CONF 9011136--1

CONF-9011136--1

DE91 002649

CHARACTERISTICS AND POTENTIAL APPLICATIONS OF AN ORNL MICROWAVE ECR MULTICUSP PLASMA ION SOURCE*

C. C. TSAI

Oak Ridge National Laboratory, P. O. Box 2009, Oak Ridge, Tennessee 37831-8071, USA

A new microwave electron cyclotron resonance (ECR) multicusp plasma ion source that has two ECR plasma production regions and uses multicusp plasma confinement has been developed at Oak Ridge National Laboratory. This source has been operated to produce uniform and dense plasmas over large areas of 300 to 400 cm^2 and could be scaled up to produce uniform plasma over 700 cm^2 or larger. The plasma source has been operated with continuous argon gas feed and pulsed microwave power. The working gases used were argon, helium, hydrogen, and oxygen. The discharge initiation phenomena and plasma properties have been investigated and studied as functions of the discharge parameters. The discharge characteristics and a hypothetical discharge mechanism for the plasma source are described and discussed. Potential applications, including plasma and ion-beam sources for manufacturing advanced microelectronics, for space electric propulsion, and for fusion research, are discussed.

---

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

MASTER

1. Introduction

Following the discovery of ions from "canal rays" at the end of the last century, a series of plasma sources has been developed for producing cold, dense and uniform plasmas efficiently and reliably. During the last 90 years, such plasma sources have been used to supply ions for application to mass spectrometers, particle accelerators, isotope separators, vacuum gages and pumps, space propulsion thrusters, neutral beam injectors for heating fusion plasmas, plasma and ion-beam processing for electronics materials, etc. The plasma source for a particular application must provide useful ion species with the needed current density, electron temperature, and plasma uniformity. It should also be compact, simple, flexible, reliable, and efficient.

At Oak Ridge National Laboratory (ORNL), a variety of plasma sources has been developed for fueling and heating fusion plasmas, beginning in the 1960s. In the 1970s [1–3], sources were scaled up to produce uniform plasmas over an ion accelerator ranging from 15 to 30 cm in diameter and used for injecting multimegawatt neutral beams. In these modified duoPIGatron plasma sources, magnetic multicusp confinement [4,5] is used to confine hot electrons and source plasma particles. The ionization efficiency of hot electrons can be enhanced substantially and the plasma particles can diffuse freely in a volume with low magnetic fields (<10 G). In such a plasma source, a dense, low-temperature plasma can be uniformly and efficiently created over a large area, extending to about 5 cm from the walls of plasma chamber. The effect of the magnetic multicusp confinement on the plasma uniformity is clearly shown in Fig. 1. In fact, the required source magnetic field (denoted by I_{SM}) for optimum duoPIGatron discharges is lower for the case with the magnetic multicusp confinement than for the case without it.

For applications to plasma and ion-beam processing for manufacturing microelectronics, large plasma sources are needed [6]. The duoPIGatron sources may be applicable. However, their hot cathodes can be attacked by reactive gases, and their lifetimes are relatively short. We have developed a new microwave ECR multicusp plasma ion source [7–9] designed primarily for producing uniform plasmas with useful densities over large areas (300–400 cm^2). In this paper we describe the plasma source, its characteristics, and discharge mechanisms. Potential applications to electronics, space propulsion, and fusion research are then discussed.

2. Experimental arrangement

The microwave ECR plasma source (Fig. 2) has been developed primarily from existing components of a 20-cm duoPIGatron [2], except for the microwave launcher. The axial solenoid magnet that surrounds the microwave launcher provides the 875-G field needed to establish an ECR zone (called the primary ECR zone) for 2.45-GHz microwaves. The primary ECR zone (located in the exit end of the launcher and near the curves identified as B_{MAX} in Fig. 3) can be adjusted by varying the magnet excitation current. At the center of the magnet, a commercial MDL glass/Kovar pressure window provides a vacuum-tight seal with the standard S-band waveguide. On the outside walls of the 30-cm-diam, 20-cm-high plasma chamber, 20 permanent magnet columns with alternating polarity form the multiple-line cusp configuration that confines the energetic electrons and the cold plasma particles. With these strong permanent magnets ($SmCo_5$, samarium cobalt), a secondary ECR zone is established in the multicusp field region, where it can heat up the electrons and enhance plasma production.

Under normal operations, the operating pressure (or gas flow rate) was kept constant. The gas was fed and distributed through apertures in the top plate on which the microwave launcher is mounted. A matching network (3-stub tuner) in the waveguide pipe between the microwave supply and the plasma source was not readjusted during a sequence of experimental runs. The plasma density and spatial uniformity were measured by scanning an electrical probe in a plane at the downstream end of the plasma chamber (Fig. 2) or along the surface of the probe position platform in Fig. 4. The probe position platform was designed with a three-dimensional (3-D) moving mechanism capable of rotating 90° in the azimuthal direction, scanning from left (–12.7 cm) to right (+12.7 cm) and up (z = 7.26 cm) and down (z = 22.5 cm). The plasma properties were studied for different discharge conditions by varying the applied magnetic field, microwave power, gas pressure, and chamber length.

3. Discharge mechanism and characteristics

The discharge of a microwave ECR plasma source is initiated and maintained by energetic or hot electrons that are accelerated to high energies in ECR zones by the microwave electric field. The discharge phenomena can be understood and explained by a hypothetical discharge mechanism, which is based on wave propagation, wave absorption, electron transport, electron ionization, and plasma diffusion and confinement.

