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0.5 BeV/c BEAM TRANSPORT SYSTEM

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October 23, 1963

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ABSTRACT

A beam transport system for externally produced pion beams has been built and used for over two years at the Berkeley 184-inch cyclotron. It features a measured acceptance mean solid angle of 6.5×10^{-3} sr over a 2-in.-diameter circle. The image has negligible momentum dispersion within the accepted 7% FWHM momentum band, but an intermediate focus is dispersed to permit collimation to a narrower momentum band.

I. INTRODUCTION

A necessary accessory for an accelerator with an external beam is a secondary beam transport system which selects a portion of the momentum phase volume of particles emitted from an external target, and forms a remote image free of background from neutrals and charged particles with momenta outside a selected pass band. There exist many such systems; the present one is described because it exceeds its predecessor by a factor of four in mean solid angle, is physically short to minimize decay in flight, is rather simple to set up and optimize, and uses relatively few magnets. It has been used for momenta between 100 and 300 MeV/c. Magnet power dissipation gives an upper limit of 430 MeV/c, but an alternative mode of operation is described which raises this to over 500 MeV/c. The system has unit positive magnification. The present system achieves its performance by using a zero dispersion pair of bending magnets to produce a wide but variable momentum pass band and by using short-focal-length lenses either singly or separated by field lenses.

II. DESCRIPTION OF SYSTEM

The physical magnet layout is shown in Fig. 1: H_1 and H_2 are "H" magnets with a 29- 36-in. pole × 8-in. gap; Q_1 and Q_3 are 12-in.-diameter circular-aperture quadrupoles, 12 in. long; Q_2 is a $15\frac{1}{2} \times 6\frac{1}{2}$-in. rectangular-aperture current sheet quadrupole, 30 in. long. The system is 32 ft long from source to image along the optic axis. The spacing of magnets is symmetrical about the center of Q_2; it is the closest permitted by the physical size of the magnets and the location of the existing shielding walls.

Figure 2 shows orbits for rays that originate parallel to, but not on, the optic axis as well as those from a point on the optic axis. Limiting apertures,

which are usually the wall of a vacuum tank surrounding the beam, are also shown. Since the system is linear, an arbitrary ray is always representable as a linear sum of those shown. The rays shown can be used to construct the phase area accepted from the source. This process is described in the Appendix; the results for horizontal and vertical source-space phase coordinates (they are not coupled) are shown in Fig. 3. Note that the solid angle remains large as one moves off the optic axis. The boundaries of the accepted phase area are labeled by the names of the apertures that generate them.

The optical behavior of the system is as follows. In a horizontal plane, H_1 and H_2 form a zero dispersion pair. The intermediate focus at the center of Q_2 results in zero dispersion only if H_1 and H_2 bend in the same direction. The bending magnets give negligible focusing (none for ideal magnets, but curvature of the magnetic pole edge results in some focusing). Essentially all of the horizontal focusing is provided by convergent Q_1 and Q_3; Q_2 has relatively little effect on the horizontal focus. Quadrupole Q_1 forms an image at the center of Q_2; since it is dispersed, a collimator at this point can be used to narrow the momentum pass band.

In a vertical plane, the edges of H_1 are a pair of thin lenses which form an inverted image at the entrance principal plane of Q_1, Q_2, and Q_3. This image is inverted by H_2 to form the final image. The triplet Q_1 Q_2 Q_3 is a field lens for the bending magnets. Divergent quadrupoles Q_1 and Q_3 largely determine the location of the principal planes of the field lens; convergent Q_2 determines the focal length of the field lens.

The overall system has unit positive magnification, as is evident from the symmetry of the system. The vertical intermediate focus has magnification -2.5; the horizontal intermediate focus has magnification -1/3. It is possible

to improve the constancy of vertical angular acceptance off axis by increasing the size of the vertical intermediate image. The use of a bending angle of 78 deg may cause some concern because of the many aberrations associated with bending magnets. Investigation of such effects shows that they cancel to first order in the zero dispersion pair, although one does have to accept a focal plane parallel to the final bending magnet pole edge. The major noncancelling abberation is a dependence of vertical focal length on vertical angle, which results from the fact that the magnetic length of a bending magnet depends upon height from the median plane.

III. OPERATION OF THE SYSTEM

The system is easily set up by the following procedure.

(a) Determine conjugate points for vertical rays in a single bending magnet at the desired bending angle θ. In this system θ is chosen to focus the system when the magnets are as close together as their physical sizes will permit. Call their separation ℓ, measured along the orbit. Also locate the bending magnet principal planes adjacent to the quadrupole.

(b) Determine, for equal gradients in Q_1 and Q_3, those quadrupole fields that give a separation of the vertical principal plane and horizontal focus equal to $\ell - R(\theta - \sin\theta)$, where R is the radius of the orbit inside the bending magnet. This is the focal condition for the system, since twice the above expression gives the optical path length between vertical foci of the bending magnet for rays in a horizontal plane. At this stage the system is focused in the sense of being able to form an image of the source, but one still must adjust the vertical focus of the quadrupoles to satisfy a field lens condition and hence optimize transmission through the system.

