Electronics Laboratory

TECHNICAL INFORMATION SERIES

R62ELS-94

MAGNETIC LIMITING APERTURES FOR ELECTRON GUNS

P. H. Gleichauf
J. Pua

GENERAL ELECTRIC

ELECTRONICS PARK
SYRACUSE, NEW YORK

APL-101 (11-57)

GENERAL ELECTRIC

TECHNICAL INFORMATION SERIES

Title Page

AUTHOR	SUBJECT CLASSIFICATION	NO.
P. H. Gleichauf J. Pua	Electron gun, Thermoplastic recording	R62ELS-94 DATE November 1962

TITLE

Magnetic Limiting Apertures for Electron Guns

ABSTRACT

Emission and prefocusing systems for thermoplastic recording guns have been developed using an object forming magnetic limiting aperture. The magnetic limiting aperture compresses the electron stream through a small limiting aperture. Thus, a bright, well-defined object is created. The resulting structure is mechanically simple and rugged;

G.E. CLASS	REPRODUCIBLE COPY FILED AT	NO. PAGES
3	ELECTRONICS LABORATORY TECHNICAL INFORMATION BLDG. 3, ELECTRONICS PARK SYRACUSE, NEW YORK	26
GOV. CLASS. none		

no axial cathode alignment is needed and, therefore, flat cathodes can be used.

Resolutions in excess of one hundred resolvable elements per millimeter (200 TV lines/mm) have been obtained in the prefocus deflection gun which is capable of 20 mm raster scan (25 to 28 mm linear scan). At high beam currents imaging has not been brought under control. Further developmental work is recommended.

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

For distribution see next page

INFORMATION PREPARED FOR General Engineering Laboratory

TESTS MADE BY P. Gleichauf and J. Pua

COUNTERSIGNED E. P. Stabler *E. P. Stabler* H. W. Katz *H W Katz*

ELECTRONICS LABORATORY, ELECTRONICS PARK
SYRACUSE, N. Y.

Distribution List

Y. Gala W. Holden R. Hard	AEC, LMED
V. C. Campbell B. A. Findeisen H. J. Hannam E. F. Schilling K. Schlesinger	CRT
H. R. Day W. E. Glenn L. A. Harris P. E. Pashler	Research Laboratory
H. L. Lester F. L. Macera S. P. Newberry J. F. Norton W. Rodstrum L. L. Stahl	GEL
A. E. Allen W. E. Good B. J. Smith	TVR
L. A. Branaman R. J. Fredericks D. V. Reinhardt	HMED
G. T. Waugh	DSD
G. J. Chafaris W. R. Chynoweth D. R. Cunningham R. B. Gethmann M. L. Noble D. D. Scofield J. D. Stone	Electronics Laboratory
I. C. Abrahams E. D. McCormick	TPO
Y. H. Haines	MSD

Introduction

The objective of this government sponsored program was to develop an electron emission and prefocusing system for a gun capable of delivering high current densities in the writing spot and having writing capabilities of several thousand resolvable elements per linear scan (about one inch long). Because of cathode life limitations, this was supposed to be achieved without operating the cathode at an excessively high temperature. A rugged structure not requiring careful cathode alignment should result.

The development of the magnetic limiting aperture gun is based on a concept of R. B. Gethmann of the Electronics Laboratory. In order to obtain a high current density object, a strong nonuniform magnetic field coaxial with an object forming aperture is used. A strong permanent magnetic ring as shown in Figure 1 surround the aperture and provides compressing means to draw high currents through it. The design with a permanent magnet is mechanically simple.

Such a design would permit the use of large area emitters required for increased ruggedness and longer cathode life. Either large diameter wire hairpins or flat, ribbon cathodes could be used. Thus, cathode alignment requirements would be eliminated or substantially reduced. Replacement of a flat cathode would be simple. The structure would be rugged. A well-defined object would be available with little change in size when intensity modulating the beam and the resulting current distribution in the writing spot would be desirable for thermoplastic recording. The cathode life might be increased because of the large emitting area from which electrons are drawn into the limiting aperture thus requiring lower cathode current densities and lower operating temperatures.

Two related modes of operation are possible. In the mode of operation suggested by R. Gethmann, compression of the electron beam takes place in the region of the aperture when the low velocity electrons are forced to follow the magnetic flux lines in a tight spiral motion. The pitch of the spirals for small angles of the electron velocities with the flux lines is given by

$$h = 21.1 \frac{V}{H}$$

in centimeters, where h is the pitch of the spiral, V is the voltage in volts in the considered region and H is the magnetic field in oersted.

In the other mode reimaging of the primary object, for example the crossover, takes place by the nonuniform magnetic field. Thus, a new demagnified object is obtained in a similar manner as in other relay-lens designs. With the field realizable with permanent magnets and at the accelerating voltages required for high cathode loading, operation in an intermediate region results.

Current Transmission Through Magnetic Limiting Apertures

The first experiments were carried out in order to determine the current densities obtainable through magnetic limiting apertures regardless of resulting imaging properties. For the permanent magnet a machinable platinum-cobalt alloy, developed at the General Electric Research Laboratory,(1) was used. The residual magnetic flux density produced by the sample used was 4600 gauss.

The basic design of the gun is shown in Figure 2. The limiting aperture was operated at 400 volts. The dimensions of the platinum-cobalt magnetic ring were: thickness 0.030" outside diameter 0.135" and inside diameter 0.043". The following electrode G_3 was at 3 kilo-

(1) D. L. Martin and A. H. Geisler, J. Appl. Phys., 24, 498, (1963), General Electric Co., reports: RL-508, March 1951, and 57-RL-1677, January 1957.

volts. The cathode was a flat tungsten ribbon 0.001" thick, 0.060" wide. The other design data can be seen in the figure. The magnetic field measured with a Hall-effect probe about 0.030" from the pole surface was about 200 gauss. For the gun performance measurements, the prefocus deflection gun was used which was developed earlier for the Bureau of Ships PPI thermoplastic recorder (Contract No. NObsr 77572).[(2)] The data obtained from such measurements are shown in Tables I and II.

Table I

Currents and Current Densities for a 0.0045" Aperture

$I_{cathode}$ µ amp	I_{beam} µ amp	$J_{aperture}$ amp/cm^2
150	14	1.1×10^{-1}
200	30	2.4×10^{-1}
400	73	5.9×10^{-1}
700	120	1
1200	270	2.1
1800	420	3.3

In another experiment a 3 milliampere beam was obtained at 4-5 milliamperes cathode current, corresponding to 24 amp/cm^2.

Similar measurements were made with a 0.0015" aperture in order to determine if current densities of the same order of magnitude can be obtained through the smaller aperture. The results are shown in Table II.

---

(2) P. H. Gleichauf, IRE Transactions, ED-9, 399, (1962), General Electric Company, TIS R61ELS-123.