In normal operation, the microwave input power is separated into right-hand circularly polarized (RHCP) and left-hand circularly polarized (LHCP) components. As fed into the high-field region of the solenoid magnet, the LHCP microwaves are not absorbed or dissipated in the primary ECR zone near the exit end of the launcher but are transmitted down to the plasma chamber. The RHCP waves are absorbed in the primary ECR zone by accelerating and heating electrons, thus creating hot electrons that then diffuse along the rapidly expanding magnetic field into the plasma chamber. These hot electrons can ionize gas particles and create a dense plasma near the primary ECR zone if the gas pressure is high enough. The plasma particles so created diffuse radially out and axially down to the substrate or the probe platform. Some hot electrons could collide with and be lost to the walls of the microwave launcher or diffuse to and produce plasma in the secondary ECR zone. At low pressures, some electrons can gain additional energy from LHCP microwaves in the secondary ECR zone and enhance plasma production there. These plasma particles diffuse radially toward the axis of the plasma chamber. However, the electric field in the secondary ECR zone may be too weak to initiate a plasma discharge alone. Thus, the primary ECR zone is essential for reliable discharges. The secondary ECR zone is mainly for enhancing the source performance by improving the confinement of charged particles and the ionization efficiency of the hot electrons.

Before the discharge is established, the vacuum electric field for electron resonance in the primary ECR zone is the sum of field components of the forward-traveling RHCP and the reflected LHCP microwaves. The mean energy of electrons gained from the microwaves in the primary ECR zone is proportional to the square of the electric field amplitude, if the electron-gas collision frequency is smaller than the microwave frequency. With sufficient gas density, these hot electrons with energies above the ionization energy of the gas particles can produce plasma, via collision ionization processes. When the length of the plasma chamber is changed (by moving the probe position platform up or down), the field component of the reflected LHCP microwaves at the primary ECR zone varies in both angle (with respect to the field component of the RHCP microwaves). The resultant electric field and thus the mean electron energy change accordingly. At some axial positions, the resultant amplitude of the electric field in the primary ECR zone becomes too weak to create sufficient hot electrons for initiating discharges, and no plasmas are produced and measured. Under such conditions, the reflected voltage (or power) is slightly lower than the forward voltage (or power), as shown in Fig. 5. We call this feature as the "cavity effect" of the plasma chamber. This figure also shows the variation of the plasma density at the center of the probe platform as a function of the chamber length. Moreover, it shows that this discharge initiation problem is easily solved by adjusting the plasma chamber length slightly.

The source has been operated with argon, oxygen, helium, and hydrogen. In general, the qualitative effects of operating parameters on the ECR plasma properties are similar for different gases. On the basis of measurements made with an electrical probe located ~20 cm below the launcher, argon plasmas normally have electron densities of up to 1×10^{11} cm^{-3}, electron temperatures of 2–5 eV, ion energies of about 20 eV, and a production efficiency near 200 W/A (200 eV/ion). Here the ion energy is equivalent to the potential difference across the plasma sheath of the probe. With the weak magnetic field over the probe scanning plane, the ion velocity (acquired from the plasma sheath potential) is expected to be normal to the substrate (or the probe scanning plane).

In general, the source can be operated to produce uniform plasmas over large areas. Figure 6 shows the plasma density distributions measured 22.5 cm from the launcher exit. The plasma uniformity has a variation of <10% over an area 12 cm in radius. Figure 6 also shows that the density increases with the microwave power. At 550 W, the source produces an ion current of about 2.8 A with a production efficiency of 200 W/A. The plasma uniformity can be further optimized by adjusting the gas pressure [7–9] and/or the magnetic field (Fig. 7). The feature of a peaked plasma profile at relatively low applied magnetic fields is due to the fact that most plasma particles are produced near the chamber axis and the primary ECR zone is deeper in the launcher throat (Fig. 3). But the plasma density tends to be lower because a large fraction of the hot electrons is lost to the launcher walls. The hollow profile feature tends to appear in relatively strong fields, under which a large fraction of the hot electrons produced in the primary ECR zone (which will now be closer to the launcher exit as shown in Fig. 3) will reach the cusp field region and produce plasma there. Both the source efficiency and the plasma density tend to be higher.

In addition to the cavity effect, we observed significant variations in density as a function of the chamber length, as shown in Fig. 5. For a relatively long chamber (z = 16.4–22.5 cm), the plasma density is lower, but uniformity is fairly good. However, for a relatively short chamber (z approaching 7.25 cm), the plasma is dense but not uniform. This chamber length effect on plasma density and uniformity is clearly shown in Fig. 8.

Plasmas can be created at relatively lower pressures if a substrate is electrically floated or biased negatively. As described elsewhere [7–9], this is because hot electrons are reflected from the substrate and are more likely to produce plasma before escaping to the chamber walls. With a sheet of insulating material (such as Mylar) over the probe platform, the source efficiency is improved substantially, but the plasma uniformity is similar to that with electrically conducting materials. The electrical conductivity effect of the substrate on plasma uniformity is shown in Fig. 9. It also shows the worst case with a metal ring (12.7 cm ID, 30 cm OD) mounted on the Mylar substrate. The plasma uniformity can be improved slightly by applying a biasing potential to the metal ring, as shown in Fig. 10. Thus, in practice, the plasma-facing material of the substrate holder should have the same electrical properties as the substrate.

