1960

Electron beam pinch

Horton, Edward R.

Monterey, California: U.S. Naval Postgraduate School

http://hdl.handle.net/10945/12092

ELECTRON BEAM PINCH

EDWARD R. HORTON
and
ROSS L. SPOERLEIN

ELECTRON BEAM PINCH

by

Edward R. Horton

Lieutenant, United States Navy

and

Ross L. Spoerlein

Lawrence Radiation Laboratory,

Livermore, Calif.

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 6 0

ELECTRON BEAM PINCH

by

Edward R. Horton

(and Ross L. Spoerlein)

This work is accepted as fulfulling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

PHYSICS

from the

United States Naval Postgraduate School

UCRL - 5989
Draft

ELECTRON BEAM PINCH

E. R. Horton and R. L. Spoerlein

ABSTRACT

One of the major objects of current plasma pinch research is an understanding of turbulence and its effects in enhanced diffusion rates within a pinch. As an approach to this problem, the electron beam pinch was conceived. In this experiment, an electron beam (400 kev, 0.1 amp, 0.1 usec. duration) enters a linear pinch at one electrode and is observed (by light from a phosphor screen) at the opposite pinch electrode. By a selection of radial positions and time of injection, the turbulent pinch configuration may be explored. Use of a probe with such small mass (as beam of electrons) may yield important information on turbulent diffusion.

This report presents the results of preliminary tests and the first effort to obtain parameter dependence of the pinch configuration so that the electron beam may be properly programmed. All runs were made at a pinch current of 200,000 amp which, from previous experience, was assumed to be a good medium value. Initial gas pressures were varied from 25 to 400 microns of deuterium and initial z-field varied from 500 to 2000 gauss. Analysis of all runs show that pressure from particles boiled off the wall dominated over any other pressure distribution. Even for field configurations which show very little turbulence, the pressure at the wall is overpowering. Pressure distribution is improved by impressing a reversed axial field and by reducing the magnitude of the pinch current.

UCRL 5989 DRAFT
5/15/60

ELECTRON BEAM PINCH

Edward R. Horton and Ross L. Spoerlein

I. INTRODUCTION

Experimental results from "Stabilized" pinch experiments have consistently shown small scale instabilities or turbulences in field configurations which should be stable according to present hydromagnetic theory[1]. Also, anomalies exist among plasma temperature estimates from conductivity, magnetic field, and neutron yield considerations . That is to say, some energy loss mechanisms are present which are either completely unknown or else not fully understood.

Considerable work is being done to explore the fundamental theories and mechanisms involved in plasma confinement. The electron beam experiment[2] was conceived as another approach to the basic question of power spectrum of turbulence so that enhanced diffusion rates can be predicted. It is conceptually possible that a probe with mass as small as an electron beam may undergo diffusion type processes that will yield information on the nature and characteristics of the turbulence and turbulent diffusion.

The experiment is designed to observe the configuration anddistortion of magnetic fields during a pinch. This is done by injecting a high energy, short pulsed electron beam longitudinally into a small linear stabilized pinch. The beam should remain on the same magnetic field line throughout its transit down the pinch. Therefore, a change in the positions of the beam as it emerges at the other end of the pinch tube is an indication of the change experienced ' by the magnetic line of force. By varying the radial distance and time of injection, the complete life cycle of the magnetic field lines may be observed. While the experimental setup which is the subject of this report is limited to a single beam pulse during each pinch cycle, supplementary experiments have shown the feasability of using a lower energy, multiple pulsed beam which could probe

the time dependent development of the magnetic field configurations more accurately.

Other refinements to the experimental setup will permit the observations of the beam (or multiple beams) at any axial distance along the pinch.

While the preliminary results in no way represent the anticipated results, the very fact of the unexpected further points to the need for a better understanding of the fundamental mechanisms involved. The resulting magnetic field configurations and associated plasma pressure distributions are now experimentally predictable and reproducible and are, therefore, explorable with the electron beam.

II. Apparatus (Figs. 1,2)

A. Electron Beam.

The electron gun is a simple heated tungsten filament within one end of the vacuum system. The filament is heated continuously by 60 cycle ac thru an isolating inductor. The beam is created by impressing high voltage across an acceleration gap between the gun and the end plate of the T-section. The energy and duration of the beam are therefore determined by the accelerating voltage applied. For this experiment, a voltage pulse of up to 400 kv, 0.25 μsec. duration is used. This pulse is generated by discharging a capacitor thru a 25:1 pulse transformer. The gun, pulse transformer, filament isolating inductor, and voltage divider used to monitor the accelerating voltage are all in an atmosphere of sulfur hexafloride to reduce high voltage arcing.

Considerable difficulty was encountered with voltage breakdown along the vacuum side of the glass wall between gun and end electrode. This arcing is reduced by using corona shields around the base of the gun so as to protect the O-ring vacuum seal from strong electrostatic field gradients.

The gun must be operated in a vacuum of at least 10^{-4} mm whereas the pinch tube will be at pressures of from 10^{-2} to 1 mm. This, then, requires maintaining different portions of the vacuum system at pressures differing by several orders of magnitude while still allowing free passage of the electron beam from one region to the other. In order to accomplish this, a system of "differential pumping" is used in which the two regions are connected by a small orifice (1/16" diam.) and vacuum pumpouts (4" oil diffusion pumps) are located at each end of the orifice section. The necessary pressure difference thru the orifice is easily maintained.

In order to get the electron beam to pass thru the orifice from the gun into the pinch tube region, it is necessary to force the beam diameter down to the size of the orifice. This is done by placing a "focussing" field thru the orifice of about 1200 gauss. A very slow rising field is necessary so that the field will grow uniformly thru the various brass and stainless steel parts. The focussing field has a rise time of about 1 second.

Once the beam is thru the orifice, the introduction of the beam into the pinch presents no special problems. The end electrode is slotted to allow the beam to enter the pinch at any radial distance from the center of the pinch. This slot also serves as the pumpout for the pinch tube. It is assumed that any perturbation in the pinch due to the asymmetry of the electrode is negligible.

The electron gun and pinch tube are so aligned that the beam is normally introduced on the axis of the pinch. To introduce the beam off axis, a pair of deflection coils are located immediately outside the entrance slit. They deflect the magnetic lines of force along which the beam is travelling so that any radial distance for beam injection may be selected.

Detection of beam position and relative intensity is accomplished by terminating the pinch on a thin foil electrode which must be strong enough to withstand the shock of the pinch current and yet be thin enough to allow transmission of the beam without too great an attenuation to the phosphor located immediately behind. First work was done with a 2 mil Cu-Be ($10^{o}/o$) foil. Later, a 10 mil Mg foil was used. For both of these foils, a beam accelerating voltage of 350 kv or better was required. Currently, a compound foil is in use. This consists of a 2 mil stainless steel screen perforated 200 holes per cm^2 which carries the pinch current, and a 1 mil Al foil which shields the phosphor from the light of the gas discharge. With this compound foil, a much lower beam accelerating voltage is required which will permit use of an r-f generator to power the gun. This will give a multiple pulsed beam with which the time dependent development of turbulence may be more closely studied.

The beam spot on the phosphor is observed with a speed graphic camera using Polaroid 3000 film. and has a time duration of 0.1 μsec.

B. Pinch Tube

The pinch tube (Fig. 3) is made of 100 mm diameter pyrex tubing with 2.5 mm walls. The tube is 16" long. The entrance electrode is stainless steel with the slot opening for the beam entrance and three other openings for ion source trigger, gas entrance and pressure gauge (see Fig. 4) . The other electrode is the foil and phosphor assembly as described above. Both sides of the electrode are evacuated so that the foil assembly is not required to support a steady state pressure difference. The return conductors are eight pair of 1 1/2 in. flexible copper braid within tygon tube insulation. These are taped tightly to the pinch tube and emerge between the two sections of the main z coil. The "Program z" winding is a single layer of 1 1/2" x 20 mil Mylar insulated copper strap wound between the glass tube and the return current braids.

C. Probes

In addition to the observation of the beam image on the phosphor, the pinch fields are also observed by inserting a pick-up loop type probe into the plasma from the side. The data for this report was obtained using a 6 mil diameter quartz tube containing 10 separate pick-up loops oriented in the same direction with centers spaced 0.55 cm apart in a radial direction. By rotating the probe 90° , the pick-up loops will indicate either B_z or B_θ changes. When scope traces from all ten pick-up loops are recorded simultaneously, a continuous profile of the field configuration is obtained.

