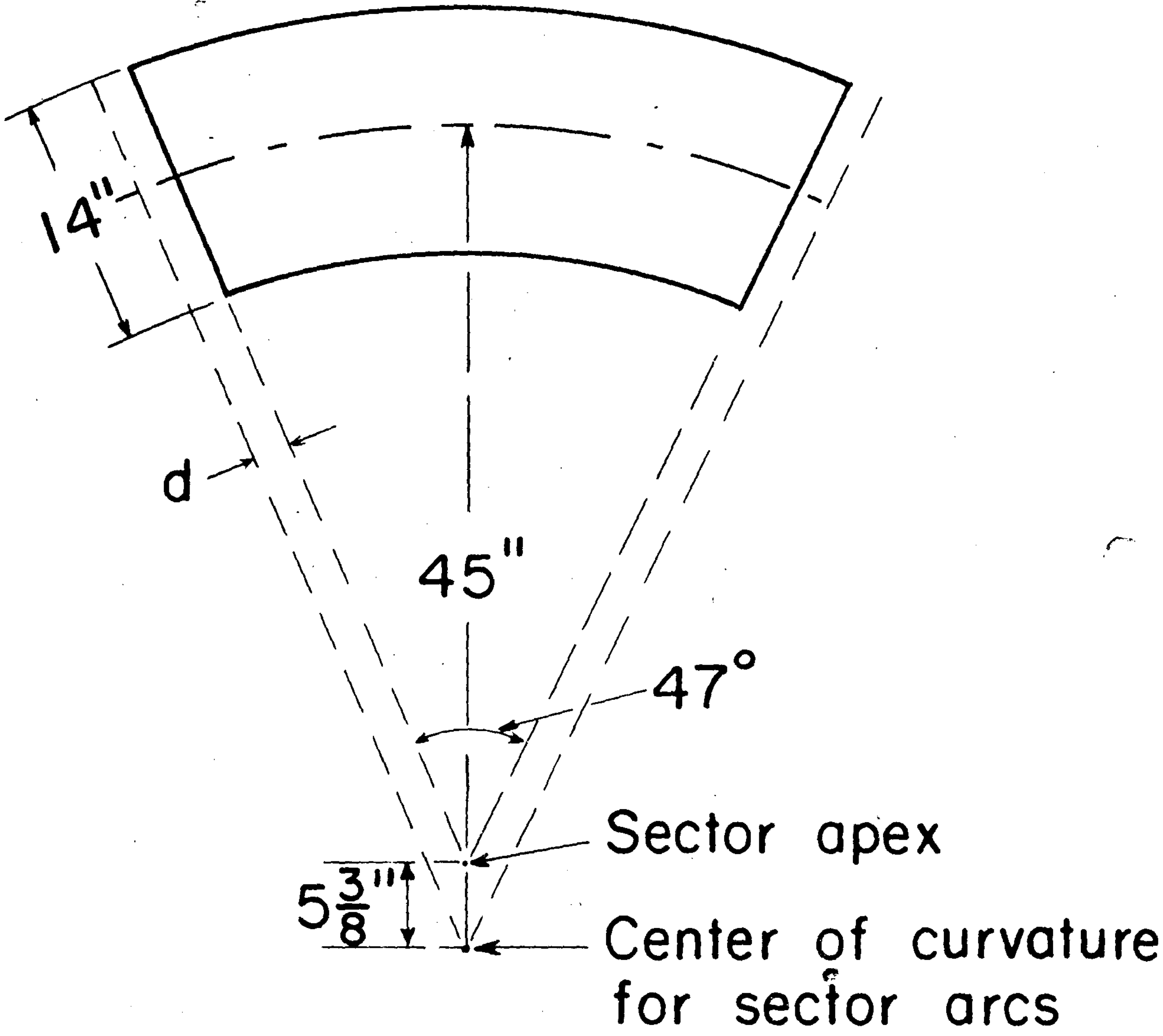

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Fig. 2