(c) From the locus of gradients that satisfy condition (b), select those that place the vertical focus of the quadrupoles at the vertical principal plane of the bending magnet. This gives optimum transmission and completes the adjustment. One then physically places the bending magnets so that their vertical focus coincides with the appropriate vertical principal plane of the quadrupoles, and orients them to bend in the same direction (bending them in opposite directions results in extremely high momentum dispersion).

One can note some empirical facts which simplify the above process. In part (a) it is necessary to integrate orbits in the actual magnet field or to wire orbit. The usual formulas for vertical focusing are invalid because so much of the bending occurs in the region where field gradients are large. Wire orbits are also necessary for the quadrupoles because of the large ratio of aperture to length. In part (b) the correction to physical path for rays passing through an ideal bending magnet in a horizontal plane is usually compensated by curvature of the magnetic pole edge found in real magnets. Focusing of Q_1 Q_2 Q_3 is simplified by the fact that the vertical principal-plane spacing is essentially independent of the gradient in Q_2 and only slightly dependent on the Q_2 Q_3 gradient.[1] Part (b) is also simplified because the position of the horizontal focus depends almost entirely on the Q_1 Q_3 gradient. (Part (c) is facilitated because the position of the quadrupole vertical focus is determined principally by the Q_2 gradient. For operation at 150 MeV/c, the following approximate field values were used: $H_1 = H_2 = 5700$ gauss, $Q_1 = Q_3 = -465$ gauss/in., $Q_2 = 345$ gauss/in. Other momenta are scaled linearly to 430 MeV/c, which is the power limit of Q_2.

IV. ALTERNATIVE MODE OF OPERATION

If the direction of bending in H_2 is reversed, and the quadrupoles are set to $\Omega_1 = \Omega_3 = -219$ gauss/in., $\Omega_2 = 250$ gauss/in., then the system is in focus at 150 MeV/c with orbits as shown in Fig. 4. While the operation is unchanged in the vertical plane, there is no longer an intermediate focus in the horizontal plane. The quadrupole is operated at lower gradient, which implies that the system can be used at momenta up to over 500 MeV/c. The physical location of the emergent beam line is changed; it becomes parallel to the beam entering the magnet system, which may be an advantage where space is restricted. The phase diagram is essentially unchanged. The major disadvantage of this mode is the absence of a horizontal intermediate focus; one cannot reduce the momentum pass band without also reducing the horizontal angular acceptance.

V. SYSTEM MEASUREMENTS

Although all properties can in principle be computed, it is interesting and perhaps more useful to demonstrate the characteristics of the system with a particle beam. We therefore prepared a $1\frac{1}{2}$-in.-diameter Am^{241} alpha source whose momentum was 200 MeV/c with a width of less than 1% from satellite lines.[2] The source was placed at the object point of the system, and a 2-in.-diameter scintillation counter was placed at the image point. Source, counter, and all accepted rays were in a vacuum; a discriminator was used to reject counter noise and background.

Wire orbits on the individual magnets, following the procedure of Sec. III, gave operating currents at 100 MeV/c as shown in the first column of Table I. Using these as a starting point, the system was tuned for maximum flux and the

resulting currents recorded in the second column of Table I. The observed differences seem consistent with measuring errors except for the Q_1 Q_3 currents, where part of the difference must be caused by horizontal focusing in the bending magnets.

The observed counting rate was used to determine the acceptance solid angle by placing source and counter in a separate vacuum tank and adjusting the separation until the count rate equaled that measured through the magnet system. A dramatic description of the efficiency of the system is given by the statement that a 2-in.-diameter counter at the focus collects the same flux through the 32-ft magnet system as it would if located 22 in. from the source with no magnet system. The mean solid angle was thus measured to be 6.5 msr, to be compared with the 8 msr computed from phase diagrams.

The momentum pass band was measured by observing the transmission of 200 MeV/c alphas as the currents in all magnets were varied proportionally so as to tune the system through a range of momenta in the neighborhood of 100 MeV/c. The results are shown in Fig. 5; the ordinate represents the momentum to which the system is tuned, not the momentum of the transmitted particles. The curve shown should be almost identical to that obtained by varying the momentum of the transmitted particles. The curve can of course be narrowed by collimating at the center of Q_2; its present width is determined by the 8-in. width of the vacuum chamber in Q_2.

VI. ACKNOWLEDGMENTS

We are grateful for the friendly aid of many persons at the Lawrence Radiation Laboratory and the University of California at La Jolla. We particularly wish to thank R. Bacastow, W. O. Brunk, and O. Chamberlain for their interest and assistance.