III. Procedures

The main bank circuitry is shown in Fig. 5 . The electron beam is created from the hot tungsten filament by the voltage impressed across the accelerating gap from bank A (0.03 μ f , 20 kv) thru the 25:1 oil bath pulse transformer. The parallel chokes in the filament current leads prevent the accelerating voltage pulse from reaching the filament power supply which is 60 cyc. a c from a line transformer.

Bank B (0.02 farad - 450 v) supplies the current to the kicker coils which deflect the beam away from axis prior to the beam's entry into the pinch.

The slow rising focus field coils are supplied from bank 1 (0.1 farad-450 v). The resistor across the load is necessary to protect against high voltage surges if the bank switch is open before the field is completely gone.

The main z—field windings are in two parts so as to permit the pinch current leads and the probe to enter at the center of the pinch tube. The current for the z windings is supplied from bank 2 (0.05 farad-900 v). The additional windings on top of the main coils, as indicated in Fig. 5 , are to counteract the normal end fringing of the field and, in the case of the winding

over the beam kicker, actually introduce a slight mirror ratio to facilitate effective displacement of the beam by the kickers. This gives a non-constant field distribution along the tube length (Fig. 14).

The current for the pinch comes from bank 4 (60 μf-30 kv) which is the "Geneva" bank* in series connection.

The preion bank 3(0.06 μf - 40 kv) is protected from multiplication of the main pinch voltage by the series resistor. A programmed z field may be added from bank 5 (7.5 μf - 15 kv).

III Procedure.

B. Operation

The first full scale operation of the apparatus showed that the beam will focus thru the orifice with proper adjustment of the focus coils and does enter the pinch volume on axis or at any desired radial distance off axis. With only the vacuum field present, a beam introduced on axis appears at the phosphor as a well defined spot on axis. When the beam is introduced on axis during a pinch, the image on the phosphor is displaced and distorted. An analysis of this type of data must await completion of the profile of the

---

*The "Geneva" bank is the portable capacitor bank which was used with the pinch display at the Second United Nations International Conference on the Peaceful Uses of Atomic Energy at Geneva, Switzerland.

pinch configuration as a function of the various experimental parameters.

To obtain the parameter dependence of the pinch configuration, a series of runs were made at various selected parameters. Field compression as a function of time was observed by the ten element probe described above. Since the probe is capable of picking up field changes in one direction only, separate pinches at the same bank voltages are necessary to record both B_z and B_θ field compressions. Also, since it is desirable to show the amount and time of turbulent behavior, scope traces of probe signals for three similar pinches (same bank voltages) are overlaid. A complete set of scope traces for one set of parameters can then be translated into a profile of field intensity. Finally, from the equation of continuity, the region of plasma pressure may be calculated. It has been shown that this simple technique does not include consideration of inertial forces.[3] However, for the anticipated needs of this report, such a degree of sophistication is not required.

A pinch current of 100,000 amps was selected as a first parameter estimate. This is supplied by a 7 1/2 kv charge on each half of the Geneva bank. This gave a reasonably strong pinch without approaching the maximum rated values of the bank or apparatus. The pinch current parameter remained fixed throughout the first series of operations.

The initial gas pressure was then set at a particular value ranging from 25 - 400 microns. For each pressure, the initial B_z was varied so as to create different pinch ratios. Ratios as high as 5:1 (volume ratio as measured by change in field intensity) were observed.

In order to force the axial field outside the pinch current sheath to zero, a reversed field was impressed by the program-z winding at 1 - 2 μsec after the beginning of the pinch current. By this time the conducting sheath was well enough formed so that the initial and reversed axial fields remained separated until the onset of turbulence.

When unexpected pressure distributions were calculated from the initial set of data, additional runs were made at a lower pinch current.

IV Results.

A. Electron Beam.

The only concrete results obtained using the electron beam show that violent reactions are occurring within the pinch configuration . When the beam is introduced on axis in a vacuum field (no pinch), a birght, well defined spot is observed at the phosphor (Fig. 6a). If the beam is introduced (still on axis) near the time the pinch current begins, the spot is displaced off axis (Fig. 6b). In more turbulent pinch distributions, violent displacements are observed (Fig. 6d). Even suggestions of an interchange type of instability have been observed (Fig. 6c). But, as said above, no thorough analysis of electron beam data is possible until the main characteristics of the pinch itself are known.

B. Radial Probe.

The radial probe data was intended to yield the main characteristics of the pinch distribution. The expected distribution was one in which B_z is high in the middle, falling off very rapidly at the sheath and is zero (or very small) outside the sheath. B_θ is essentially zero within the sheath (all current in the sheath) rising very rapidly thru the sheath, and then falling in a 1/r manner outside the sheath. This type of distribution yields a plasma pressure peak at the sheath and essentially no pressure elsewhere, neglecting inertial effects. Even with inertial contributions, the pressure

curve should still peak at the sheath.

In this report all plasma pressure are represented as the square root of the pressure so that they may be plotted on a scale of gauss.

Fig. 7 is a set of scope traces for a relatively non-turbulent distribution. Initial gas pressure was 400 μ , init al B_z was 3500 gauss and pinch current was 200,000 amp. Pressure distributions was calculated from the equation of continuity (see appendix 1) and a plot of field and pressure distribution was made. Fig. 8 shows the distribution at 1 μsec and at 4 μsec after the start of the pinch current. The characteristic temperature of the plasma is 15 ev.

The plasma pressure curves did not peak at the sheath region but was highest at the wall and in the region between the wall and the sheath. This indicated that a conducting sheath did not, in fact, form and the plasma pressure is a result of impurity particles being released from the wall due to rapid heating of the glass. This same general distribution was observed for all runs at 200,000 amp. pinch current with a few exceptions to be noted later. This is taken as an indication that the pinch current was too large and later runs were made with lower current.

One of the first runs, which indicated some of the characteristics of a conducting sheath is shown in Figs. 9 and 10. Note that this run showed much more turbulence. The plasma pressure curve showed a tendency to peak at the current sheath. Initial pressure was 25 μ and initial axial field was 1000 gauss. However, considerable pressure was still observed outside the sheath. The characteristic temperature of the plasma is 11 ev.

In an effort to form a more distinct boundary layer a reversed axial

field was impressed from the outside after the start of the pinch. This programmed field has a rise time of about 1 μ sec. The resulting field and pressure configuration is shown in Fig. 11 . A better definition of the sheath region is observed and the characteristic temperature is increased to 24 ev.

When the pinch current was reduced to 60,000 amp, a quite different distribution is observed (Fig. 12) . Initial pressure was 100 μ and initial axial field was 700 gauss. This shows much better containment of the gas but still no pressure peak at the sheath is observed. Characteristic temperature is reduced to 2.3 ev.

With a still greater reduction of pinch current to 30,000 gauss, the amount of energy input is not sufficient for the desired effects to be shown over other competing phenomena (Fig. 13). Characteristic temperature is only 1.6 ev.

Comments.

No definite conclusions as to the nature of turbulence are possible on the basis of the data of this report. The unexpected results obtained serve only to confirm the lack of containment of the gas. The problem of turbulence and the associated diffusion of charged particles across magnetic field must be understood before the future of pinch type devices can be ascertained.

The report forms the ground work upon which the future utility of the electron beam pinch may be based.

The authors are indebted to Stirling A. Colgate and Harold P. Furth for their guidance and support, and to L. P. Sandy for operational assistance.

APPENDIX 1

Calculation of plasma pressure.

Equation of continuity:

$$\frac{1}{4\pi}(B \times \Delta \times B) + \nabla p = 0$$

Assumming $B_r = 0$;

$$-4\pi \frac{\partial p(r)}{\partial r} = B_z \frac{\partial B_z}{\partial r} + \frac{B_\theta}{r} \frac{\partial (r B_\theta)}{\partial r}$$

Integrating:

$$\Big[8\pi p(r) \Big]_R^r = \Big[B_z^2 + B_\theta^2 \Big]_r^R + 2\int_r^R \frac{B_\theta^2(r)}{r} dr$$

Replacing the integral with a summation:

$$p(r) = \frac{1}{8\pi}\Big\{ p(R) + \Big[B_z^2(R) - B_z^2(r) \Big] + \Big[B_\theta^2(R) - B_\theta^2(r) \Big] + 2\sum_r^R \frac{B_\theta^2}{r} \Delta r \Big\}$$