Table II

Current and Current Densities for a 0.0015" Aperture

$I_{cathode}$ μ amp	I_{beam} μ amp	$J_{aperture}$ amp/cm^2
200	1	5×10^{-2}
650	3	1.5×10^{-1}
1000	6	3×10^{-1}
1700	11	5.5×10^{-1}
2800	23	1.1
4500	40	2

After these tests it was noticed that the magnetic field had dropped to as low as 1/30 of its original value. This effect will be discussed later.

Although high beam currents have been obtained, imaging properties were lost. At high current the spots were surrounded by a large fuzzy area, in appearance different from spherical aberrations. At very high currents the bright core disappeared and only the fuzzy area remained. Deflecting the beam with an external magnet indicated that the origin of the electrons producing the bright spot was different from those producing the fuzzy area.

Gun Designs

In the gun tests, several designs of the image forming system were used as shown in Figures 2, 3, 4 and 5. Figure 3 shows a modified structure of the prefocusing structure of the prefocus deflection gun. In this structure an electrostatic prefocusing lens precedes the magnetic limiting aperture. Another design is shown in Figure 4. This structure was developed in order to increase the magnetic flux in the aperture region. The aperture was placed between two magnets, separated 0.035". The final gun design with an additional large limiting aperture is shown in Figure 5.

Either a heavy wire hairpin using 0.012" diameter tungsten wire, or a ribbon cathode were used. A large diameter wire hairpin was selected because of the expected less noticeable effect of misalignment, than with thin wire cathodes. For maximum demagnification of the object, that is for maximum resolution, it is desired to operate the limiting aperture at the lowest possible voltage. Nevertheless, it was found that higher voltage operation than desired from the demagnification point of view, seems preferable.

Electrostatic Prefocusing Lens

With a flat cathode it was found that high current interception took place by the first anode (G_2). Therefore, the accelerating Einzelens formed by the first grid (G_1), the first anode (G_2) and the third grid (G_3) was redesigned. The diverging parts of the lens were weakened to reduce current interception by increasing the fields penetration into G_2. This was achieved by a wide angle taper at the aperture edge and by increasing the aperture size. (see Figures 6 and 7)

Magnetic Limiting Aperture

A closer study of the magnetic lens was carried out. This study, required for optimization of the lens design, permits one to estimate the magnetic flux in the aperture and cathode regions and thus the constricting effect on the electron beam. It also was required for evaluating the interference of the magnetic and the electrostatic fields in the curvilinear flow emission system.

Since Biot-Savart's law states that the line integral of the magnetic field intensity if taken along any given closed path must be equal to the current enclosed by this path, one obtains for a current free region:

$$\oint \bar{H} \cdot d\bar{l} = 0 \tag{1}$$

Therefore, there exists a scalar potential function Φ such that

$$-\nabla\Phi = \bar{H} \tag{2}$$

From

$$\nabla \cdot \bar{B} = 0 \tag{3}$$

it follows that $\nabla^2\Phi = 0$ in homogeneous isotropic media; that is, the magnetostatic potential satisfies the Laplace equation and its distribution may be determined in an electrolytic tank. The axial component of the magnetic flux density,

$$B_z = \mu H_z = -\mu \frac{\partial \Phi}{\partial z} \tag{4}$$

An equipotential plot for the region to the left of the midplane of one of the magnetic rings used is shown in Figure 8. The plot is identical for the region to the right of the midplane. The equipotentials are marked in percentage of the maximum potential. The axial potential variation is plotted in Figure 9a and the axial magnetic flux density normalized with respect to the flux density of the face of the magnetic ring is plotted in Fig. 9b.

From the last three figures, it is quite clear that there exists a saddle point where the magnetic flux reverses its direction. If a magnetic condensing effect exists, the beam will have a minimum diameter at the midplane of the magnetic ring and a large diameter at the plane perpendicular to the axis containing the saddle point. Therefore, care must be taken that the aperture is not positioned in the saddle point. One can see that in some of the gun designs with a flat cathode the magnetic flux density in the cathode region decreases to about 20 to 25% of the value at the pole face, resulting in practical values of about 300 gauss at the cathode surface.

In order to have a better insight into the variation of the axial magnetic field with axial distance and the various dimensions of the magnetic ring, an approximate analytic expression was derived. The magnetic ring with inside radius "a", outside radius "b", and thickness "l" as shown in Figure 10 may be considered as formed by two equal but opposite magnetic surface charges with charge density "m" located on the two faces of the magnet. At a point P on the axis in free space where the permeability is μ_o, the incremental magnetostatic potential due a filamentary magnet having a cross section area (dA) is

$$\begin{aligned} d\Phi &= \left(\frac{1}{S_1} - \frac{1}{S_2}\right)\frac{m\,(dA)}{4\pi\mu_0} \\ &\approx \left(\frac{1}{S - \frac{\ell}{2}\cos\theta} - \frac{1}{S + \frac{\ell}{2}\cos\theta}\right)\frac{m(dA)}{4\pi\mu_0} \\ &\approx \frac{m\ell(dA)}{4\pi\mu_0}\cdot\frac{\cos\theta}{S^2 - \frac{\ell^2}{4}\cos^2\theta} \\ &\approx \frac{m\ell(dA)}{4\pi\mu_0}\cdot\frac{\cos\theta}{S^2}\left(1 + \frac{\ell^2}{4S^2}\cos^2\theta\right) \end{aligned} \qquad (5)$$

If $l/2$ is very small compared to S, the second term in the last expression may be omitted. The axial component of the field strength corresponding to this filamentary magnet is

$$dH_z = -\frac{\partial}{\partial z}(d\Phi)$$
$$= \frac{-ml(r^2-2z^2)}{4\pi\mu_0(r^2+z^2)^{5/2}}(dA) \qquad (6)$$

The total axial field intensity

$$H_z = -\int_a^b 2\pi r \cdot \frac{ml(r^2-2z^2)}{4\pi\mu_0(r^2+z^2)^{5/2}}\,dr \qquad (7)$$

or

$$H_z = -\frac{ml}{2\mu_0}\int_{\sqrt{z^2+a^2}}^{\sqrt{z^2+b^2}}\left(\frac{S^2-3z^2}{S^4}\right)dS \qquad (8)$$

Therefore

$$H_z = \frac{ml}{2\mu_0}\left[\frac{b^2}{(z^2+b^2)^{3/2}} - \frac{a^2}{(z^2+a^2)^{3/2}}\right] \qquad (9)$$

As expected with a dipole, its far field varies inversely as z^3. The saddle points are located at

$$z_s = \pm \frac{(a\,b)^{2/3}}{(b^{2/3} + a^{2/3})^{1/2}} \tag{10}$$

By differentiating H_z with respect to z and equating the result to zero, the positions of the maxima of H_z are found to be at

$$z_m = \pm \left[\frac{a^{4/5} b^2 - b^{4/5} a^2}{b^{4/5} - a^{4/5}} \right]^{1/2} \tag{11}$$

A first order correction to account for the effect of the thickness l of the magnet is obtained by retaining the last term of equation (5). This gives

$$H_z = \frac{m\,l}{2\,\mu_0} \left\{ \frac{b^2}{(z^2+b^2)^{3/2}} - \frac{a^2}{(z^2+a^2)^{3/2}} + \frac{l^2 z^2}{20} \left[\frac{3b^2-2z^2}{(z^2+b^2)^{7/2}} - \frac{3a^2-2z^2}{(z^2+a^2)^{7/2}} \right] \right\} \tag{12}$$

The sum of the last two terms reduce to zero at $z = 0$ and $z \to \pm\infty$. However, for z in the neighborhood of b and a it does have an effect on H_z and consequently the saddle points and maxima.