4. Potential applications

The ECR plasma source is electrodeless (i.e., no thermionic cathodes in the plasma chamber) and can be developed for producing reactive plasmas. Such a reliable and long-lived plasma source is expected to create clean plasma, free of undesired impurities. With its capability of creating dense plasmas efficiently and uniformly over large areas (300–400 cm^2), this source is an attractive candidate for applications in manufacturing electronics, space propulsion, and fusion research.

For plasma dry etching, etching rates can be affected by local ion energy, ion flux, excited neutrals, and substrate temperature. To evaluate the feasibility of this source for etching applications [7–9], we exposed 12.7-cm-diam silicon wafers with positive photoresist to oxygen plasmas. The wafers were clamped on a water-cooled copper substrate holder. The measured etching rate was 0.15 μm/min and considered reasonable. Nonuniform etching at wafer edge could be due to the changes of ion flux (similar to that shown in Fig. 10) and ion energies. In fact, the wafer is coated with photoresist film and the substrate holder is made of copper. This etching problem can be solved by covering the substrate holder with insulating material. This microwave ECR plasma source can be scaled up and developed for etching of large wafers (300 mm or larger), using existing components of the 30-cm duoPIGatron ion source [3]. It could also be used for thin-film deposition.

Such plasma sources can supply ions of inert or reactive gases to an ion accelerator for forming broad ion beams. With beam energies up to 2000 eV, these ion beams can be used in ion-beam processing of thin films for making submicron circuits for electronics and protecting surfaces of special tools or devices. The application is often found in ion milling, ion-beam etching, ion-beam deposition, and ion-assisted deposition. It can also be used to preclean sample surfaces for enhancing the quality of ion-beam deposition by improving adhesion and increasing nucleation sites. Thus, this ECR plasma source could be further developed for forming broad ion beams for applications in making advanced thin-film materials.

For future National Aeronautics and Space Administration (NASA) exploratory missions, megawatt units of space propulsion thrusters are needed [10]. Both of the two leading candidates, ion thrusters and magnetoplasmadynamic (MPD) thrusters, need reliable and long-lived cathodes. This ECR source can be configured to supply electrons as a reliable 1000-A–class cathode for both types of thrusters. Moreover, for ion thrusters, this source can be modified and developed for producing noncircular argon ion beams with currents up to 1000 A. It can also be used to produce plasmas to neutralize the ion beams. This source is definitely an ideal candidate for the next generation of lightweight, reliable thrusters for space propulsion applications.

These plasma sources have numerous applications in fusion research. They can be used to produce light or heavy ions and their neutral beams for heating plasmas in magnetic fusion or pellets in inertial fusion. Capable of fast switching, this source is ideal for producing beams of desired gases to probe plasmas. It may be used as a electron source for electron-beam current drive applications in tokamaks. It can be used to produce continuous wave (cw) plasmas or beams for testing or developing high-heat-flux components or materials.

Acknowledgments

This research was carried out within the Fusion Energy and Solid State divisions of ORNL with support from the Director's Exploratory Fund. The author thanks those who helped with this project, particularly B. E. Argo, G. C. Barber, L. A. Berry, T. S. Bigelow, S. M. Gorbatkin, H. H. Haselton, J. B. Roberto, D. E. Schechter, J. E. Simpkins, and F. Sluss.

References

[1] W. L. Stirling, C. C. Tsai, and P. M. Ryan, Rev. Sci. Instrum. **48**, 533 (1977).

[2] C. C. Tsai et al., in Proc. 7th Int. Symp. on Engineering Problems of Fusion Research (IEEE, New York, 1977), pp. 278–283.

[3] W. L. Gardner et al., Rev. Sci. Instrum. **53**, 424 (1982).

[4] R. D. Moore, paper 69-260 presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Va., March 3–5, 1969.

[5] R. Limpaecher and K. R. Mackenzie, Rev. Sci. Instrum. **44,** 726 (1973).

[6] H. R. Kaufman, J. J. Cuomo, and J. M. E. Harper, J. Vac. Sci. Technol. **21**, 725 (1982).

[7] L. A. Berry et al., "Characteristics of the ORNL ECR Multiple Plasma Source," presented at the SRC Topical Research Conference on Plasma Etching, Cambridge, Mass., February 1–2, 1989 (unpublished).

[8] C. C. Tsai et al., Potential Applications of an Electron Cyclotron Resonance Multicusp Plasma Source, ORNL/TM-11442 (Oak Ridge National Laboratory, 1990).

[9] C. C. Tsai et al., J. Vac. Sci. Technol. A **8** (3), 2900 (1990).

[10] J. Sovey, "Overview of Electric Propulsion," presented at the NASA/DOE/DOD Nuclear Electric Propulsion Workshop, Pasadena, California, June 19–22, 1990.

Figure Captions

Fig. 1. Effect of magnetic multicusp confinement on plasma uniformity of a duoPIGatron ion source.

Fig. 2. Sketch of a microwave ECR multicusp plasma source.

Fig. 3. Curves of a primary ECR zone for different maximum applied magnetic fields.

Fig. 4. Experimental arrangement with 3-D probe position platform for studying plasma properties.

Fig. 5. Chamber length effect on establishing discharges and plasma density.

