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Authors
Panofsky, W.K.K.
Baker, W.R.

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W. K. H. Panofsky and W. R. Baker

November 15, 1949

Berkeley, California

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A Focussing Device for the External 350 Mev Proton Beam

of the 184-inch Cyclotron at Berkeley

W. K. H. Panofsky and W. R. Baker

Department of Physics, Radiation Laboratory
University of California, Berkeley, California

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The external beam of the 184-in. synchro-cyclotron[1] is produced by a pulsed electrostatic deflector displacing the cyclotron orbits to enter a magnetic shield which channels the beam to the outside of the magnetic field. The beam thus produced covers an area of approximately 8 sq. in. at the bombarding position (about 46 ft. from the center of the cyclotron). Since the total beam attained thus far is only of the order of 10^{-9} amp., the resultant beam density is insufficient for many experiments or at least leads to long run-times. Since in most experiments beam density rather than total current is the determining factor a focussing device was considered of advantage.

Both horizontal and vertical focussing is possible by means of a wedge shaped deflecting magnet[2]. The use of such a device, although practical in principle was rejected here since it involved re-location of the target facilities and also since the physical size of a focussing magnet at this energy

(1) W. M. Powell, L. R. Henrich, Q. A. Kerns, D. C. Sewell, R. L. Thornton Rev. Sci. Instrum., 19, 506-12 (1948)

(2) MDDC-350, Leo Lavatelli

and aperture is very considerable. It was therefore decided to study an "in-line" focussing device, i.e., a device focussing without deflection.

The device chosen consists essentially of a current carrying cylindrical conductor whose axis is parallel to the beam and which is transparent to the passage to the beam. If the current density is uniform, the magnetic field will increase linearly with the radius, and a linear restoring force on the beam will result (Fig. 1). It can easily be shown that if such a device is effectively a "thin" lens, it will give rise to a focal length

$$F = \frac{a}{L} \frac{(B\rho)}{B_0} \tag{1}$$

where $(B\rho)$ is the momentum of the beam, B_0 the magnetic induction at the outer edge of the transparent conductor and the a and L are dimensions defined in Fig. 1.

A current carrying conductor transparent to the proton beam was realized physically in the form of an arc inside a cylindrical glass tube 3 in. in diameter and 48 in. in length. The arc was struck between two cylindrical aluminum electrodes protruding into the arc tube. The physical layout is shown in Fig. 2. The entrance of the tube is closed by a 1-1/2 mil dural foil; the foil has to be thin enough such that the multiple scattering in the foil will not produce appreciable broadening of the beam. Even at a proton energy of 350 Mev this necessitates the thin foil as indicated owing to the large distances involved. The arc was operated at a pressure of .3 to .5 mm of hydrogen. The hydrogen was circulated continuously to purify the gas from gases generated from the surfaces of the discharge. The exit foil (.010 in. Al) which has to stand atmospheric pressure was located near the target to make scattering effects unimportant.

The arc was fed from a condenser bank consisting of sixteen .03 μf condensers through a spark gap triggered by a 70 kv pulse transformer. The trigger arrangement is shown in Fig. 3. The arc was operated at a pulse repetition rate of approximately 60 c.p.s., in synchronism with the rotating condenser of the synchro-cyclotron. The time sequence of firing the electrostatic deflector and the arc is shown in Fig. 4. At this repetition rate it was found necessary to air-cool the condenser bank and to water-cool the gas discharge tube.

The location of the lens relative to the bombardment position required a focal length of approximately 200 in. and an arc current of 4000 amp. The arc drop under these conditions is 9 kv, principally inductive.

In order to produce a good focal point, two requirements have to be fulfilled: 1. The current density of the arc has to be uniform. 2. The incoming beam must originate from a (real or virtual) point source. Neither of these requirements can be fulfilled accurately in practice. The current distribution in the arc is affected by a number of factors, including the magnetic contraction effect which focusses the beam. There is however, also, at this rate of rise of current, a skin depth effect which tends to keep the arc apart. These and other effects depend on the arc conditions; the arc was thus adjusted empirically to give most uniform current density so judged by end-on photographs of the discharge.