The flux density inside the magnetic ring depends on the loading of the magnet by the external magnetic circuit. The operating point is the intersection of the load line and the B-H curve of the magnetic material of the magnet. The total magnetic flux is

$$\Phi = \frac{l\,H_m}{R} \tag{13}$$

where l is the thickness and H_m the magnetic intensity in the magnetic ring and R is the total reluctance of the external circuit. The flux density in the magnet is

$$B_m = \frac{\Phi_m}{A_m} = \frac{l\,H_m}{\pi(b^2-a^2)R} \tag{14}$$

where b and a are respectively the outer and inner radii of the ring. The reluctance R, is again obtained from electrolytic tank measurements. Most of the magnetic rings give a load line of about

$$B_m = 0.75\,H_m \tag{15}$$

For the platinum-cobalt alloy magnetic material this gives a maximum flux density of 1800 gauss at the midplane of the magnet.

Magnetic Materials

During the experiments it was repeatedly observed that the field of the platinum-cobalt permanent magnet decreased to very low values after short operating times. This was apparently caused by heating due to heat radiations from the cathode and the electron bombardment of the magnet and of the adjacent parts including the limiting aperture strip. The demagnetization was surprising since the Curie point of the material was supposed to be at about 500°C. Furthermore, after repeated use of the magnet and remagnetization, finally it became impossible to remagnetize the ring. This was explained by a change in structure of the magnetic material. It was assumed that the magnet material was improperly heat treated. Machining of the material apparently was not the cause of the unsatisfactory performance. A new sample of material was received, giving only slightly better results.

The magnets in new structures were shielded from heat radiations and electron bombardment. The aperture "disk" was physically separated from the magnet. In some structures the aperture disk was placed between the cathode and the magnet, in other guns the magnet containing electrode was provided with a special shielding electrode.

High uniformity of the magnetic field is required. Otherwise the electron beam is deflected off axis and the core of the beam is not in the aperture region. Operation of the gun in the emission electron microscope mode indicated non-uniformities. The non-uniformities of some permanent magnetic materials were studied by L. I. Mendelsohn.[(3)] For platinum-cobalt non-uniformities of about 7% were found. Soft iron pole pieces were considered for improving the uniformity of the field. This idea was abandoned because of expected difficulties in maintaining close tolerances during machining of the small pole pieces.

Because of the above mentioned difficulties a grain oriented ferrite, Indox V, was introduced. This material proved more satisfactory for our applications. Nevertheless, in some experiments demagnetization was observed which might have been caused by arcing in the gun. The material is more difficult to machine; ultrasonic machining was used. Its life properties could not be fully evaluated under this program.

---

(3) L. I. Mendelsohn, J. of Appl. Phys., 29, 407, (1958).

Space Charge Effects

A factor which might limit the performance of the magnetic aperture is the apparent formation of a space charge or possibly of a virtual cathode in front of the limiting aperture. This was indicated in some experiments by a decrease of current transmitted through the aperture with increasing cathode current at high cathode currents, whereas at low cathode currents the beam current, that is the current through the aperture, increased with increasing cathode current. The formation of such a space charge may have been assisted by a magnetic mirror effect; no analytical evaluation is yet available. Instabilities, that is slow current fluctuations, could sometimes be observed when operating the gun as an emission electron microscope. By increasing the electron velocity it was possible to overcome these instabilities and to increase the beam current.

Resulting Gun Designs and Performance

The guns developed under this program are shown in Figures 3 and 5. These designs should not be accepted as final since further refinements seem possible. The dimensions of the Indox ferrite ring were: thickness 0.055", outside diameter 0.155" and inside diameter 0.053". The guns were operated with G_2, G_3, G_4 and G_5 at 1200 volts.

The performance data of the gun shown in Figure 3 with a 0.0015" limiting aperture and a 0.012" diameter tungsten wire hairpin, using the prefocus deflection system were: at one microampere beam current and 10 kilovolts the spot size was about 5 microns which is equal to about 5 amperes per centimeter square in the spot. The shrinking raster method (on a transparent phosphor) was used for these measurements. It was pointed out to us by H. Lester of the General Engineering Laboratory that the spot sizes are actually smaller than measured because of optical aberrations caused by the thick face plate with the phosphor. The prefocus deflection gun is capable of writing a square raster of about 20 mm, or single sweep 25 to 28 mm long. Thus, using dynamic controls, the limiting resolution corresponds to about 5,000 lines on a single scan. At currents above 5 microamperes the spot became somewhat fuzzy.

For comparison an identical gun with a 0.0015" aperture but without the magnet was built. The maximum obtainable current through the aperture was one half microampere.

Recordings with 100 lines per millimeter at one half microampere have been obtained in a slide recorder on 0.009" thick thermoplastic coated glass slides under conditions corresponding to optical correlation read-out. This corresponds to 2500 resolvable elements on a 25 mm scan (or 5,000 TV lines) and possibly up to 2800 elements on 28 mm scan. The resolution while recording at one microampere has not been determined.

Only scant data are available on the gain in resolution when using smaller limiting apertures. Operation with an 0.0005" aperture was not very satisfactory, but after the measurements it was found that partial demagnetization took place which was apparently caused by an arc in the gun. Beam currents of only 0.3 microamperes were obtained.

The same gun was operated with a flat (ribbon) cathode. The performance was the same as with the 0.012" diameter wire hairpin. This structure offers the advantage that axial cathode alignment is not required, and cathode replacement becomes simple. A suitable flat cathode structure has not been developed yet.

For better protection of the magnet from heating effects, caused by bombardment an additional 0.015" aperture was placed into G_2, as shown in Figure 5. The spot size in this gun with a 0.0015" object forming limiting aperture and a 0.012" diameter tungsten wire hairpin was indicated to be at one microampere beam current and 10 kilovolts less than 4 microns. At two microamperes it was about 4 microns and at three microamperes about 7 microns. The insufficient stability of the circuits made reliable measurements difficult.