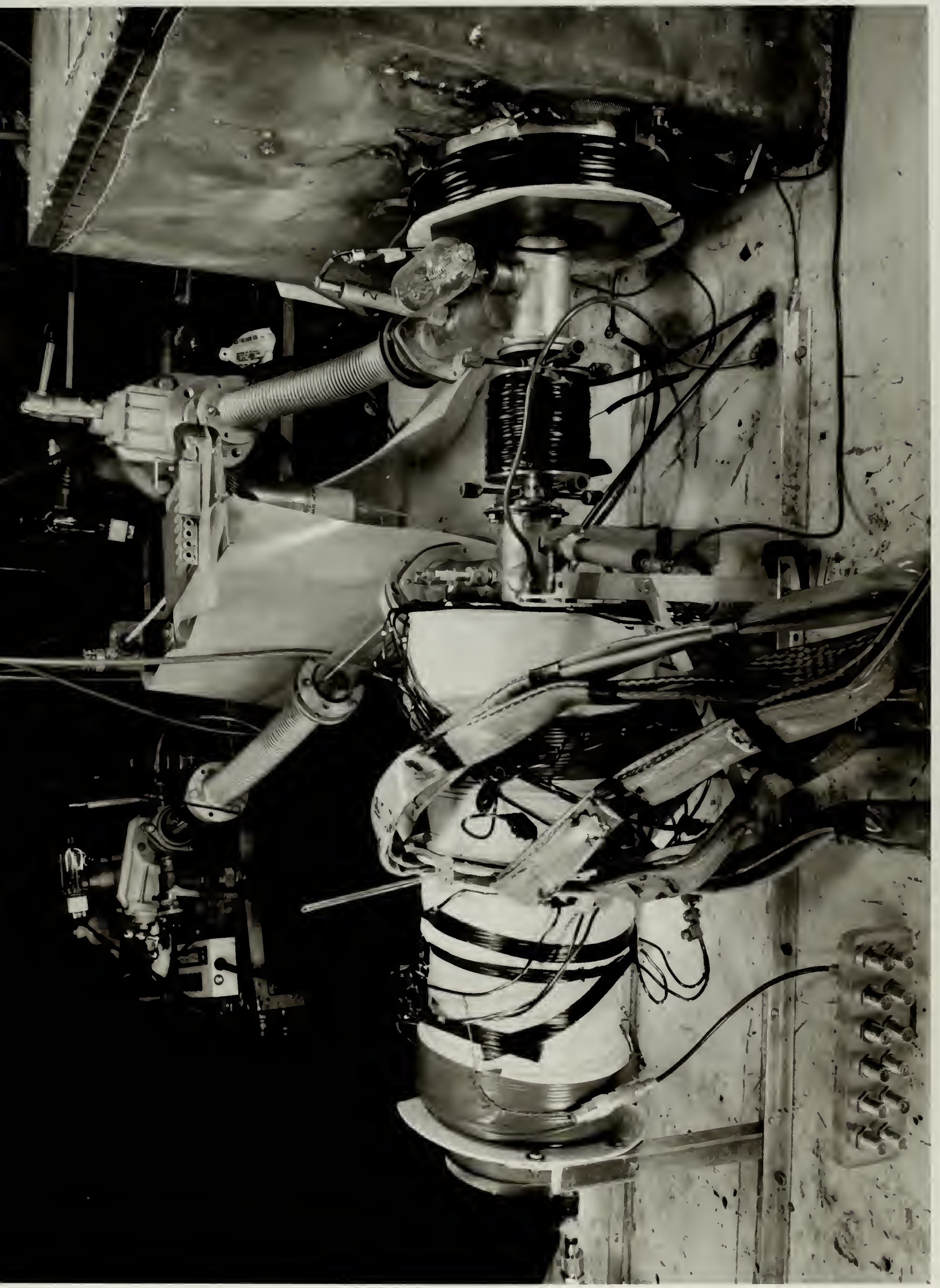
This form lends itself quite readily to numerical calculations.