APPENDIX: CONSTRUCTION OF PHASE DIAGRAMS

We wish to determine the phase area accepted from a source. This is conveniently represented as a region in a phase diagram such as Fig. 3, where x (or y) is a transverse beam coordinate, $\dot{x} = \frac{dx}{dz}$, and z is measured along the optic axis from the source. For a phase diagram at the source we evaluate x and $\dot{x}$ at $z = 0$.

The phase diagram is easily constructed if we have two orbits $x_1(z)$ and $x_2(z)$ chosen such that $x_1(0) = 0$, $\dot{x}_2(0) = 0$, $\dot{x}_1(0) \neq 0$, $x_2(0) \neq 0$. An arbitrary orbit is then given by

$$x(z) = \frac{x_2(z)}{x_2(0)}\, x(0) + \frac{x_1(z)}{\dot{x}_1(0)}\, \dot{x}(0) .$$

At various points in the system one has apertures that impose the conditions $A_+(z) > x(z) > -A_-(z)$. In most cases of interest the apertures are symmetric about the optic axis, so one writes $0 \leq |x(z)| < A(z)$. An orbit that just intercepts the aperture is then given by the condition

$$A_+(z) = \frac{x_2(z)}{x_2(0)}\, x(0) + \frac{x_1(z)}{\dot{x}_1(0)}\, \dot{x}(0) .$$

In $x(0)$, $\dot{x}(0)$ space (source phase space) this is evidently the boundary line that defines which particles are transmitted by the aperture A_+.

One thus sees that the boundary of the accepted phase area is composed of pairs of parallel straight lines; if all apertures are symmetrically located with respect to the optic axis, the boundary curve is invariant under reflection through the origin. It is evident from its construction that the boundary curve never reverses the sign of its curvature; a straight line which intersects the boundary at two points has no other intersections unless it is coincident with the boundary between those points.

We emphasize phase diagrams here because it is relatively easy to design optical systems that have high angular acceptance for a source point on the optic axis, but accept little or nothing from source points off the optic axis. We also note that rays computed for thin lenses or a principal plane equivalent of a thick lens are not useful for the construction of phase diagrams; in any system which includes quadrupoles, the physical orbits may deviate from the optic axis far more than the thin-lens rays that represent them.

The orbits used in the design of the above system were computed by using an electronic analog computer developed by R. H. Good and O. Piccioni.[3] We stress the great utility of this machine, which has an accuracy compatible with that of the models used for magnets, is easily programed to permit quick changes in the system under study, and rapidly develops in the user the intuition needed to optimize and adjust a magnet system.

FOOTNOTES AND REFERENCES

*This work was supported by the U. S. Atomic Energy Commission. It was carried out at the Lawrence Radiation Laboratory, Berkeley, California.

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1. For our system, a 1% change in vertical principal-plane spacing requires a 20% change in Q_2 gradient or 5% in Q_1 Q_3 gradient. A 1% change in Q_1 Q_3 gradient makes the same change in horizontal focus as a 16% change in Q_2 gradient.

2. Since the alpha particles are doubly charged, they follow the orbit of a 100-MeV/c single charge. All references to the system momentum are for singly charged particles.

3. R. H. Good and O. Piccioni, Rev. Sci. Instr. 31, 1035 (1960).

Table I. Comparison of predicted and observed magnet currents.

Magnet	Magnet currents, 100 MeV/c	
	From wire orbit (A)	From a source (A)
H_1 (Atlas)	169	171
H_2 (Titan)	175	173
Q_2 (Juno center)	237	240
Q_1 Q_3 (Juno ends)	182	174

FIGURE CAPTIONS

Fig. 1. Physical layout of beam transport system.

Fig. 2. Computed rays for normal operation of system.

Fig. 3. Phase diagram showing phase space accepted from source.

Fig. 4. Computed rays for high-momentum operation of system.

Fig. 5. Measured momentum resolution at maximum aperture.