Recordings with more than 110 lines per millimeter have been obtained on thermoplastic coated slides in the slide recorder at 0.6 microamperes and 10 kilovolts. The grooves were shallow. Because of instability of the circuits it is not certain whether this is the resolution limit.

The large demagnification of the order of 7 to 10 calculated from measured spot sites indicates that a cross-over might have been formed in the vicinity of the limiting aperture. The occurrence of focus at two voltages at 150 and 210 volts, might also be an indication of cross-over imaging at the higher focusing voltage and aperture imaging at the lower voltage; higher resolution has been obtained at the higher voltage.

In the modified structure shown in Figure 4 in which the magnetic flux in the aperture region was increased and extended over a longer axial region, the current transmission through the 0.0015" aperture was lower than in the single magnetic ring structures.

Further development of a strongly converging magnetic field should be considered. Such fields are desired for stronger compressive action on the electron beam. Stronger magnetic fields could possibly be produced by an external electromagnet with internal shaped pole pieces. One may encounter difficulties in building such a structure because of the small required dimensions of the pole pieces.

Other work is recommended on development of a suitable refractory flat cathode. Tests to determine the life of the permanent magnets are required.

Conclusion

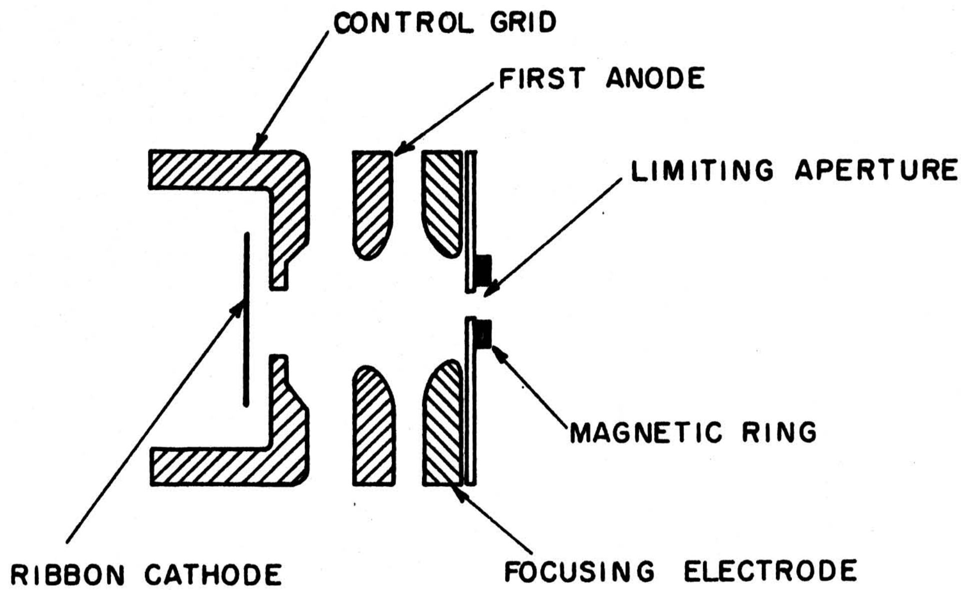
Magnetic limiting aperture structures were developed in which high currents can be drawn through small apertures. Thus a high current density object can be formed. The required structures are mechanically simple.

More than one hundred resolvable elements per millimeter have been recorded on thermoplastic coated slides at about one half microampere beam current and 10 kilovolts under conditions required for optical correlation read-out. The emission and object forming system was used in the prefocus deflection gun which is capable of recording single scan 25 to 28 millimeters long, or a 20 x 20 millimeter raster; it should be possible to record about 2800 resolvable elements per linear scan. An emission system with a ribbon cathode was successfully operated. Thus, it has been shown that a rugged emission system without a hairpin cathode can be built.

Up to several amperes per centimeter square have been obtained through such apertures. At high currents imaging problems remain unsolved. Some problems of optimizing gun and magnet dimensions, as well as obtaining high magnetic fields have not been completely solved.

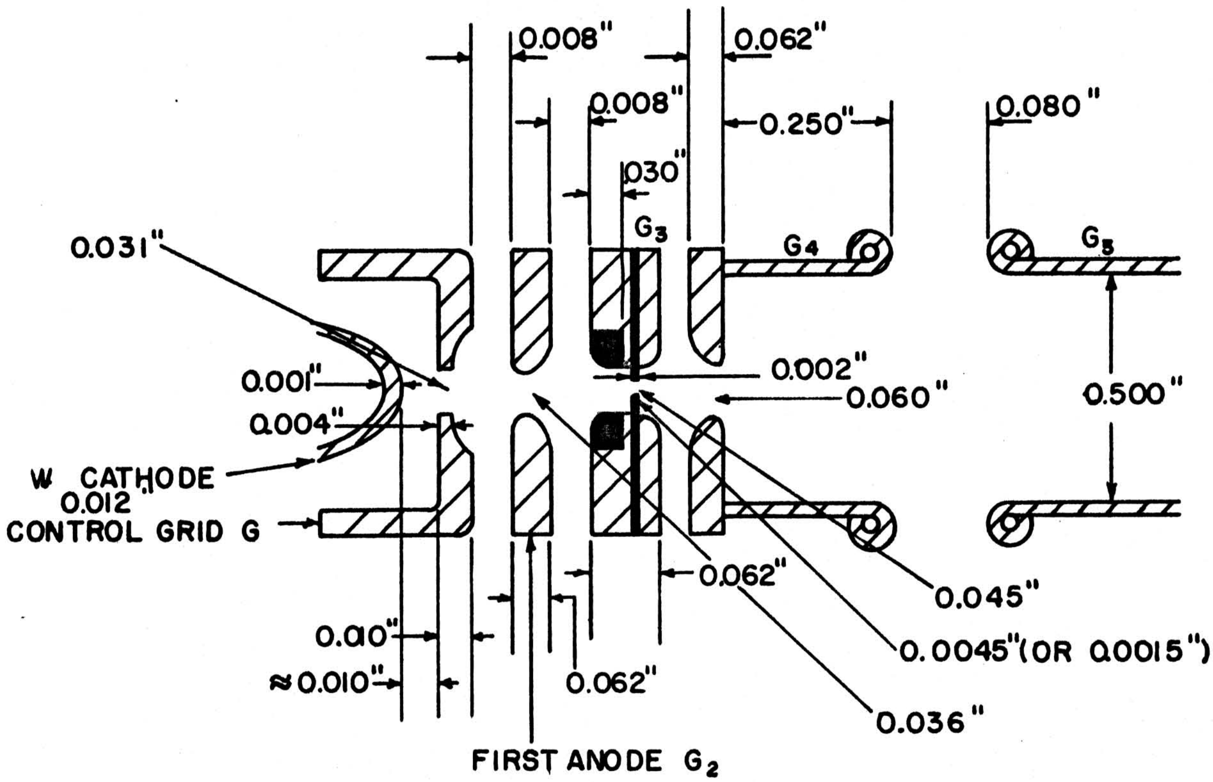
Acknowledgment

Recording experiments were made possible by the close cooperation of L. E. Somers, D. R. Cunningham, D. D. Scofield and J. D. Stone. Mr. D. Osborn assisted in the redesign of the electrostatic prefocusing lens and carried out the required evaluations in the electrolytic tank.