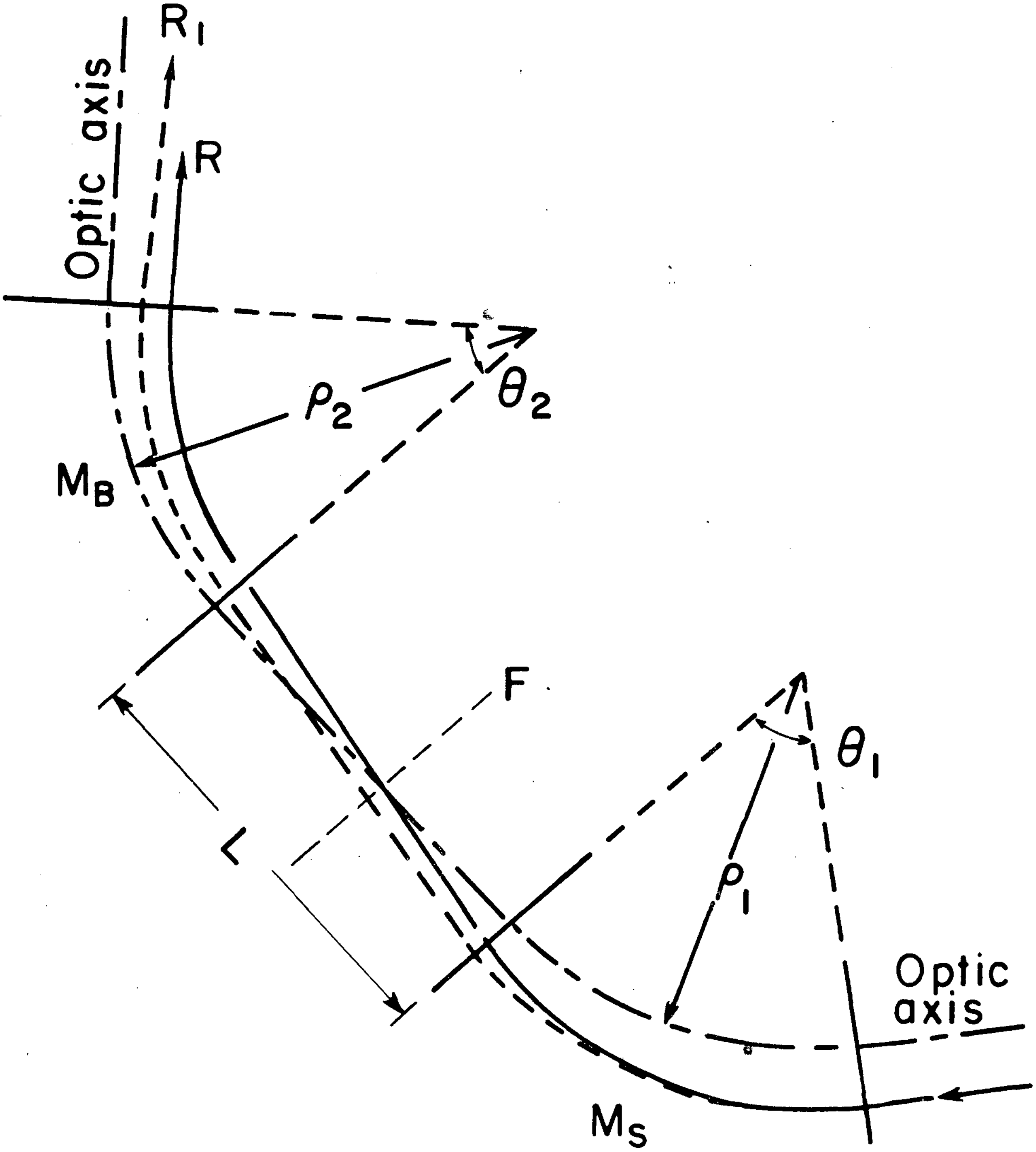

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Fig. 3

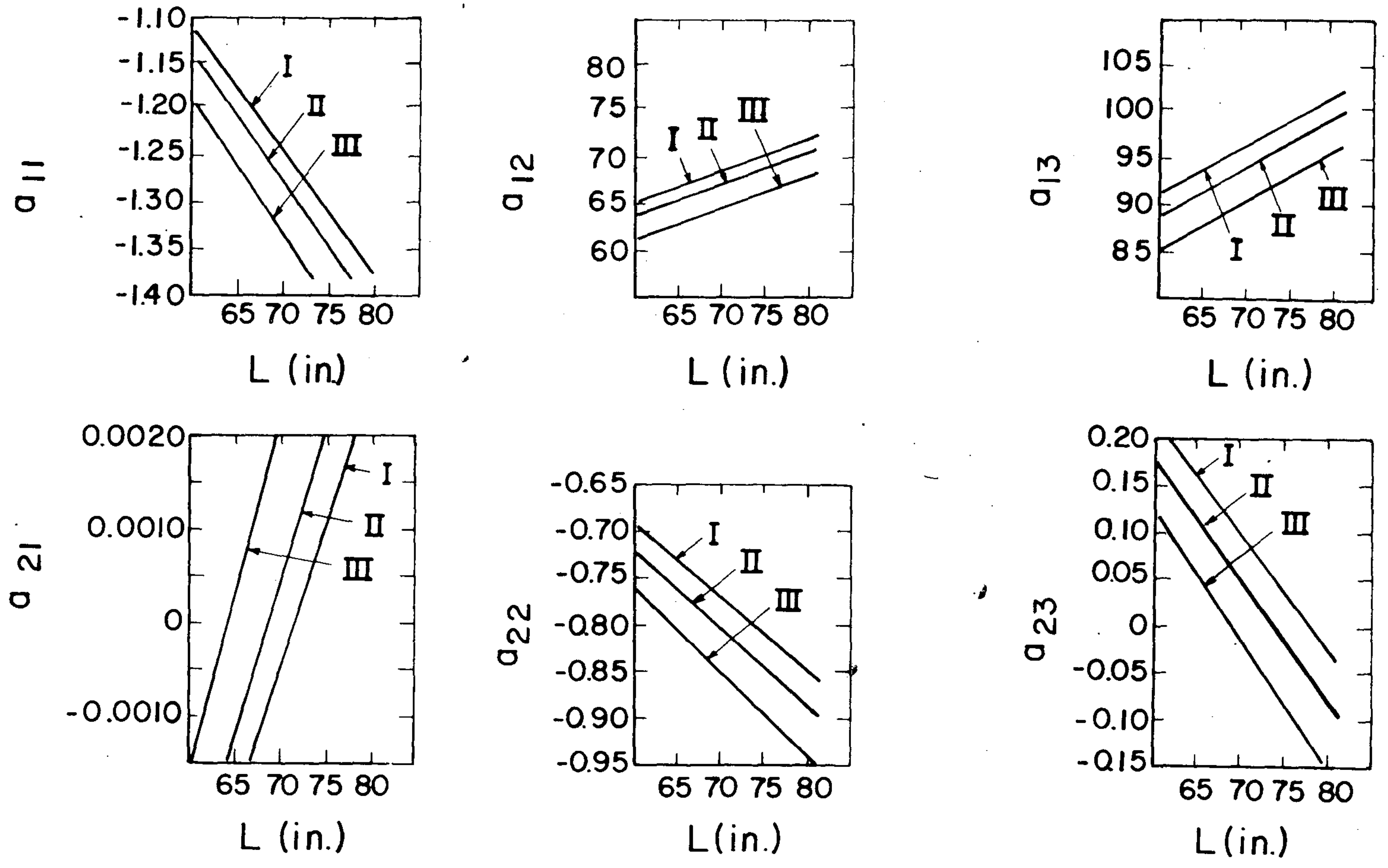