The deflected beam of the 184-in. cyclotron is somewhat astigmatic, i.e., has a different divergence of the beam horizontally and vertically. Fig. 5a shows the cross-section of the deflected beam in the external bombardment area of the 184-in. cyclotron with the "arc lens" inoperative. Fig. 5b shows the beam shape at 7 kv arc voltage and Fig. 5c shows the beam shape at 13 kv arc voltage. Note that the optimum focussing condition for the vertical and horizontal direction are different, indicating astigmatism in the primary beam. An attempt was made to correct the astigmatism with a transverse magnetic field produced by a magnetic quadrupole consisting of two opposed Alnico magnets (see Fig. 6). These magnets, as can be seen by inspection of Fig. 6, produce a vertical focussing and horizontal defocussing force. By choosing magnets of suitable strength (250 gauss at 1-1/2 in. radius for 4 in. depth), the beam astigmatism could be compensated. The resulting beam shape is shown in Fig. 5d. The ratio in area of Fig. 5a (lens not operating) and Fig. 5d (lens at optimum) is 8.5. The current density within a central circular area of 1 in. diameter is increased by approximately a factor of five.

The writers are greatly indebted to Messrs. David Vance and Robert Meuser for mechanical design. Mr. Harvey Orrin and Mr. Charles Park aided in the design and installation of the timing and safety circuits. We also owe thanks to Mr. James Vale and Robert Watt and the crew of the 184-in. cyclotron for assisting effectively in these tests. This work was done under the auspices of the Atomic Energy Commission.