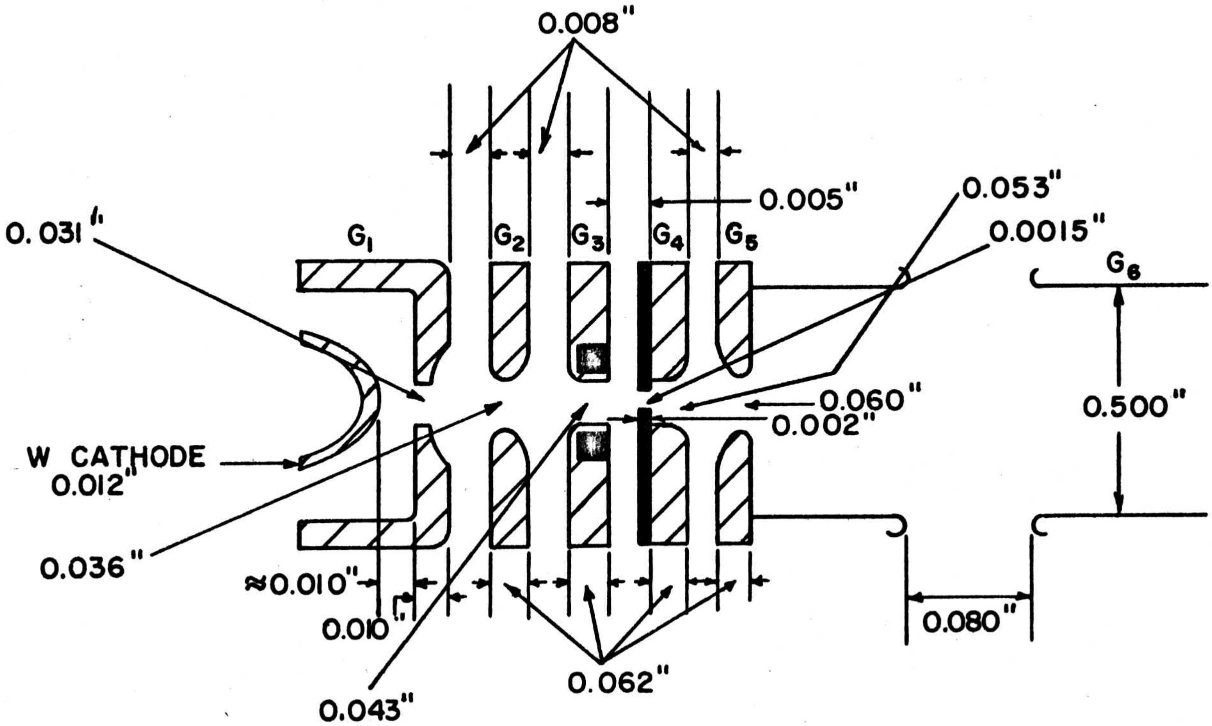
EMISSION AND PREFOCUSING STRUCTURE WITH MAGNETIC LIMITING APERTURE

FIGURE I



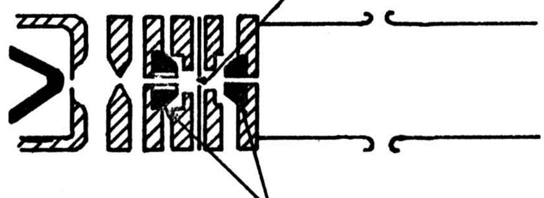
EMISSION AND PRE-FOCUSING STRUCTURE WITH MAGNETIC LIMITING APERTURE FOR CURRENT TRANSMISSION MEASUREMENTS