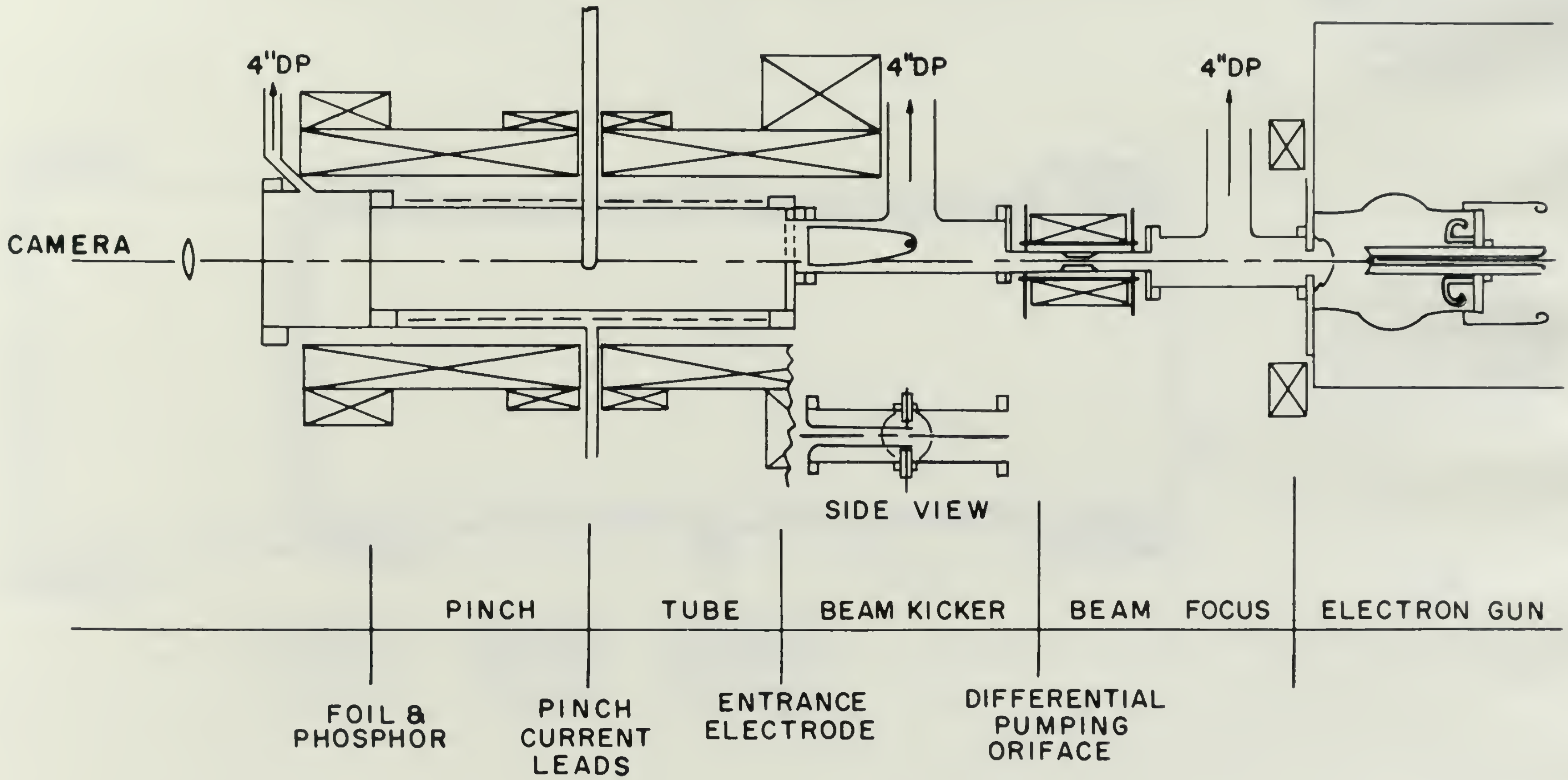
REFERENCES

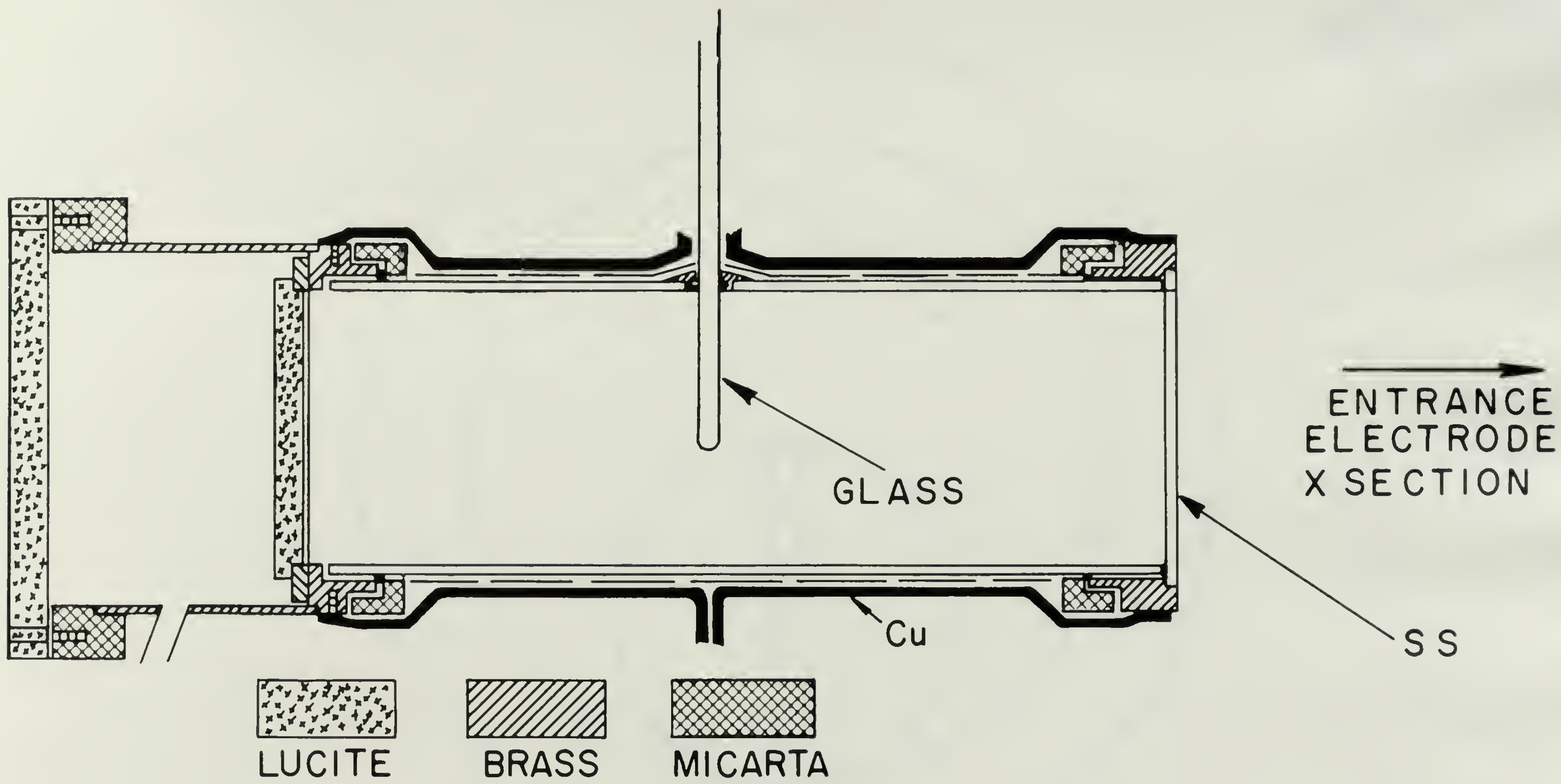
1. Colgate, S. A.; Ferguson, J.; Furth, H. P.; "A Toroidal Stabilized Pinch" 2nd International Conference on Peaceful Uses of Atomic Energy, Vol. 32.,p.129

2. Spoerlein, R. ; Birdsall, D. H.; Colgate, S. A.; Furth, H. P.; "Electron Beam Transmission along a Stabilized Pinch", UCRL-5489-T Abstract, February 1959.

3. Burkhardt, L. C. and Lovberg, R. H.; "Field Configurations and Stability in a Linear Discharge. 2nd International Conference on Peaceful Uses of Atomic Energy, Vol. 32, p. 29.



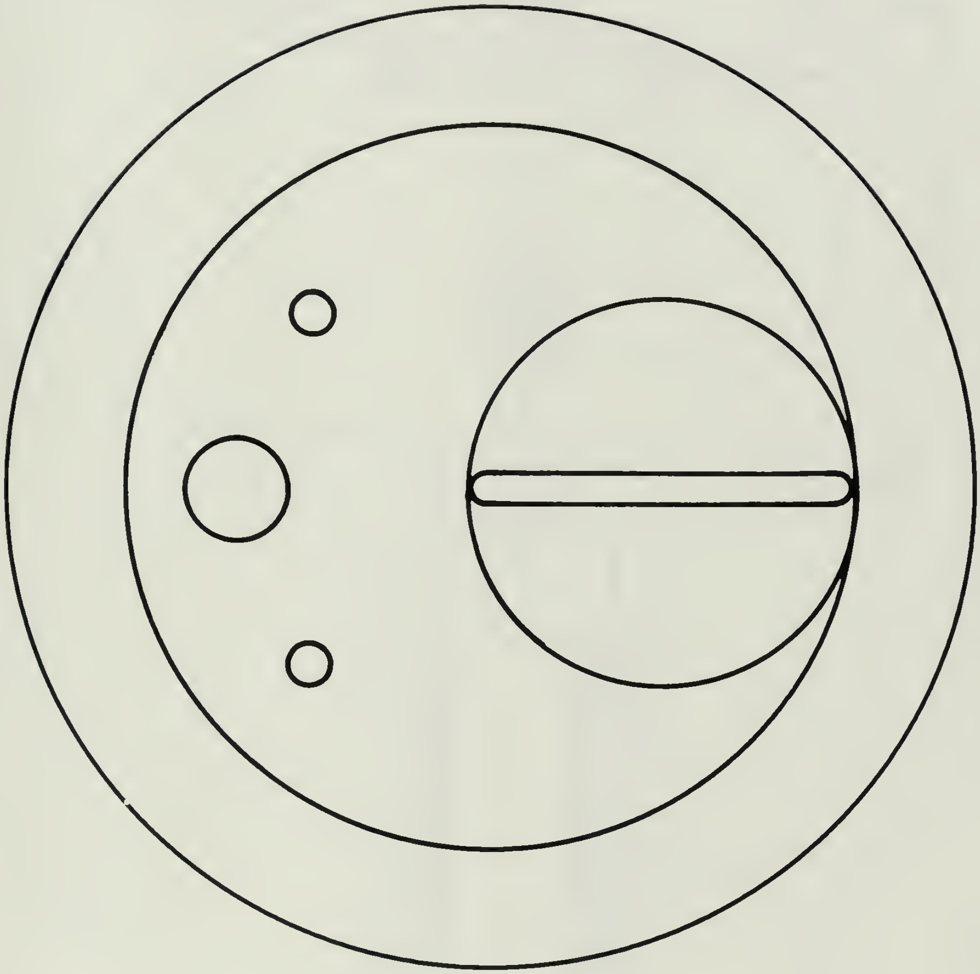

4"DP
4"DP
4"DP
CAMERA
SIDE VIEW
PINCH
TUBE
BEAM KICKER
BEAM
FOCUS
ELECTRON GUN
FOIL &
PHOSPHOR
PINCH
CURRENT
LEADS
ENTRANCE
ELECTRODE
DIFFERENTIAL
PUMPING
ORIFACE