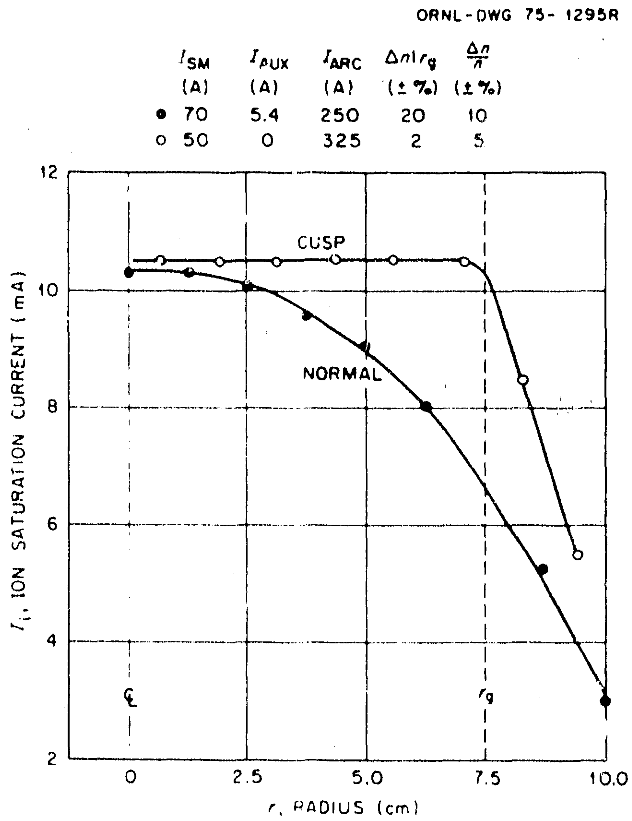
Fig. 6. Increase in plasma density with input microwave power.

Fig. 7. Magnetic field effect on plasma uniformity.

Fig. 8. Chamber length effect on plasma uniformity.

Fig. 9 Substrate electrical conductivity effect on plasma uniformity.

Fig. 10. Effect of biasing a metal ring (on the substrate) on plasma uniformity.



ORNL-DWG 75- 1295R
I_{SM} (A) I_{AUX} (A) I_{ARC} (A) $\Delta n | r_g$ (± %) $\frac{\Delta n}{n}$ (± %)
● 70 5.4 250 20 10
○ 50 0 325 2 5
CUSP
NORMAL
I_i, ION SATURATION CURRENT (mA)
r, RADIUS (cm)
r_g