FIGURE 2



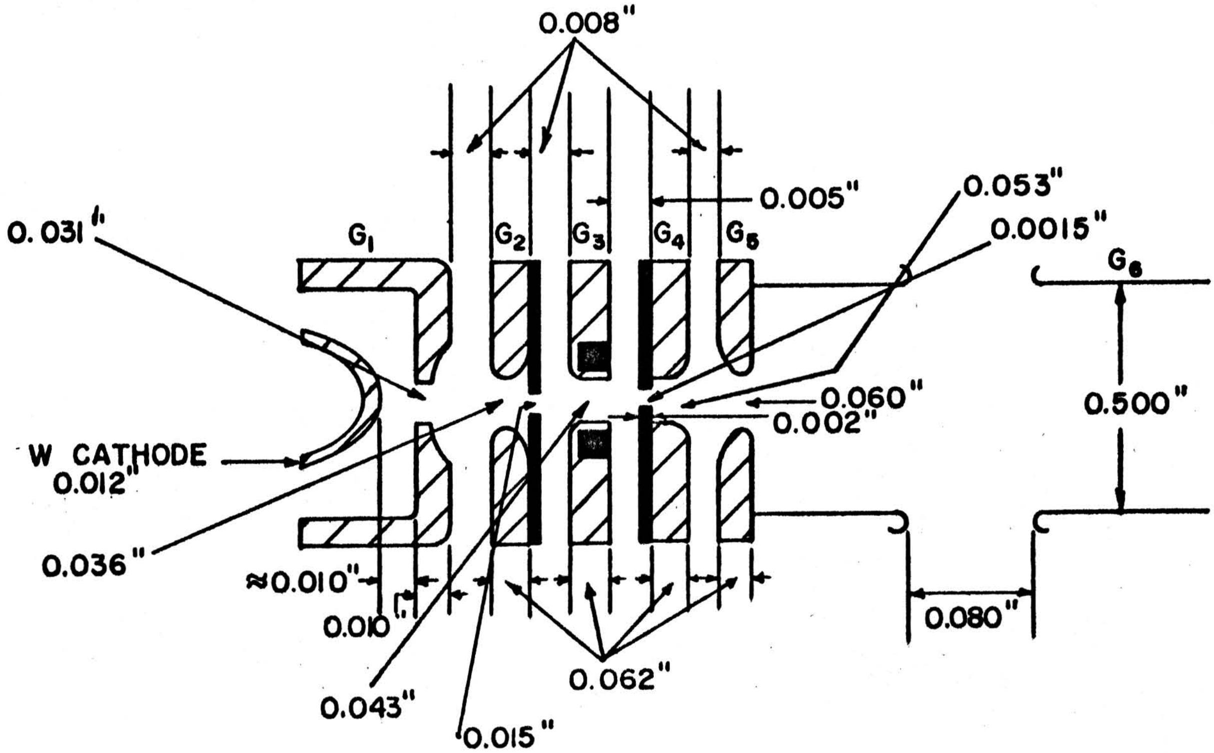
MODIFIED EMISSION AND PRE-FOCUSING STRUCTURE
WITH MAGNETIC LIMITING APERTURE

FIGURE 3



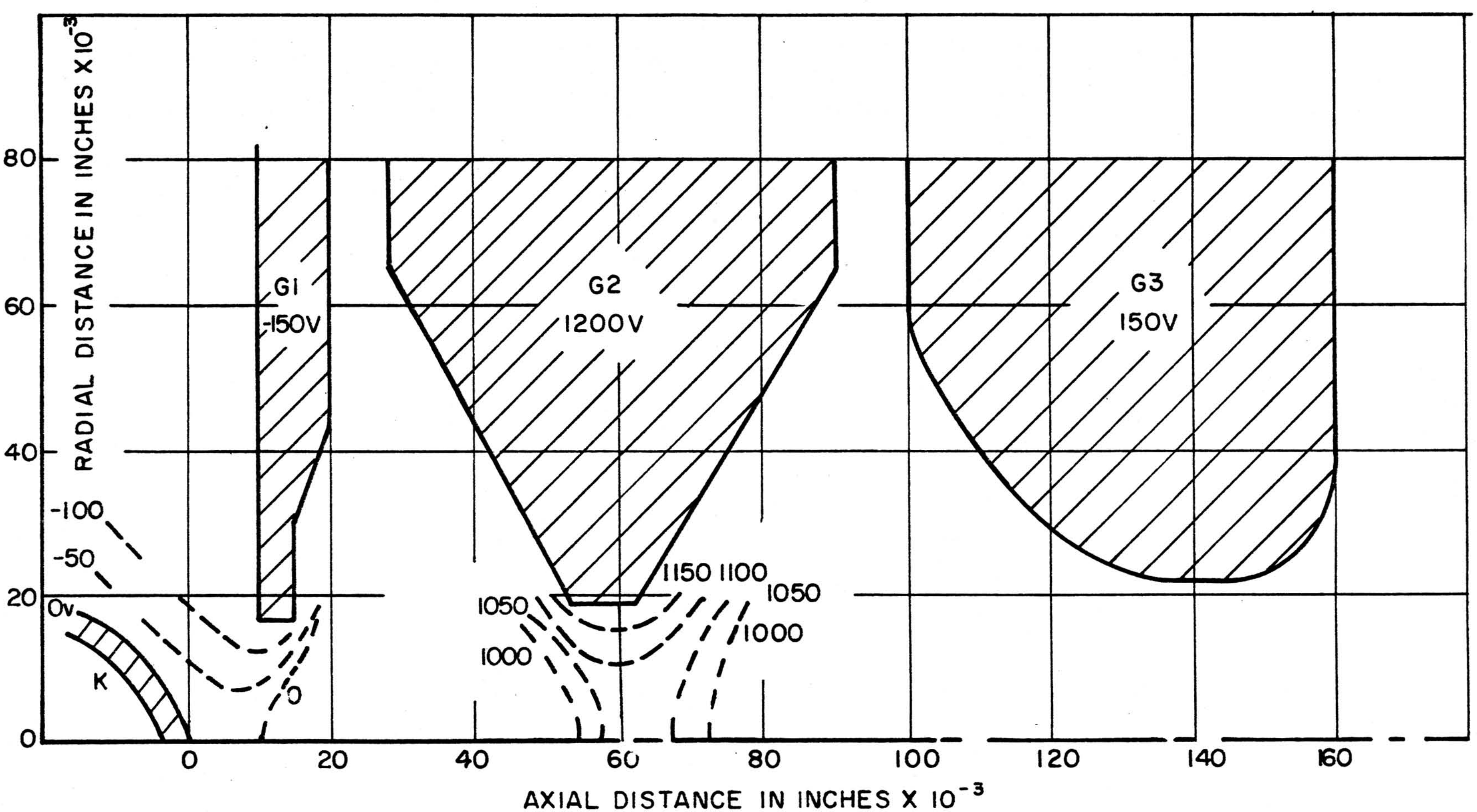
EMISSION AND PREFOCUSING STRUCTURE WITH DOUBLE MAGNETIC RING LIMITING APERTURE