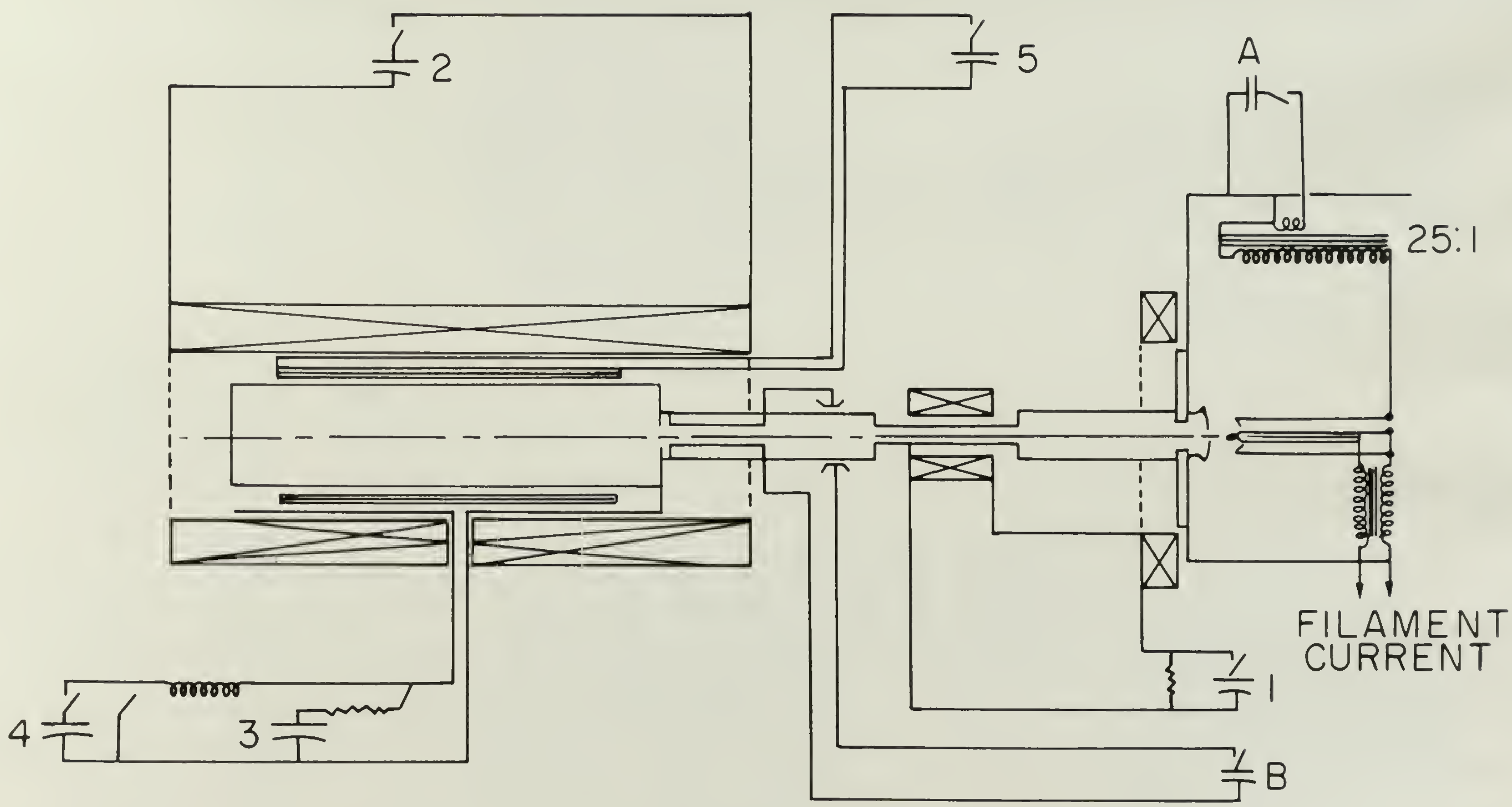


ENTRANCE
ELECTRODE
X SECTION
GLASS
SS
Cu
LUCITE
BRASS
MICARTA

Graphic Arts

Neg. No. MUL-9400

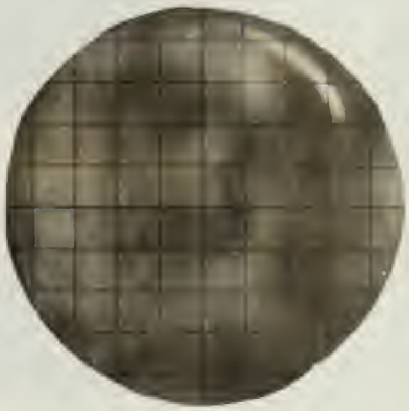



2
5
A
25:1
FILAMENT
CURRENT
1
B
4
3

a - NO PINCH

b - PINCH DISPLACEMENT

c - VIOLENT TURBULENCE



d - LONG SMEAR

ELECTRON BEAM SPOT ON PHOSPHOR
(BEAM INTRODUCED ON AXIS)