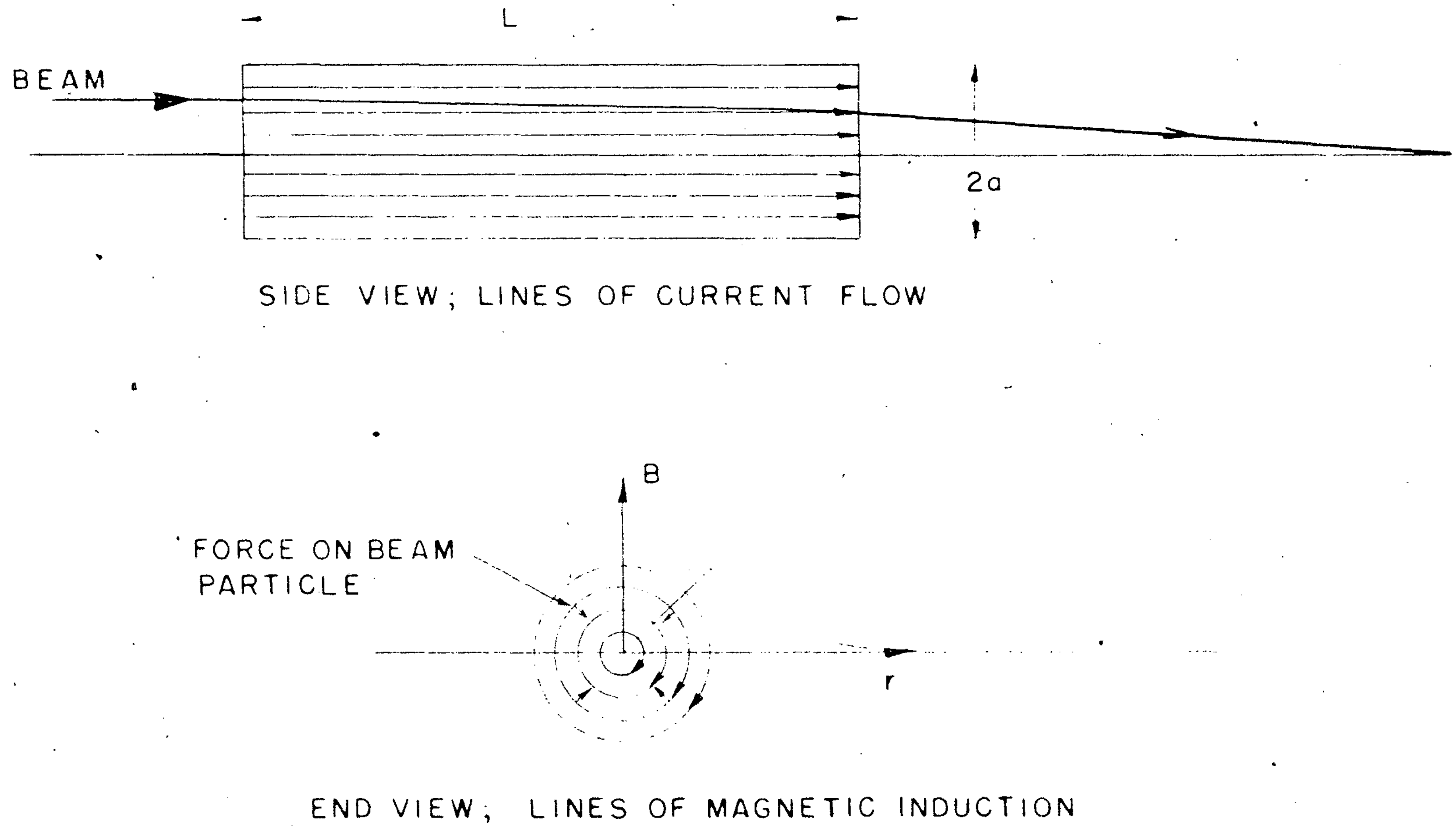

FIG. 1

Focussing action of magnetic arc lens. The top figure shows the beam trajectory and the arc current flow; the bottom figure shows the lines of magnetic field and the radial variation of the field.