FIGURE 1

ORNL-DWG 88-3031RA FED

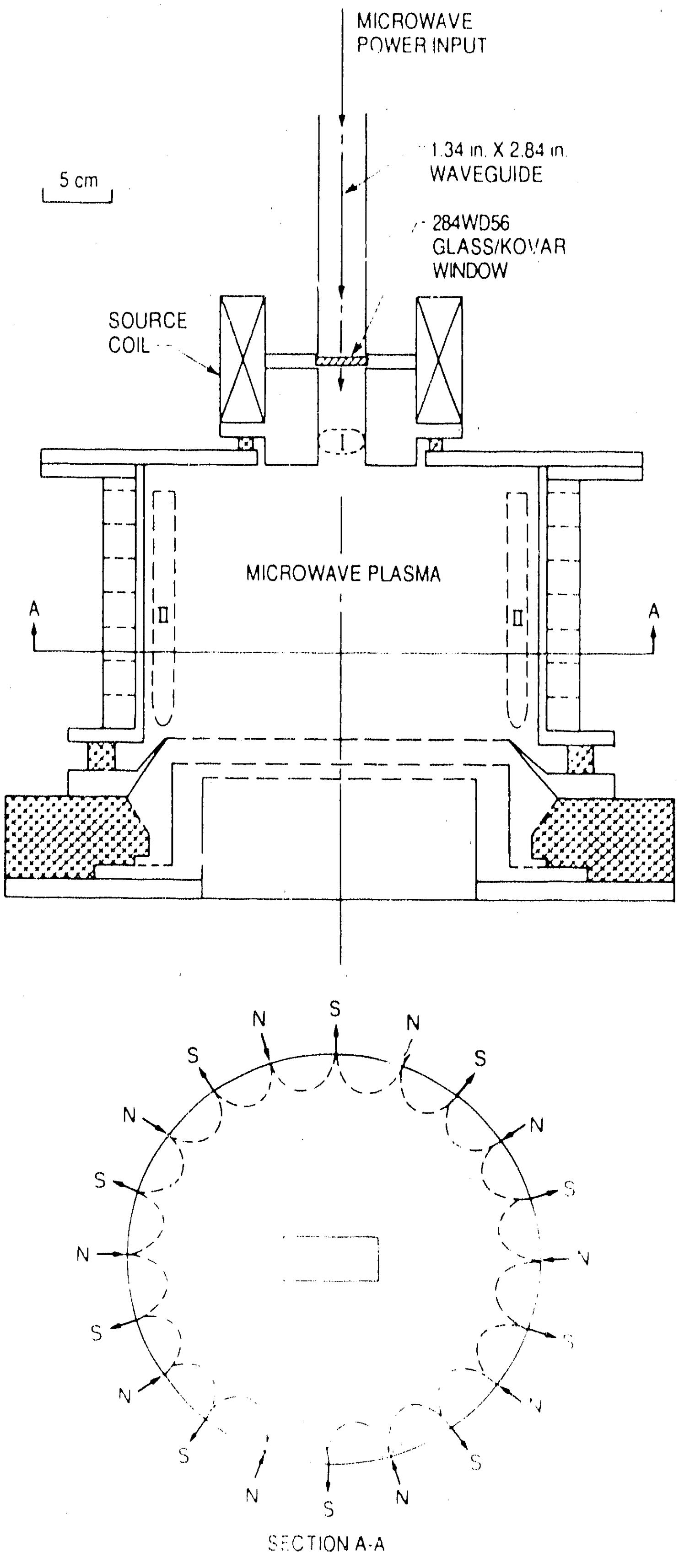
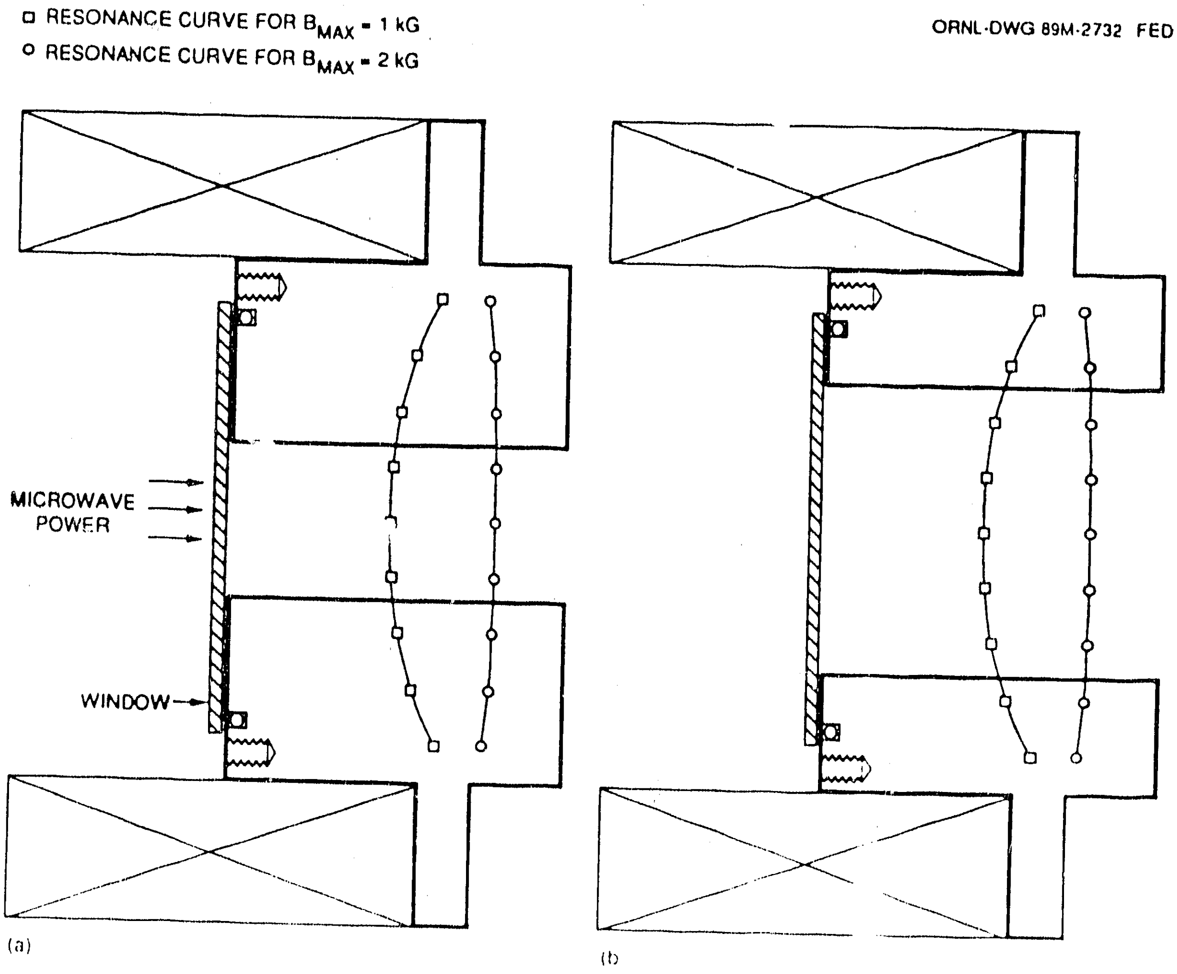


FIGURE 2



□ RESONANCE CURVE FOR BMAX = 1 kG
○ RESONANCE CURVE FOR BMAX = 2 kG
ORNL-DWG 89M-2732 FED
MICROWAVE POWER
WINDOW
(a)
(b)