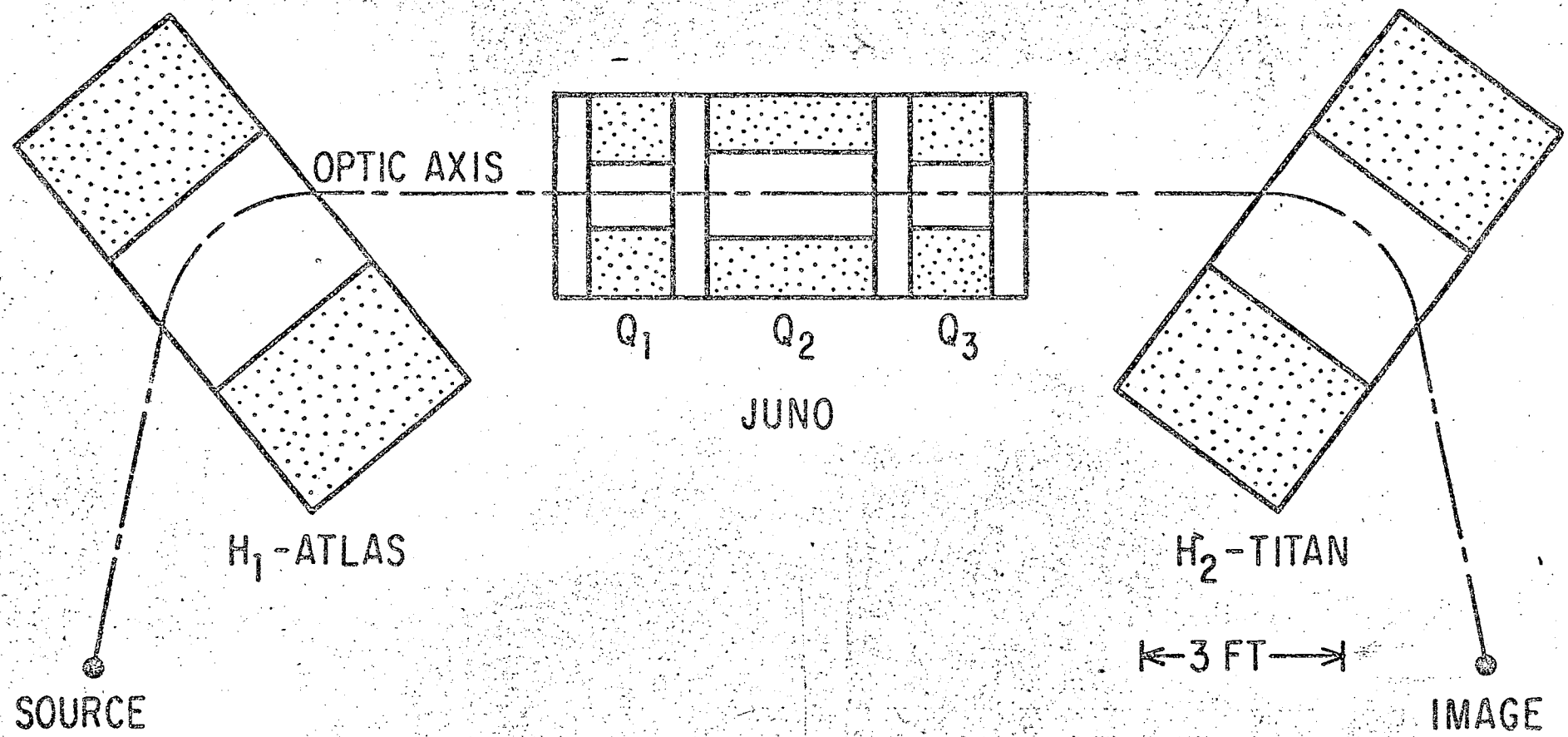

Fig. 1