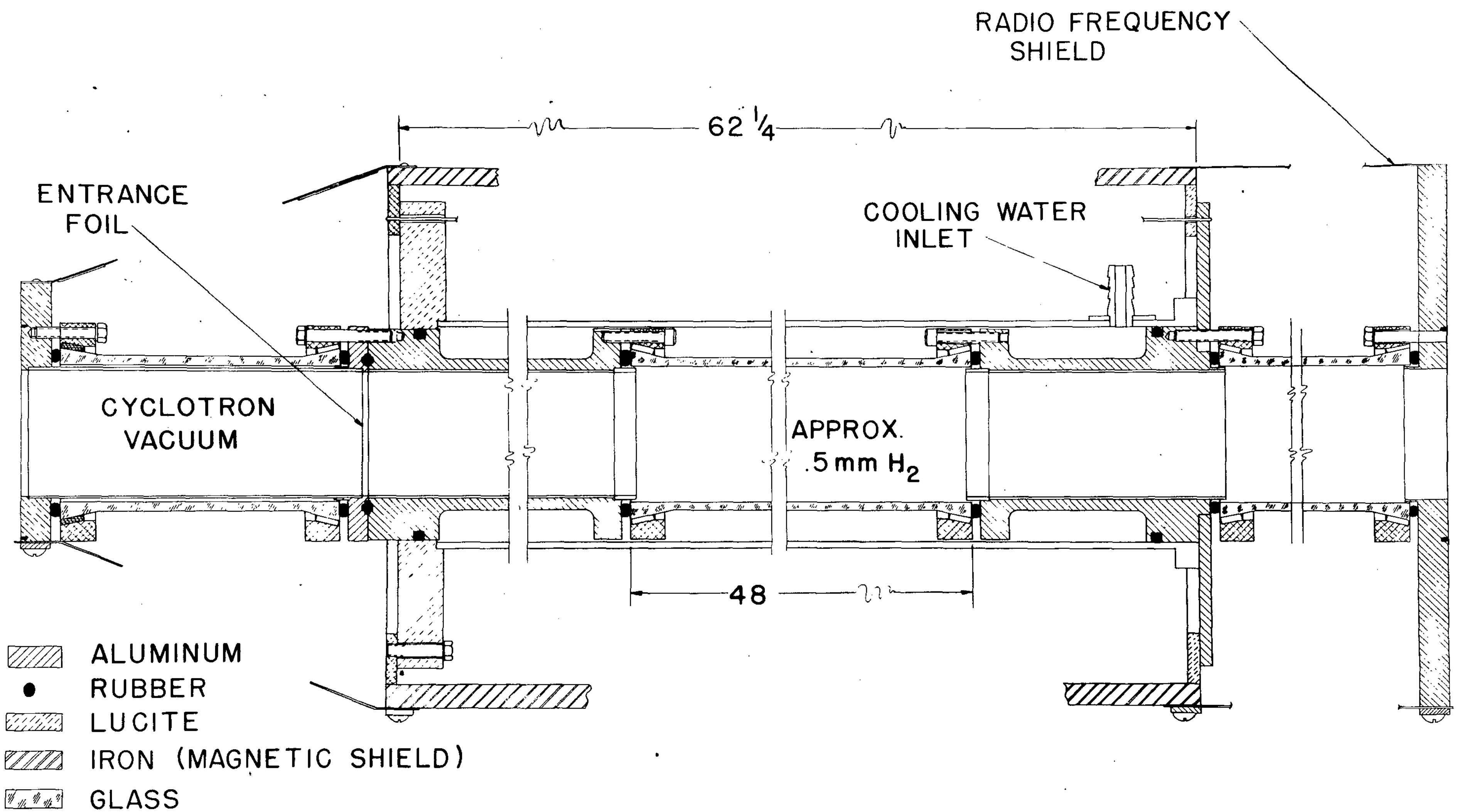

FIG. 2 CROSS SECTION OF MAGNETIC ARC LENS.

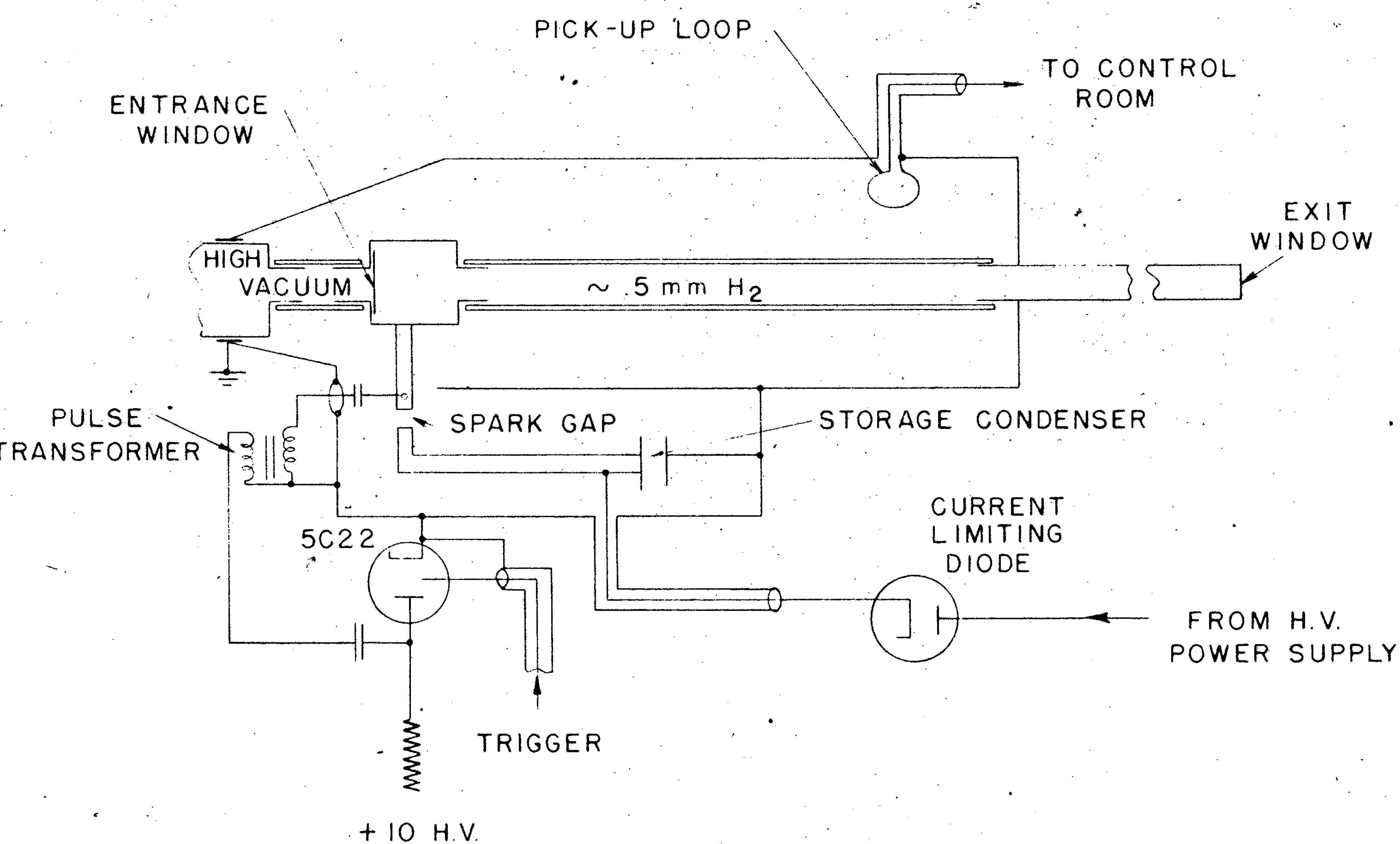

FIG. 3

Diagram of arc lens pulse connections. Note the co-axial connections of the storage condenser in relation to the spark gap and discharge tube.