FIGURE 3

EXPERIMENTAL ARRANGEMENT WITH 3-D PROBE POSITION PLATFORM FOR STUDYING PLASMA PROPERTIES

ORNL-DWG 90M-2538A FED

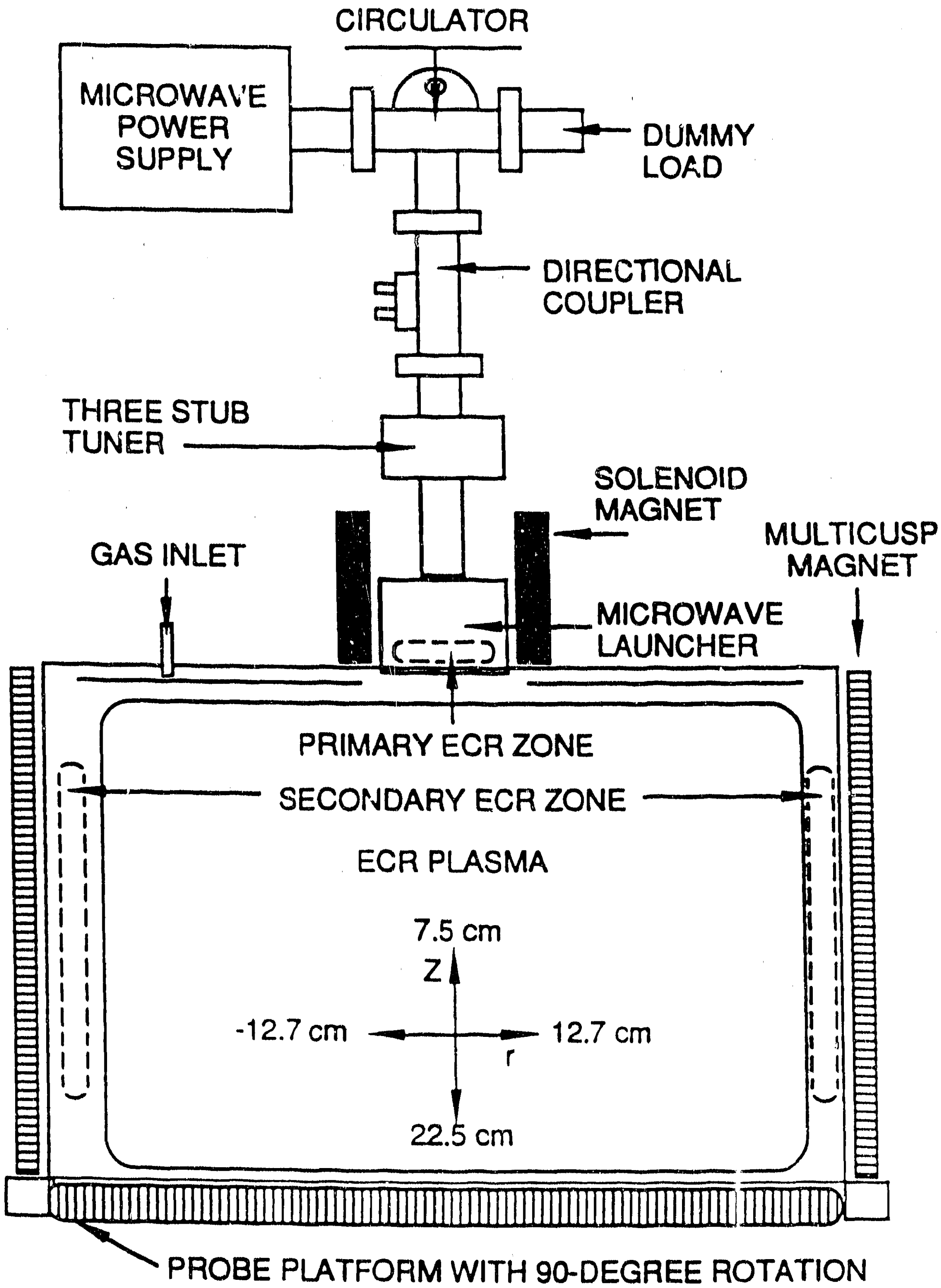


FIGURE 4

RESONANCE CAVITY EFFECT OF PLASMA CHAMBER LENGTH