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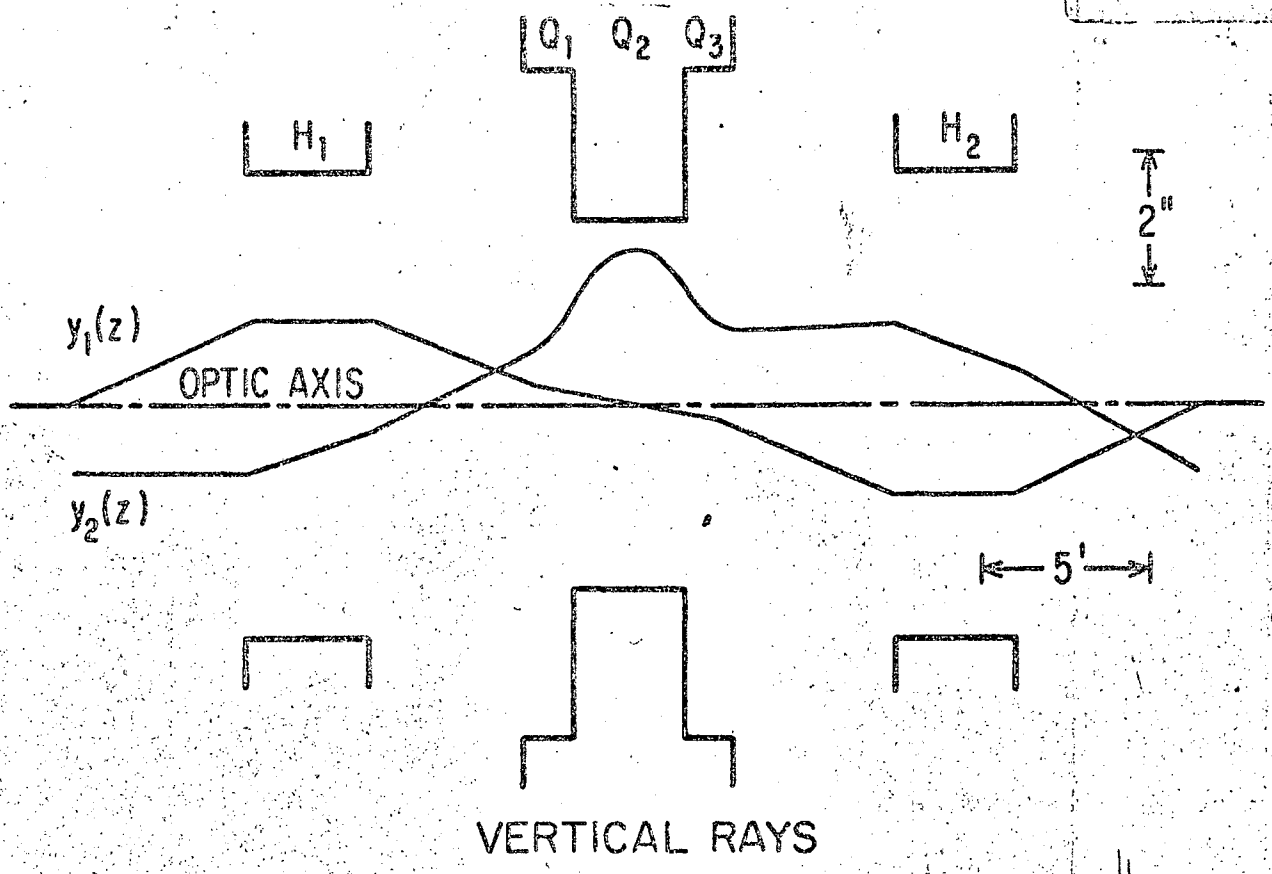