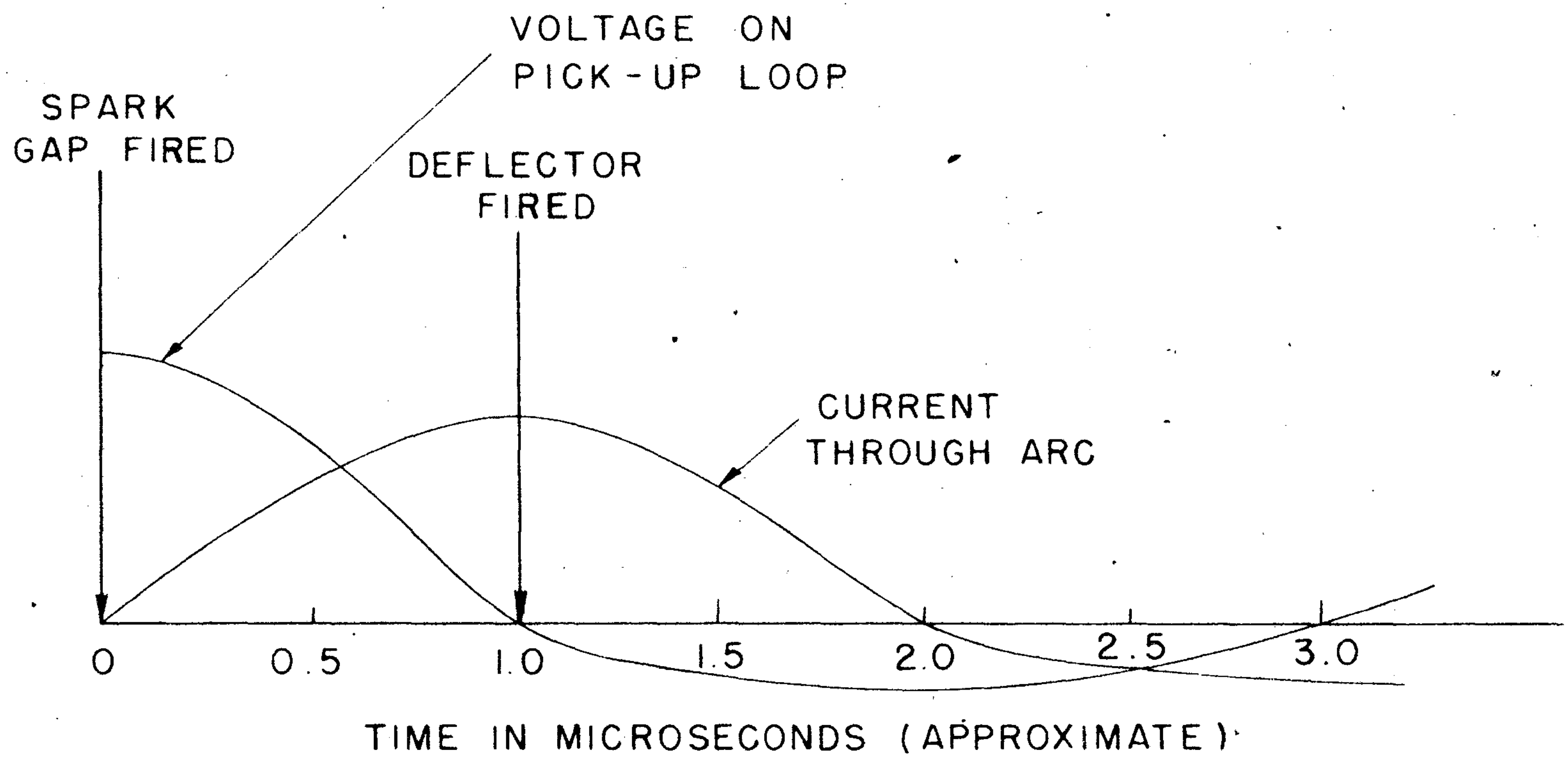

FIG. 4

Time sequence of arc operation. Note the relative firing times of the arc and electrostatic deflector.