Fig 6

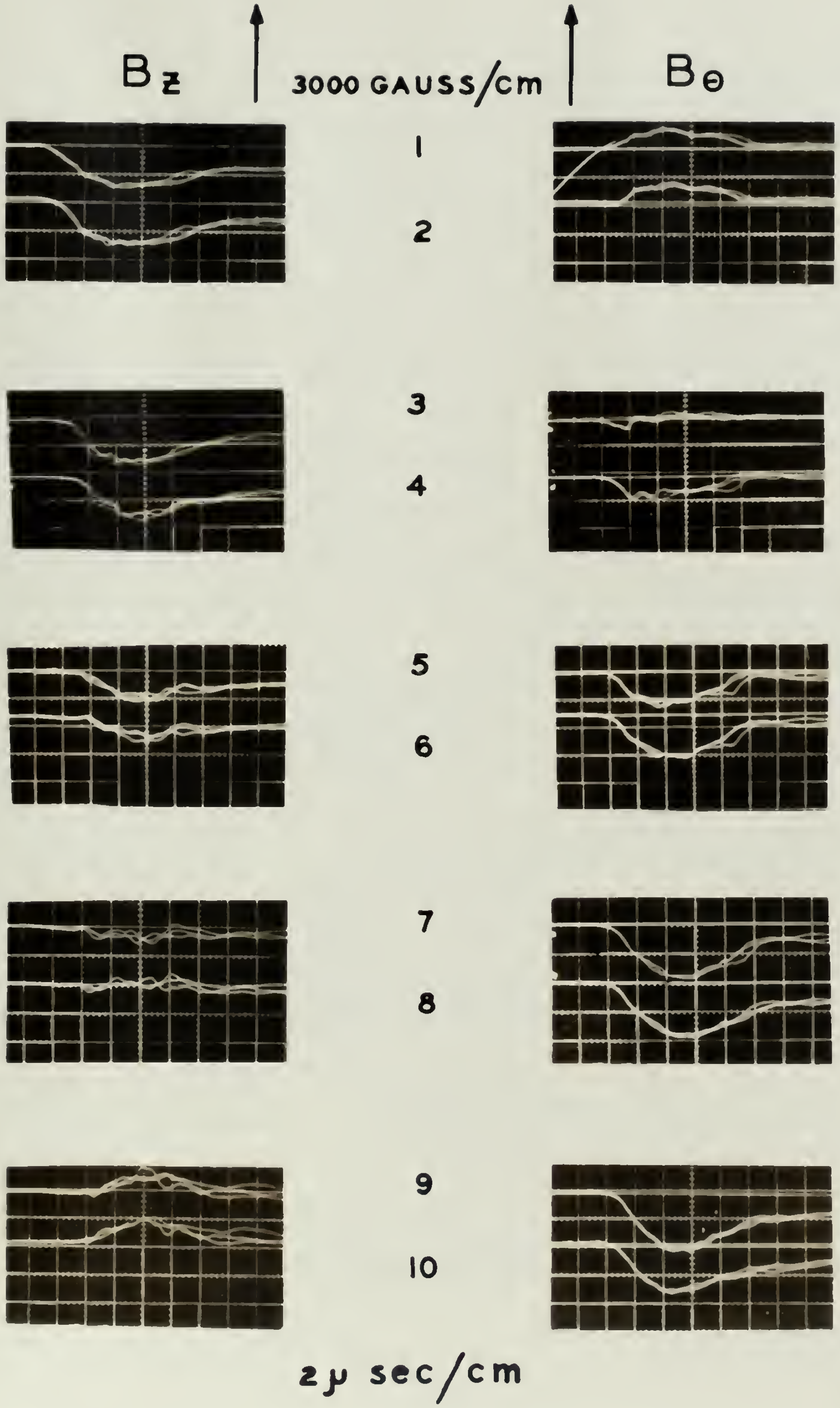


Fig 7

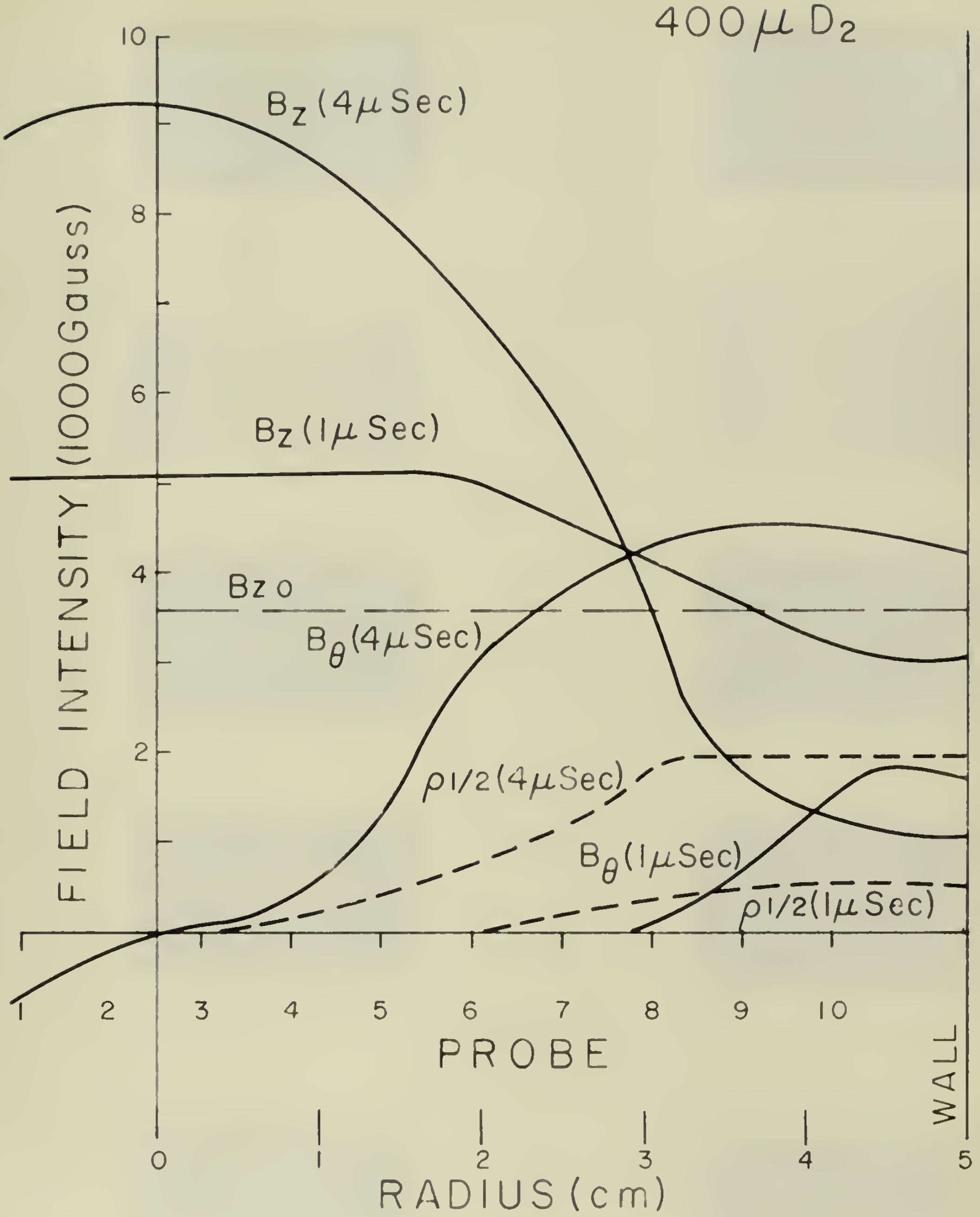

400 μ D2
Bz (4μ Sec)
Bz (1μ Sec)
Bzo
Bθ(4μSec)
ρ1/2(4μSec)
Bθ(1μSec)
ρ1/2(1μSec)
FIELD INTENSITY (1000Gauss)