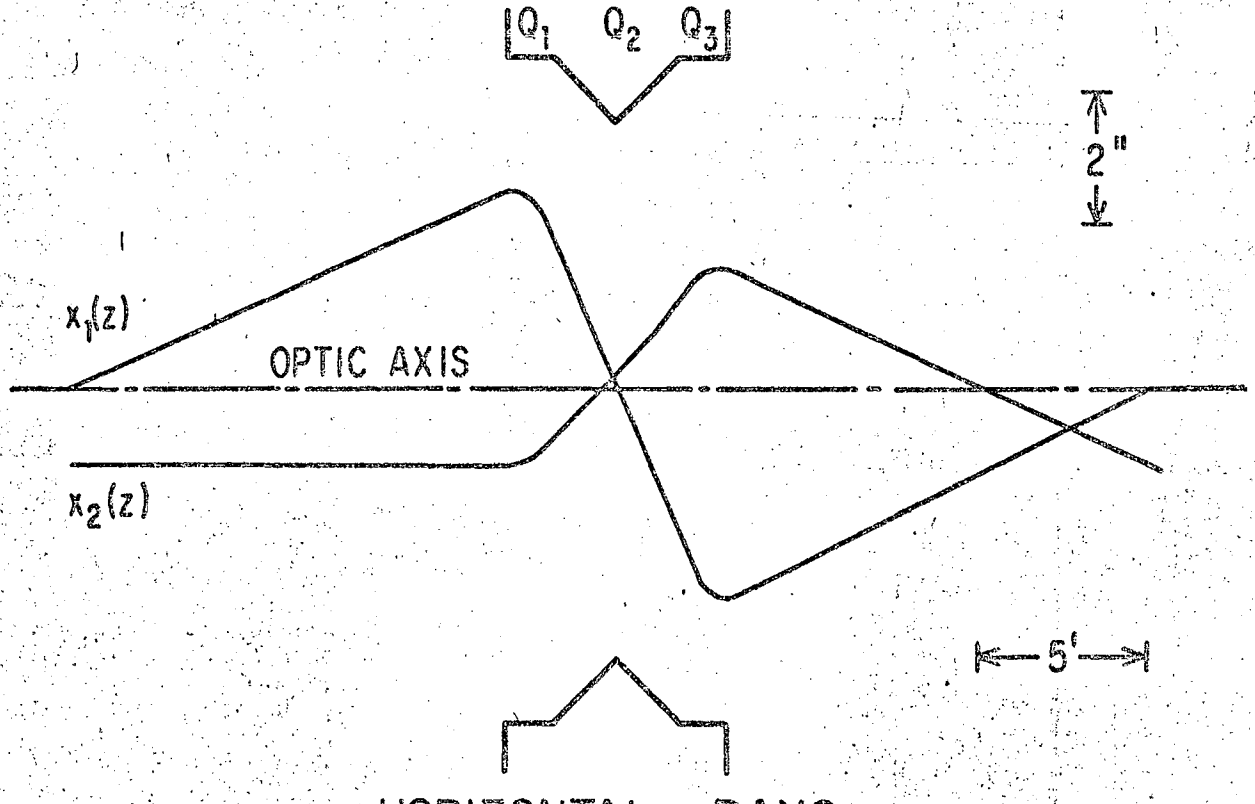
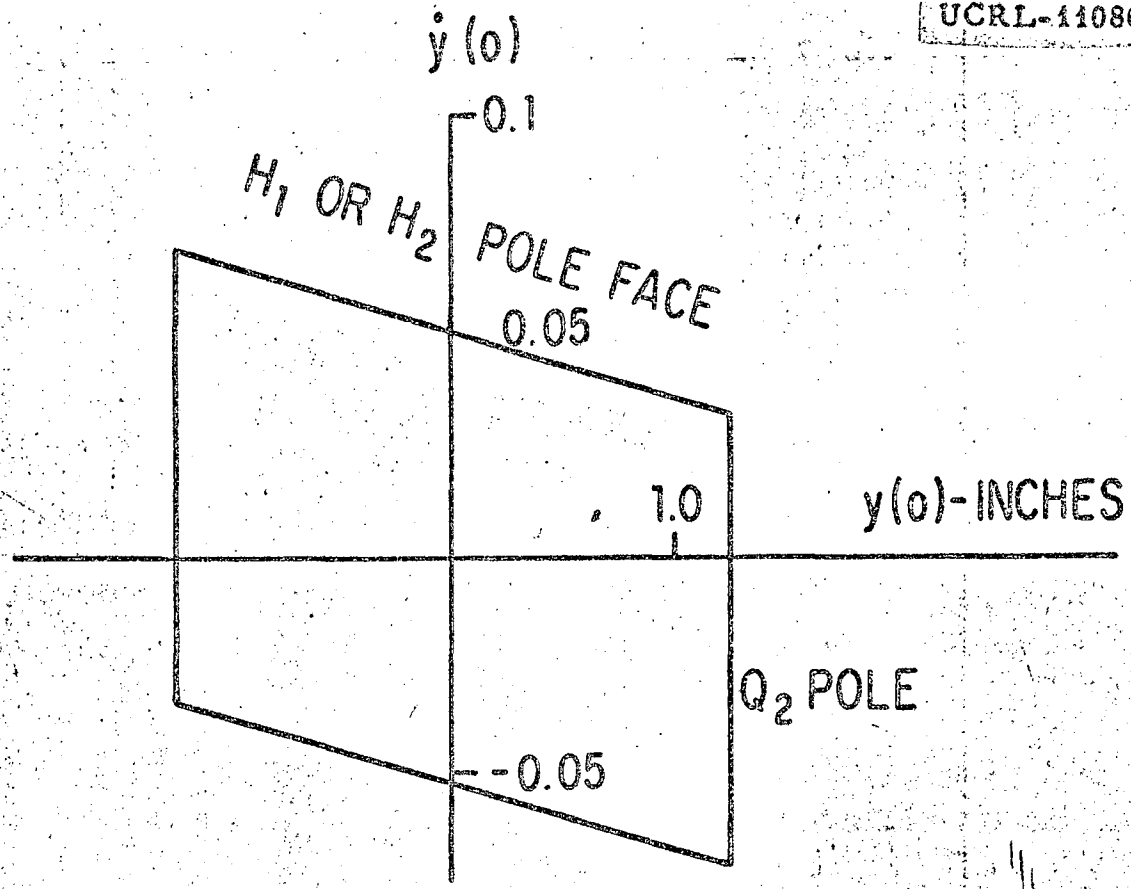