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Beam cross sections taken on x-ray film. Operating conditions are as follows:

5a - No arc
5b - Arc voltage 7 kv.
5c - Arc voltage 12 kv.
5d - Arc voltage 8.5 kv; astigmatism corrected.

Note: The round marks are fiducial marks and of no significance here.

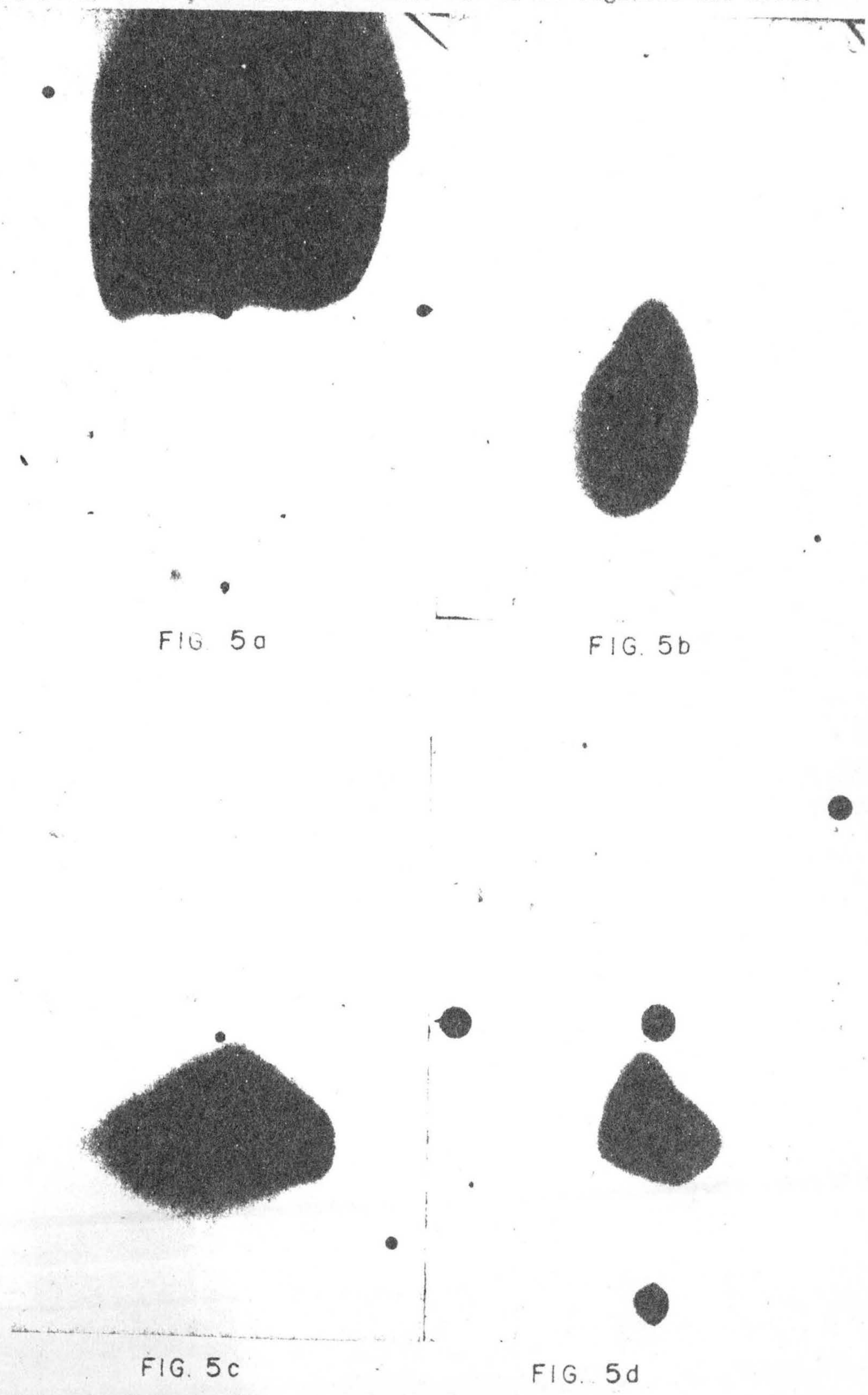

FIG. 5

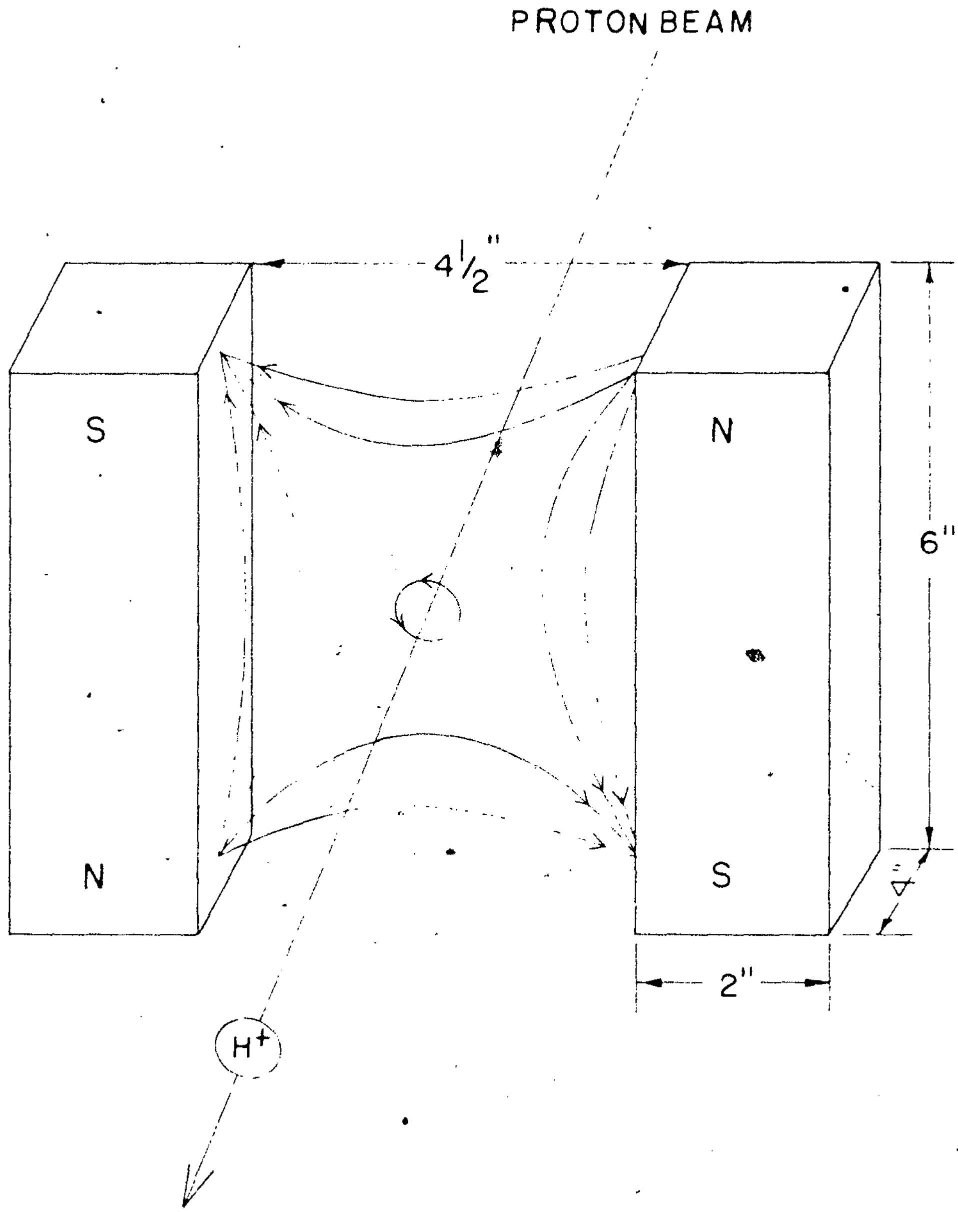

FIG. 6

Geometry of Alnico Magnet "Quadrupole" to correct astigmatism.