10
8
6
4
2
1 2 3 4 5 6 7 8 9 10
PROBE
WALL
0 1 2 3 4 5
RADIUS (cm)

Fig. 8

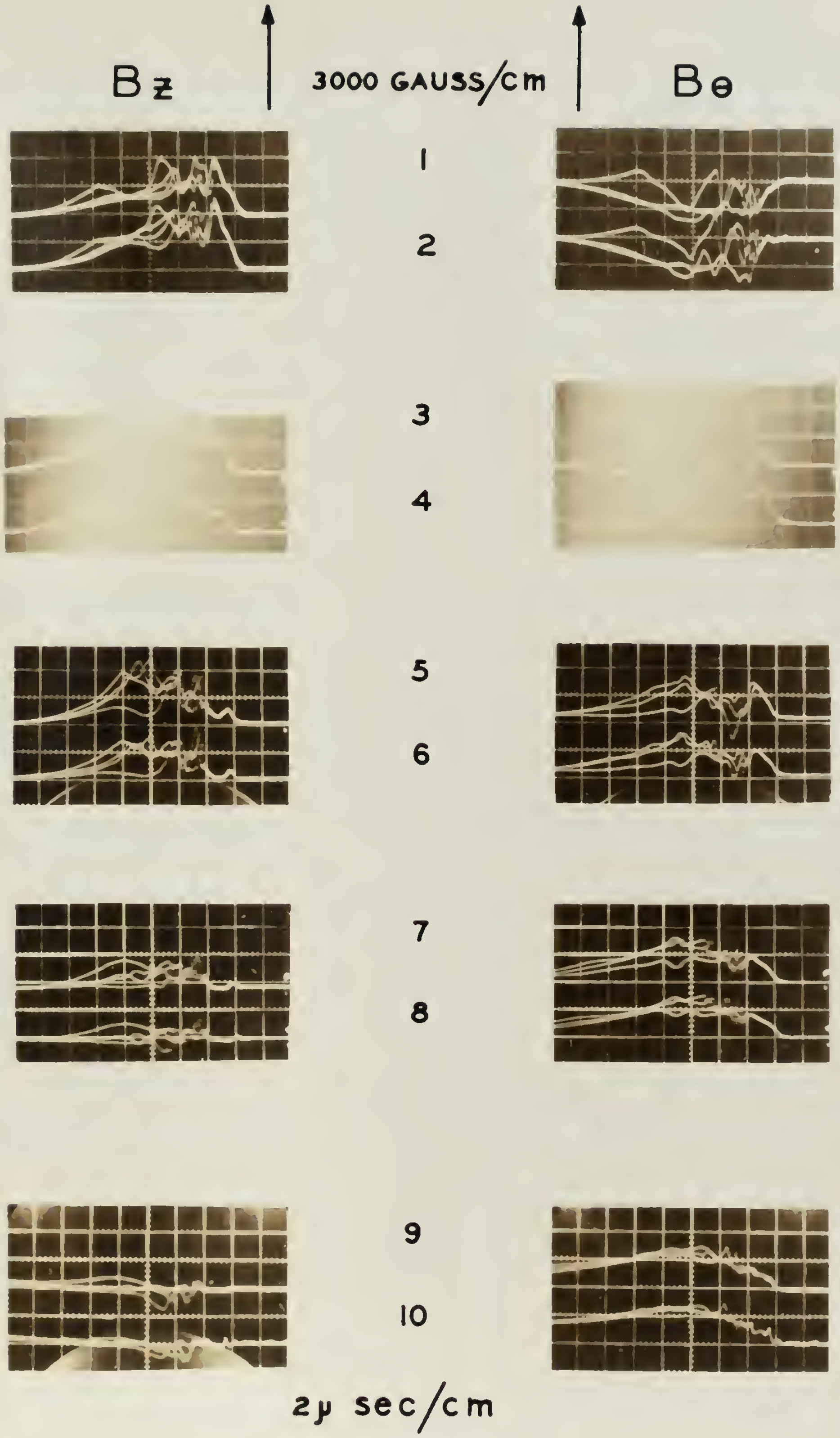
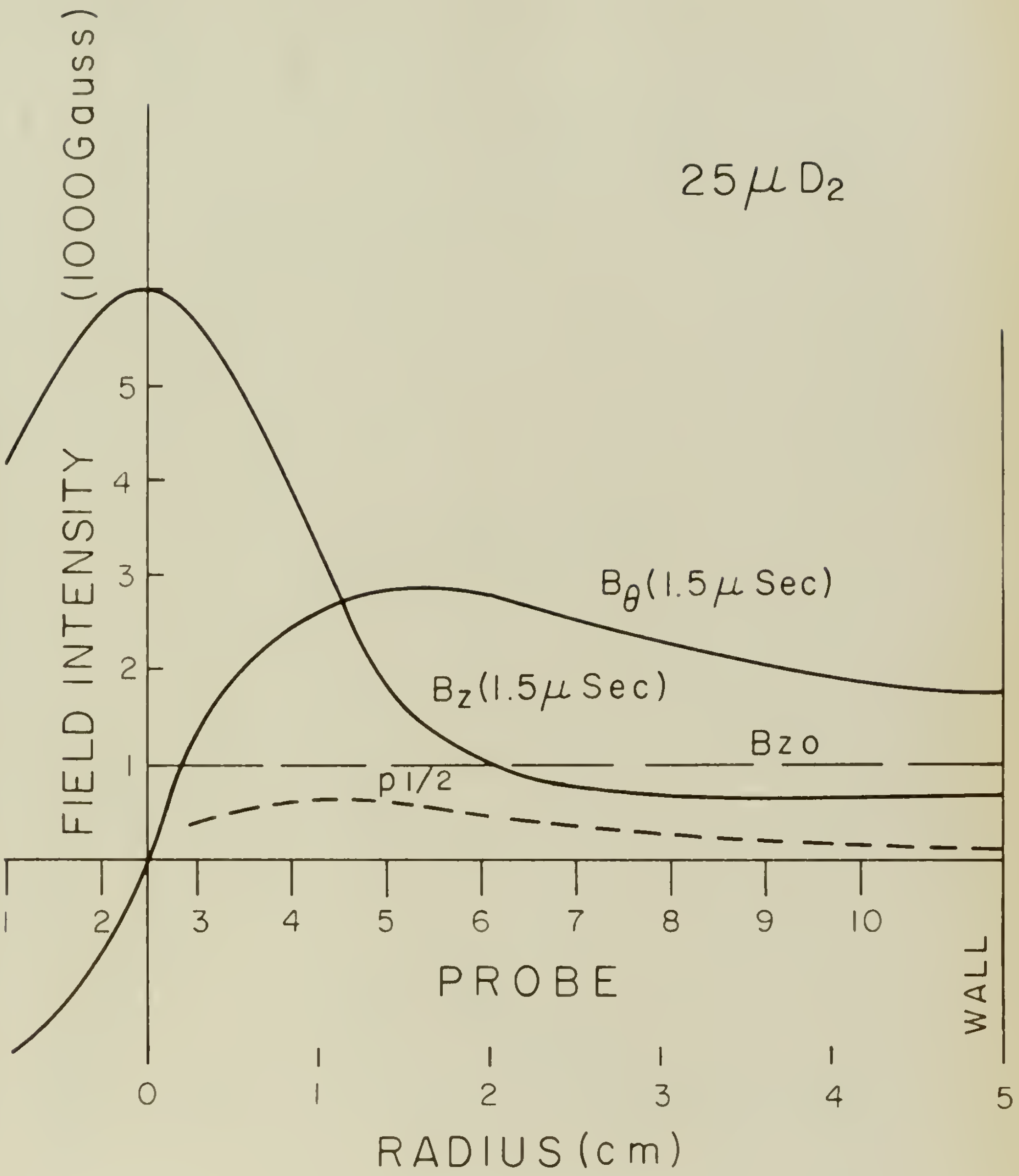
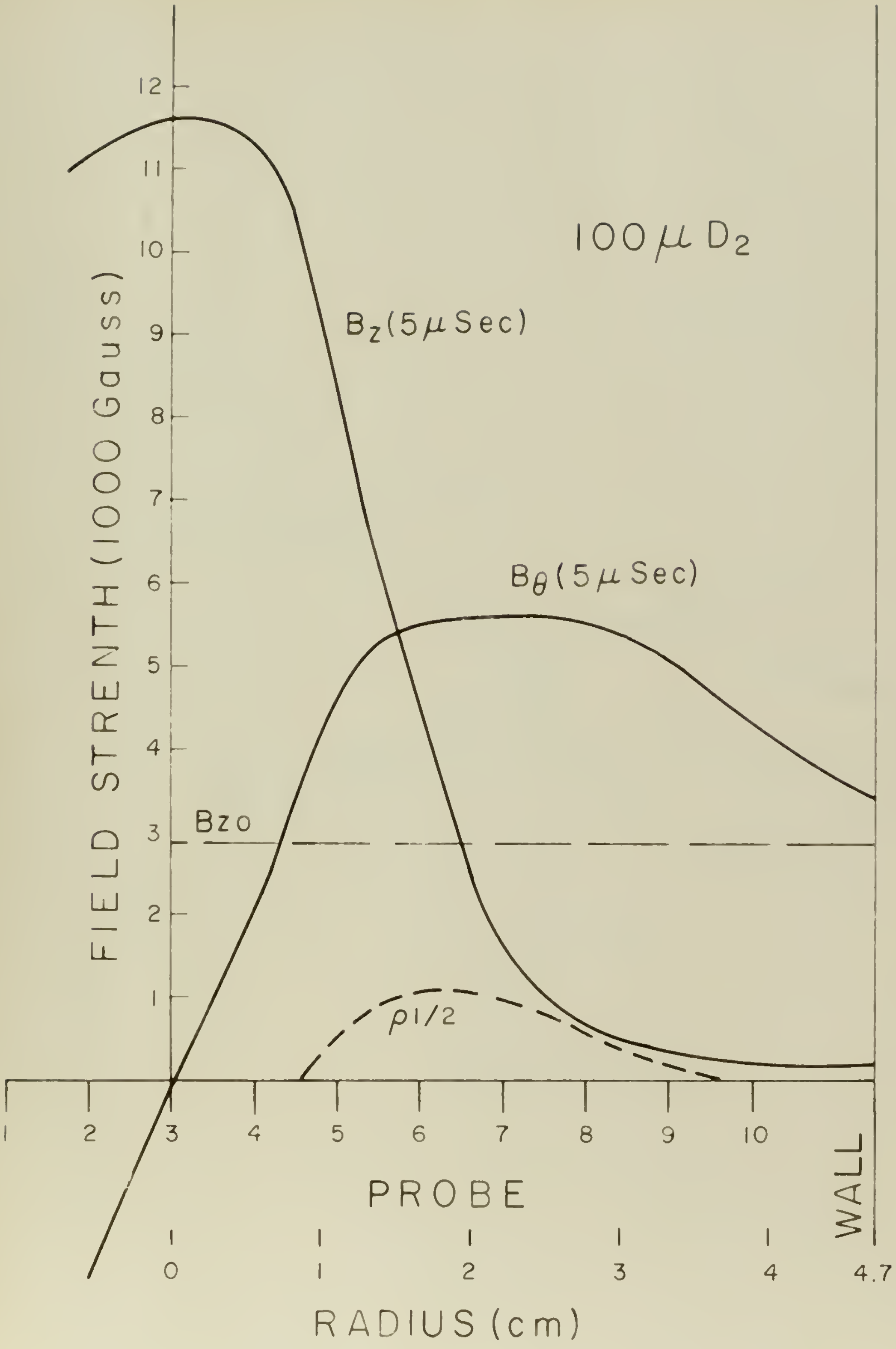