FIGURE 4



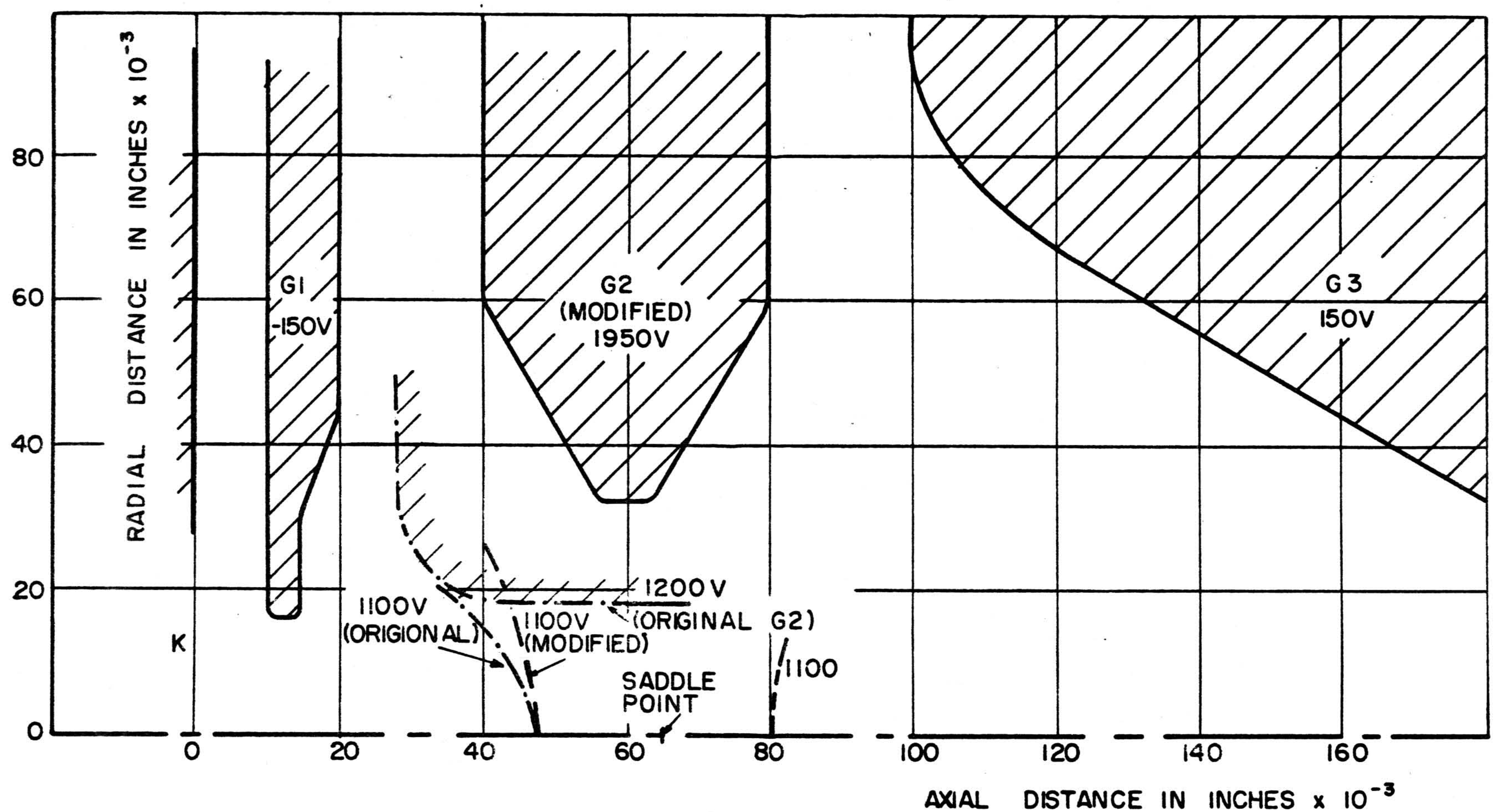
FINAL EMISSION AND PRE-FOCUSING STRUCTURE
WITH MAGNETIC LIMITING APERTURE

FIGURE 5



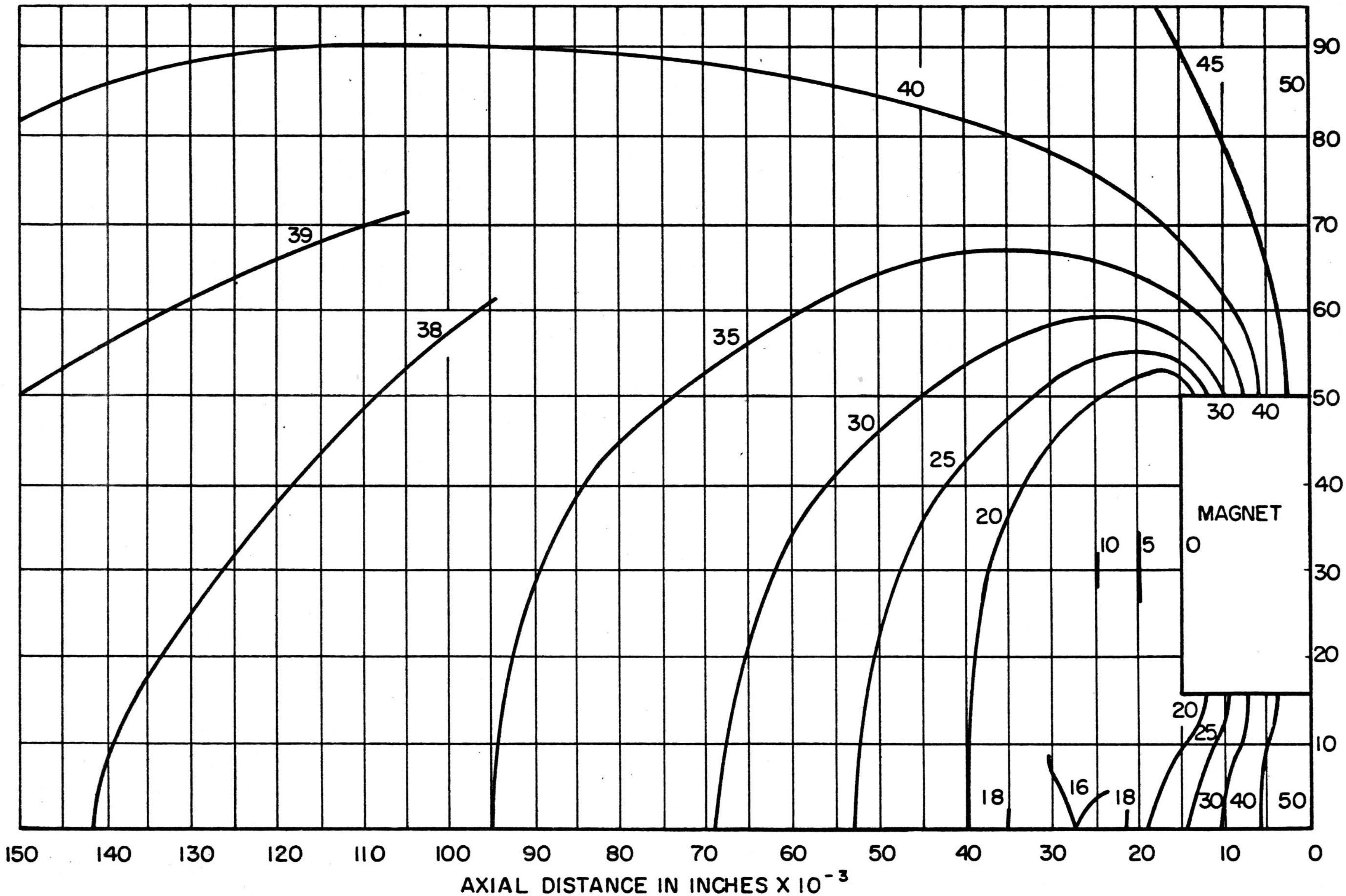
FIELD PLOT OF RE-DESIGNED PRE-FOCUSING LENS
WITH SUPPRESSED DIVERGENT PART
(HAIRPIN CATHODE)