VERTICAL RAYS

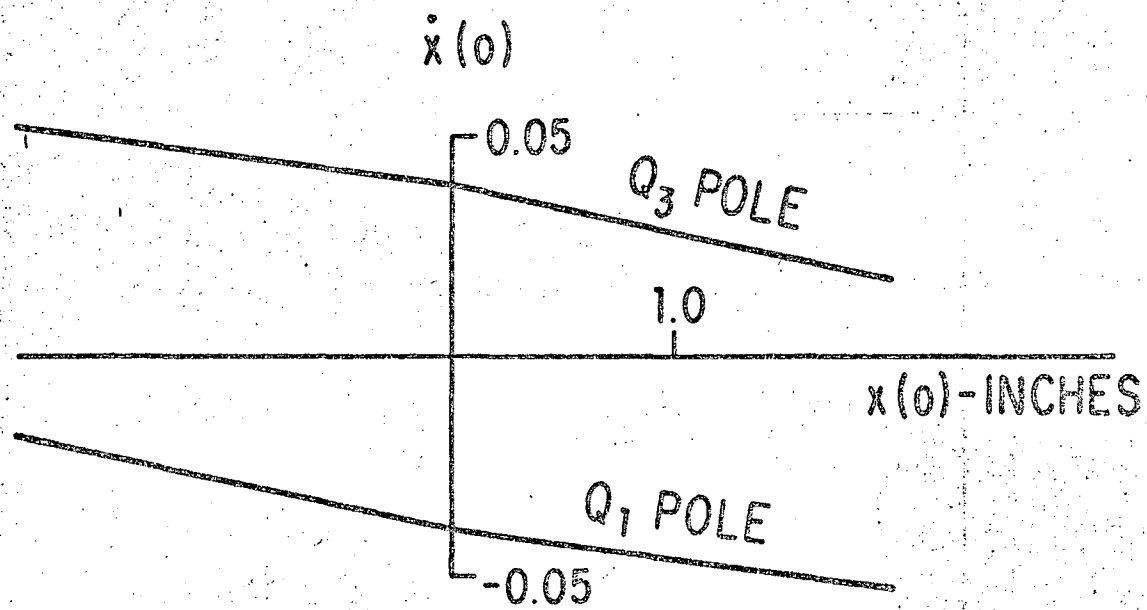


HORIZONTAL RAYS

Fig. 2



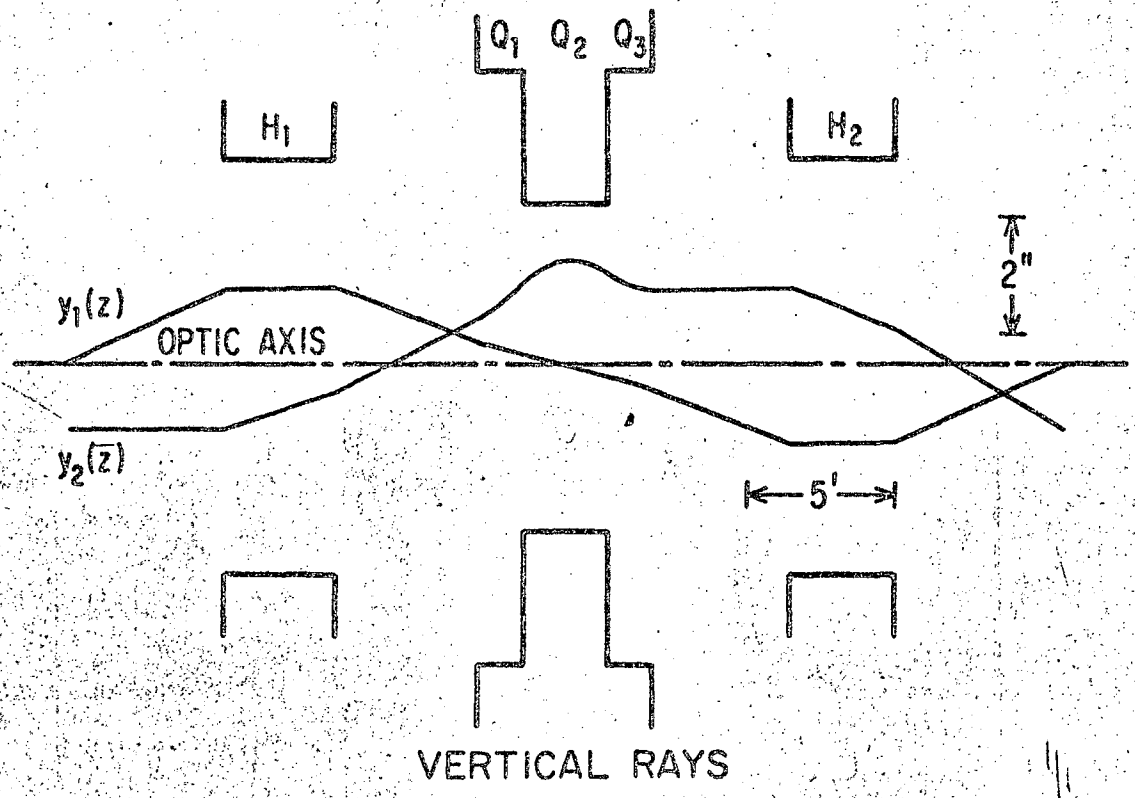
VERTICAL PHASE BOUNDARY



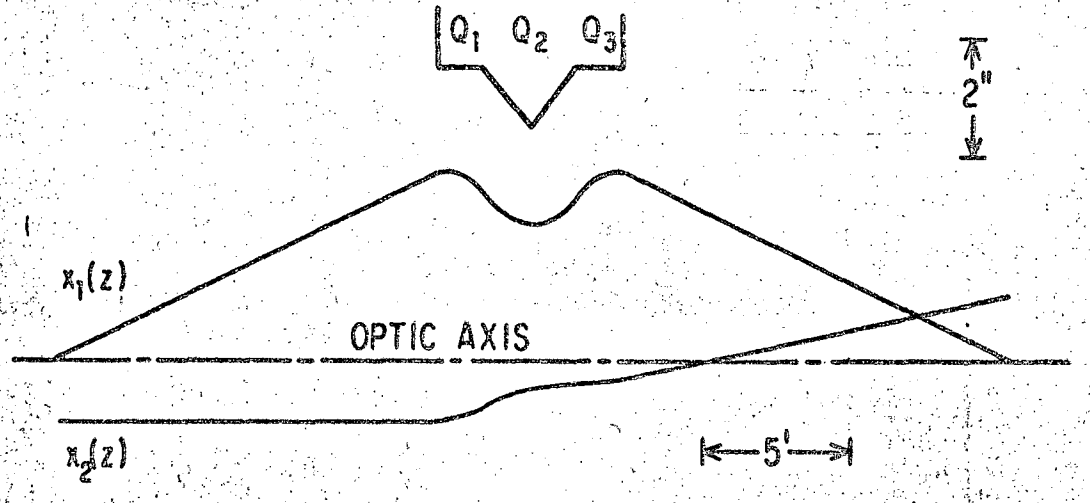
HORIZONTAL PHASE BOUNDARY