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Fig. 4

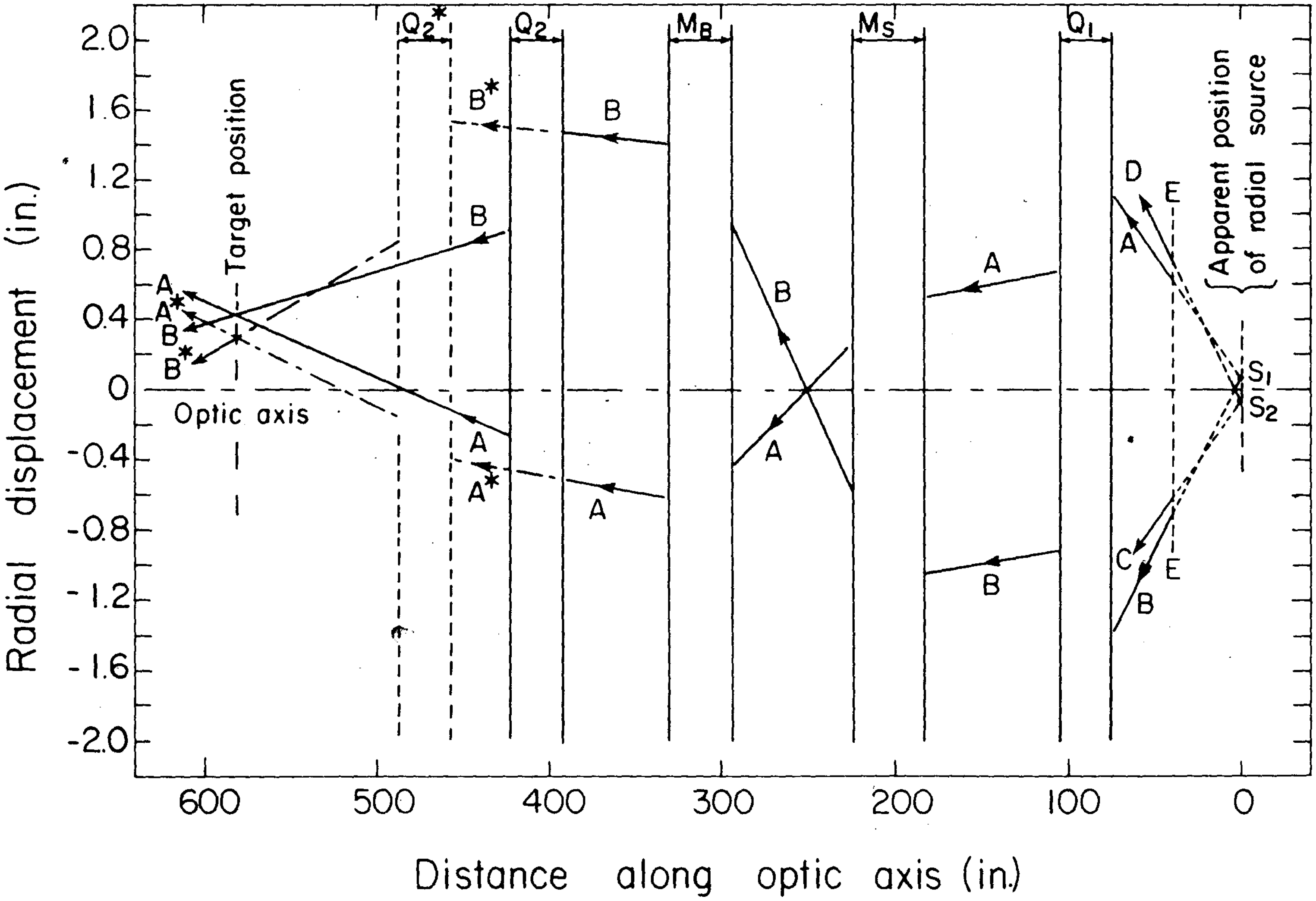

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Fig. 5

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