FIGURE 6



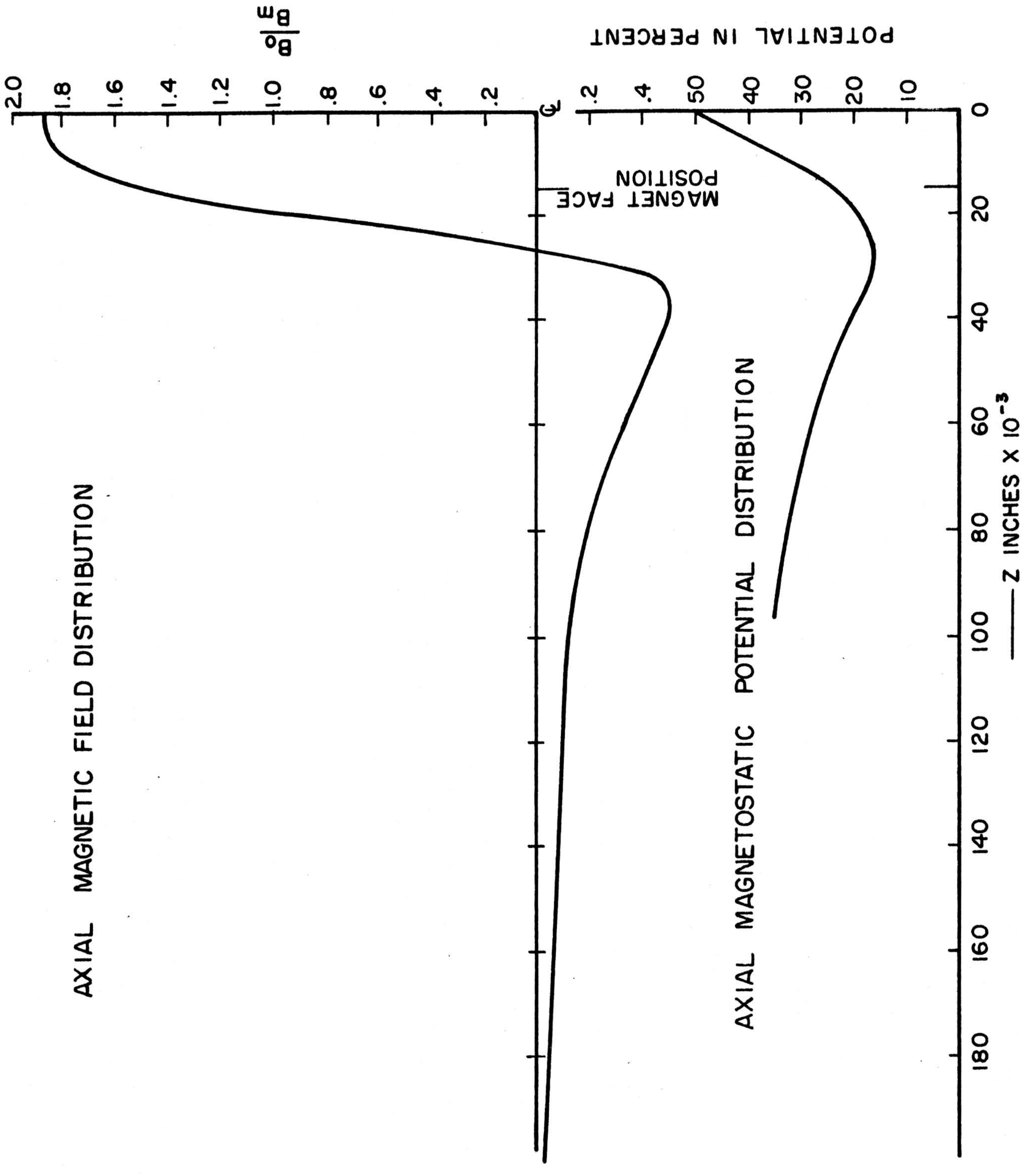
FIELD PLOT OF RE-DESIGNED PRE-FOCUSING LENS
WITH SUPPRESSED DIVERGENT PART
(FLAT CATHODE)

FIGURE 7



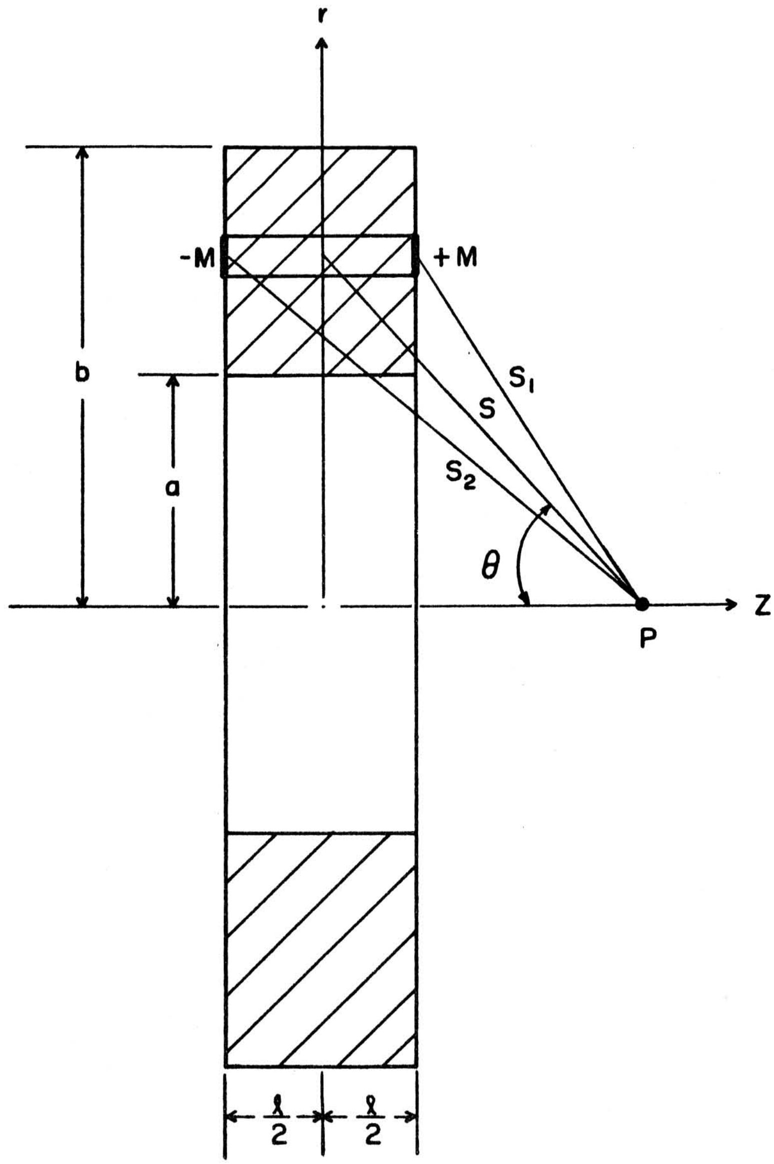
EQUIPOTENTIAL PLOT OF RING MAGNET

FIGURE 8



POTENTIAL IN PERCENT
$\frac{B_o}{B_m}$
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
℄
.2
.4
50
40
30
20
10
0
MAGNET FACE POSITION
AXIAL MAGNETIC FIELD DISTRIBUTION
AXIAL MAGNETOSTATIC POTENTIAL DISTRIBUTION
20
40
60
80
100
120
140
160
180
Z INCHES X 10^{-3}

FIGURE 9



RING MAGNET DIMENSIONS FOR THE DERIVATION OF AXIAL MAGNETIC FIELD STRENGTH

FIGURE 10