Fig. 3

MU-32602



VERTICAL RAYS



HORIZONTAL RAYS

Fig. 4

MU-32603

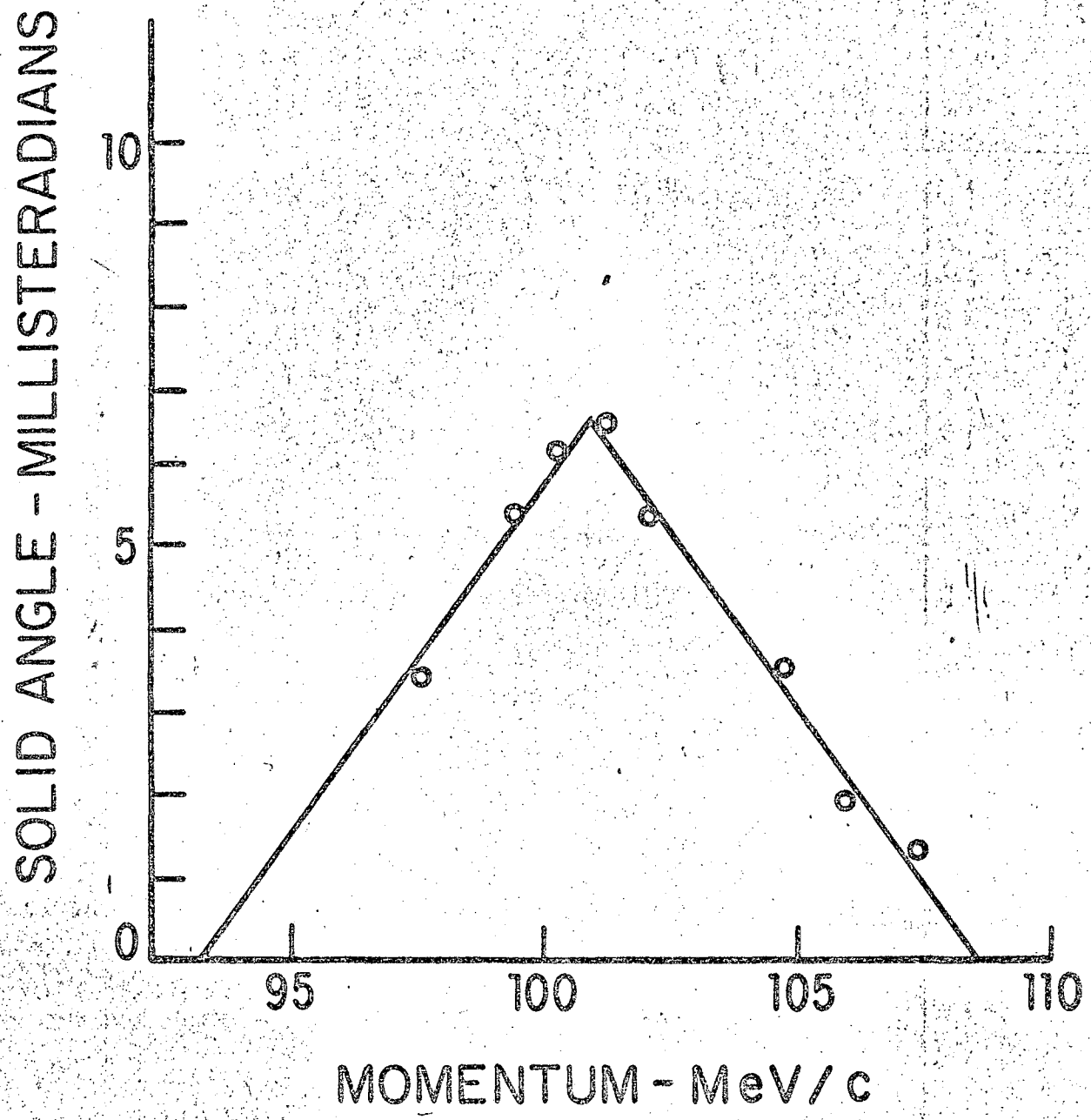


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Fig. 5

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