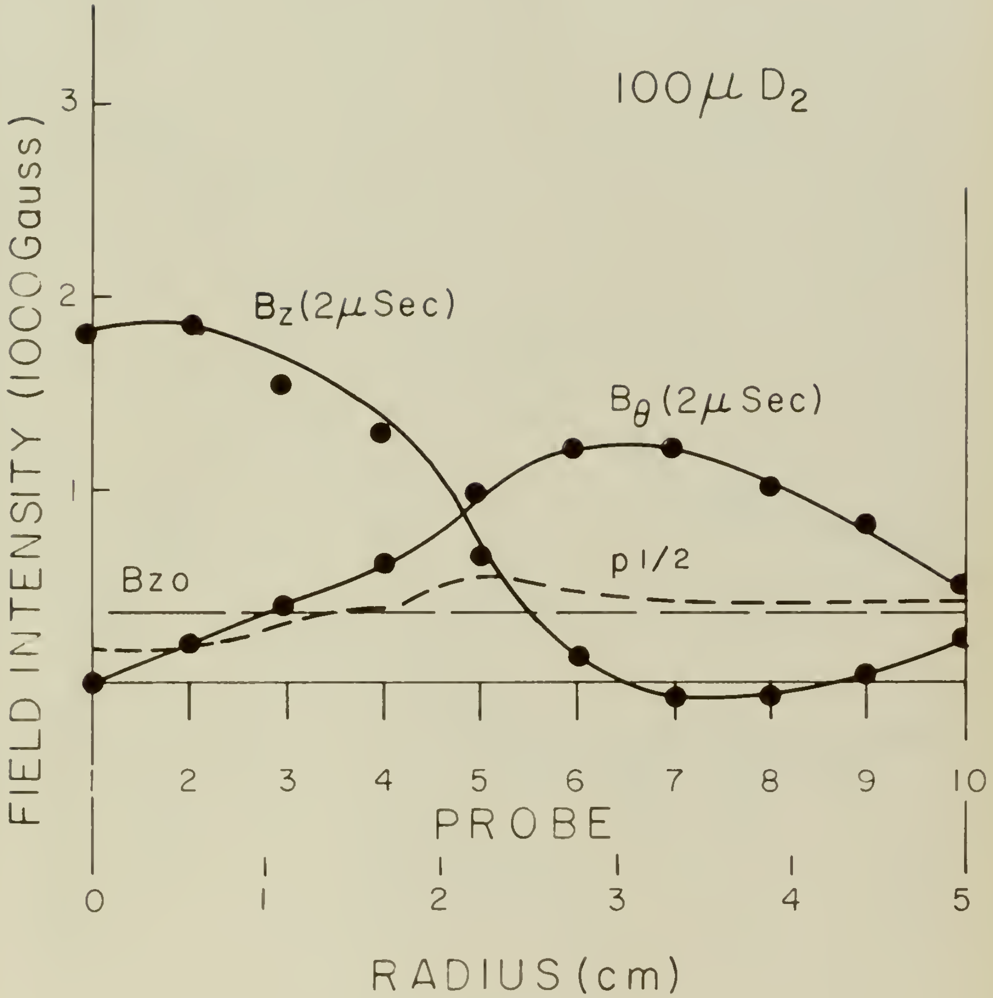
Fig 9

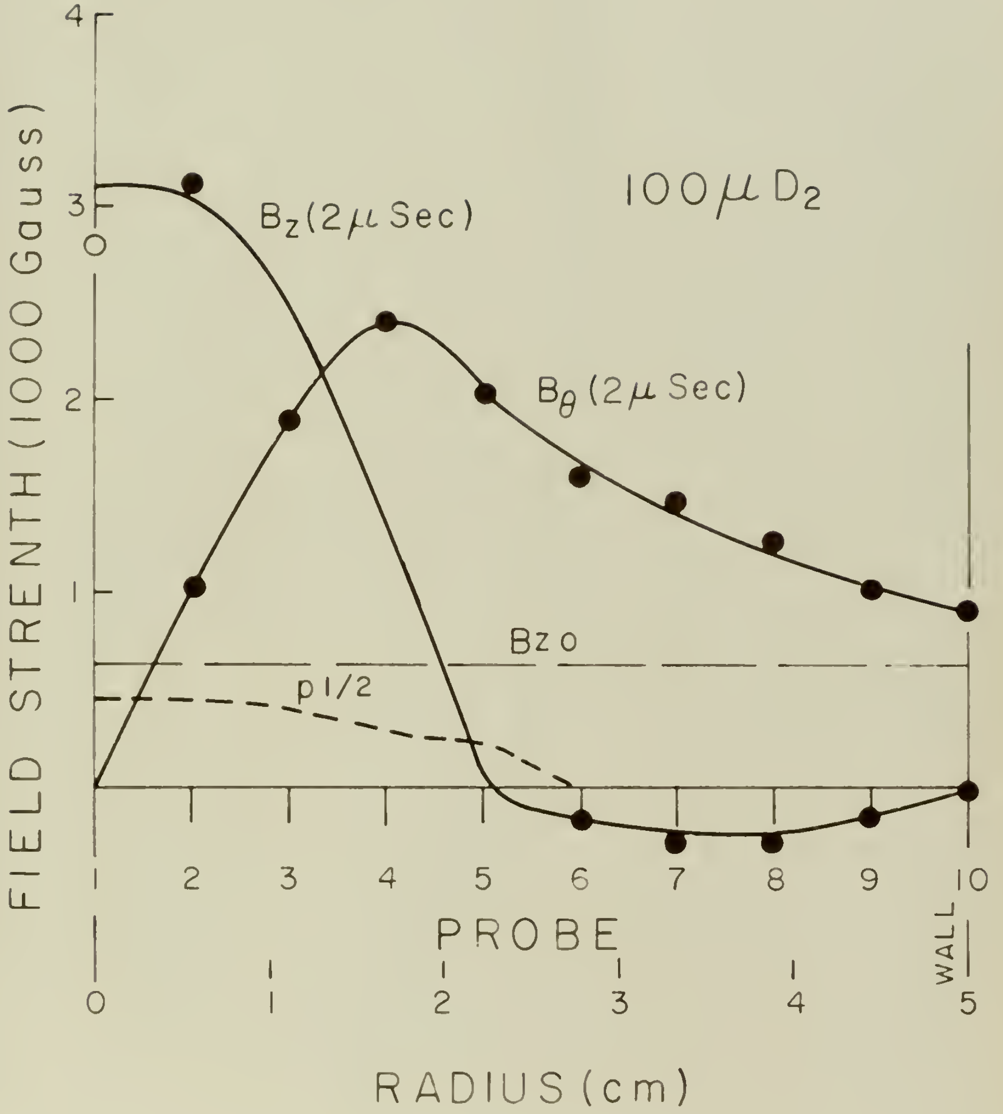


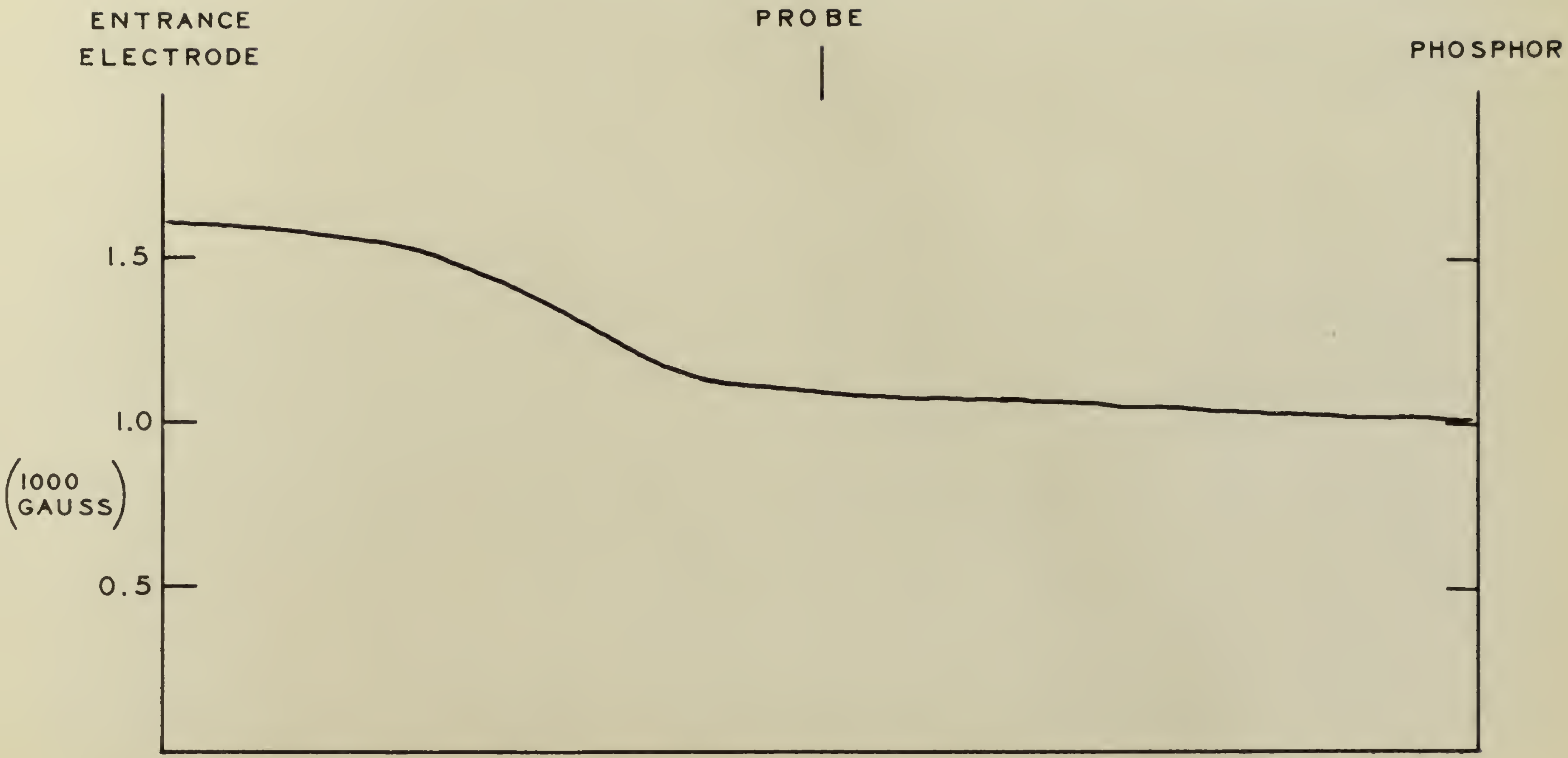
25 μ D_2
(1000 Gauss)
FIELD INTENSITY
5
4
3
2
1
B_θ(1.5 μ Sec)
B_z(1.5 μ Sec)
Bzo
p 1/2
1
2
3
4
5
6
7
8
9
10
PROBE
WALL
0
1
2
3
4
5
RADIUS (cm)



100 μ D2
Bz(5 μ Sec)
Bθ(5 μ Sec)
Bzo
ρ1/2
FIELD STRENTH (1000 Gauss)
12
11
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10
PROBE
WALL
0 1 2 3 4 4.7
RADIUS (cm)


100μ D2
FIELD INTENSITY (1000 Gauss)
3
2
1
Bz(2μSec)
Bθ(2μ Sec)
p 1/2
Bzo
1
2
3
4
5
6
7
8
9
10
PROBE
0
1
2
3
4
5
RADIUS (cm)


FIELD STRENTH (1000 Gauss)
4
3
2
1
100 μ D2
Bz(2μ Sec)
Bθ(2μ Sec)
Bz o
p 1/2
1
2
3
4
5
6
7
8
9
10
PROBE
WALL
0
1
2
3
4
5
RADIUS (cm)



PROFILE OF INITIAL FIELD INTENSITY

Fig 14