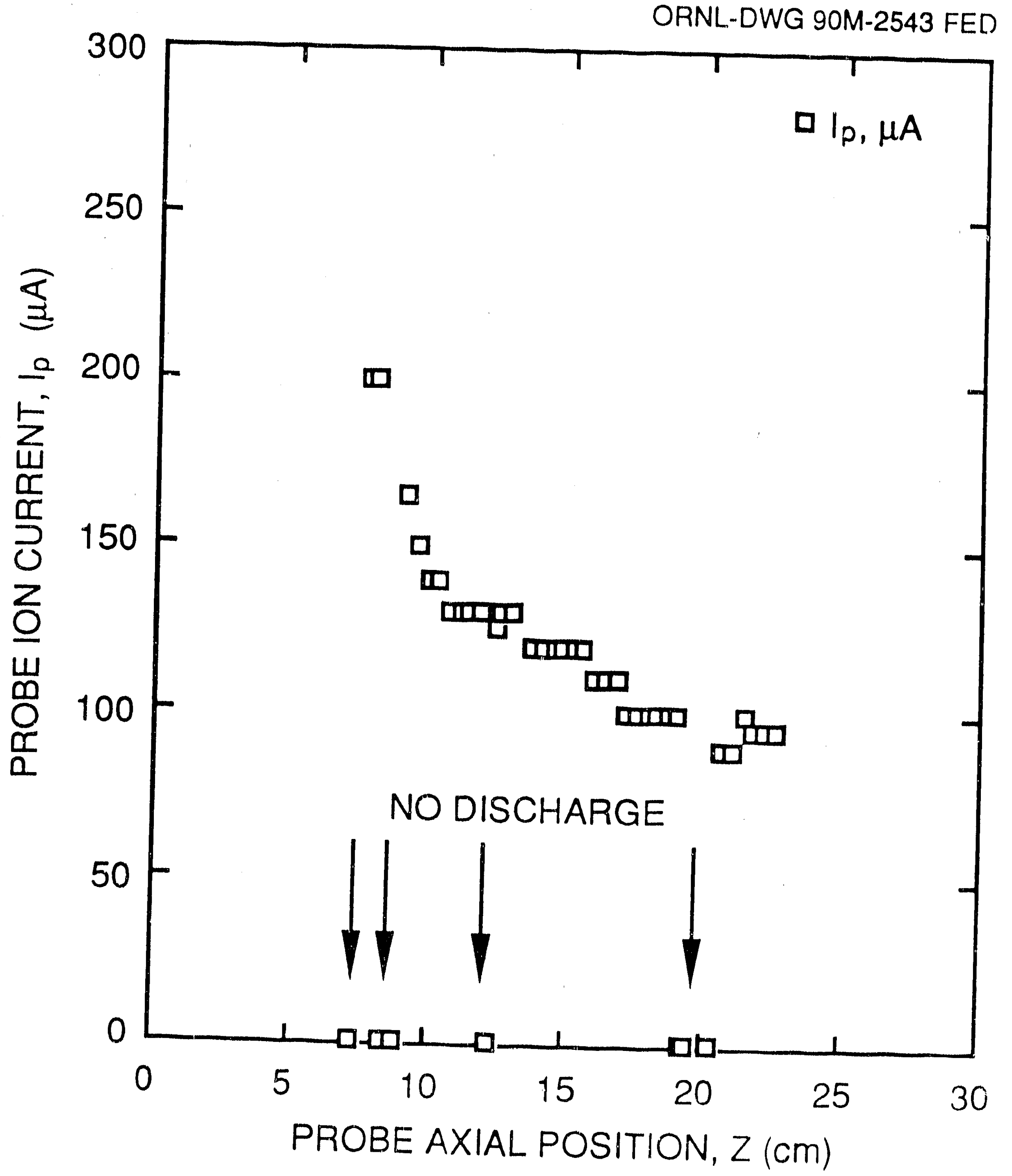


FIGURE 5

PLASMA DENSITY INCREASES WITH INPUT POWER

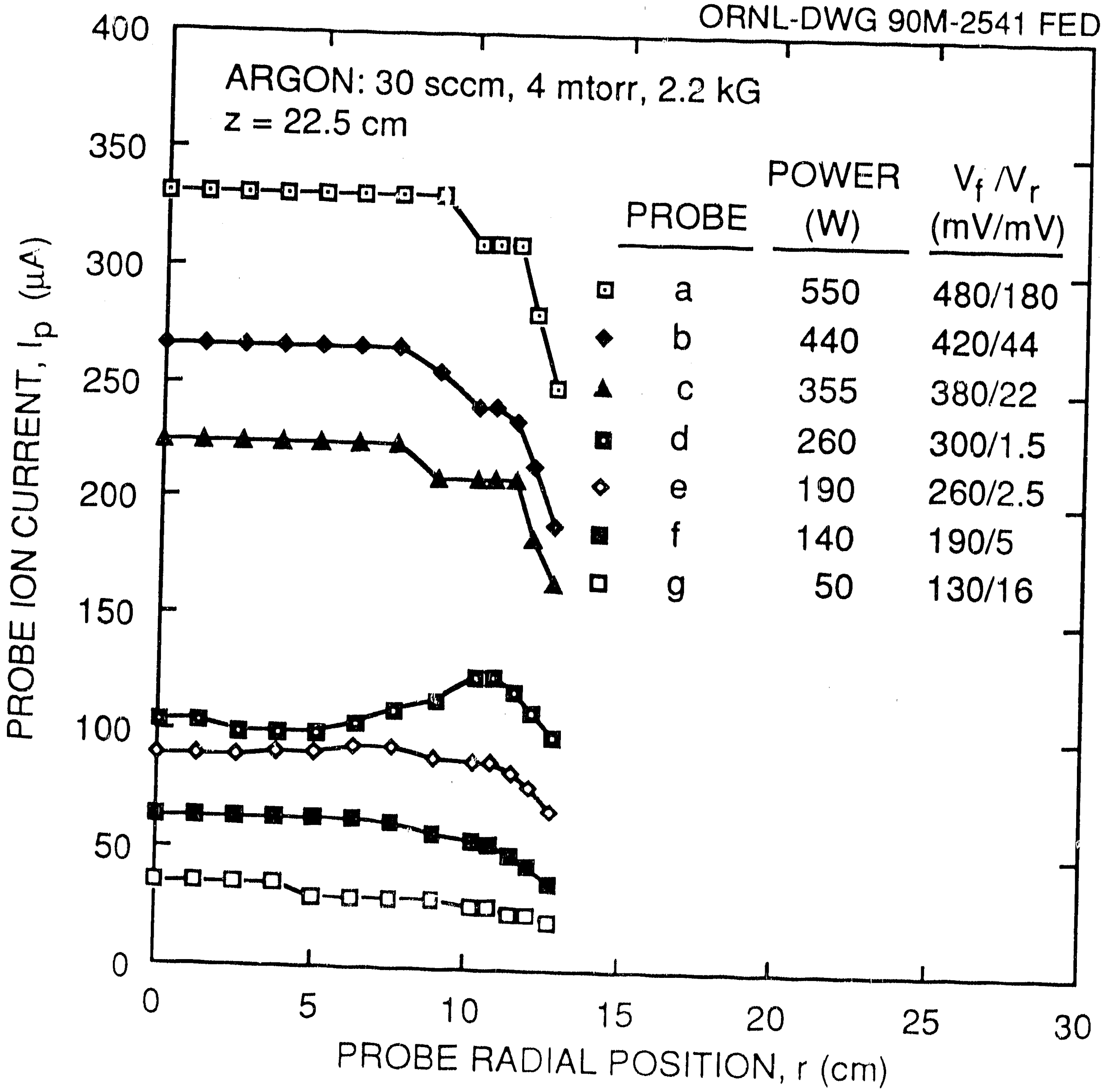


FIGURE 6

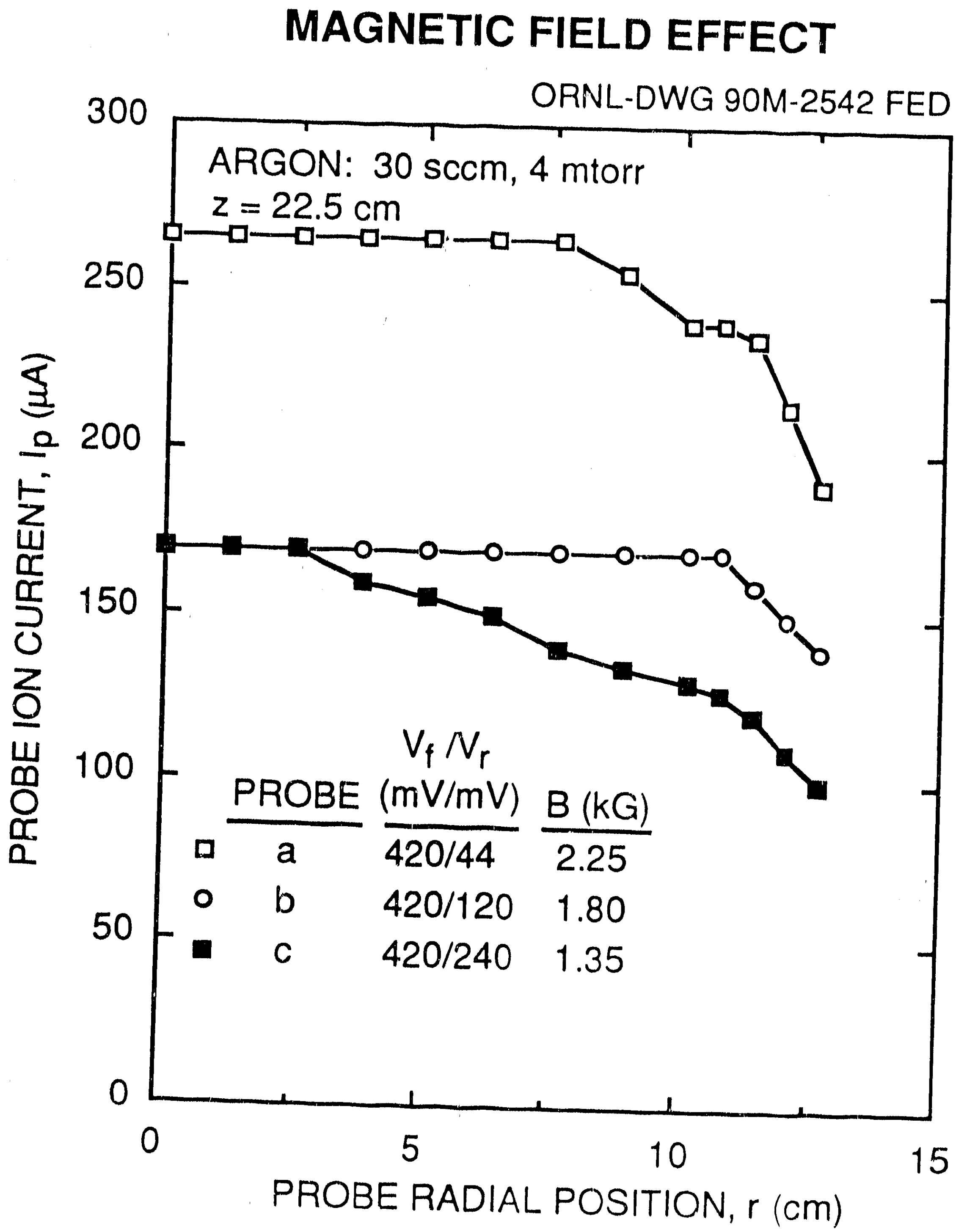

MAGNETIC FIELD EFFECT
ORNL-DWG 90M-2542 FED
ARGON: 30 sccm, 4 mtorr
z = 22.5 cm
PROBE ION CURRENT, I_p (μA)
PROBE RADIAL POSITION, r (cm)
PROBE
V_f / V_r (mV/mV)
B (kG)
a 420/44 2.25
b 420/120 1.80
c 420/240 1.35
0
50
100
150
200
250
300
5
10
15

FIGURE 7

PLASMA RADIAL PROFILES AT DIFFERENT AXIAL PLANES

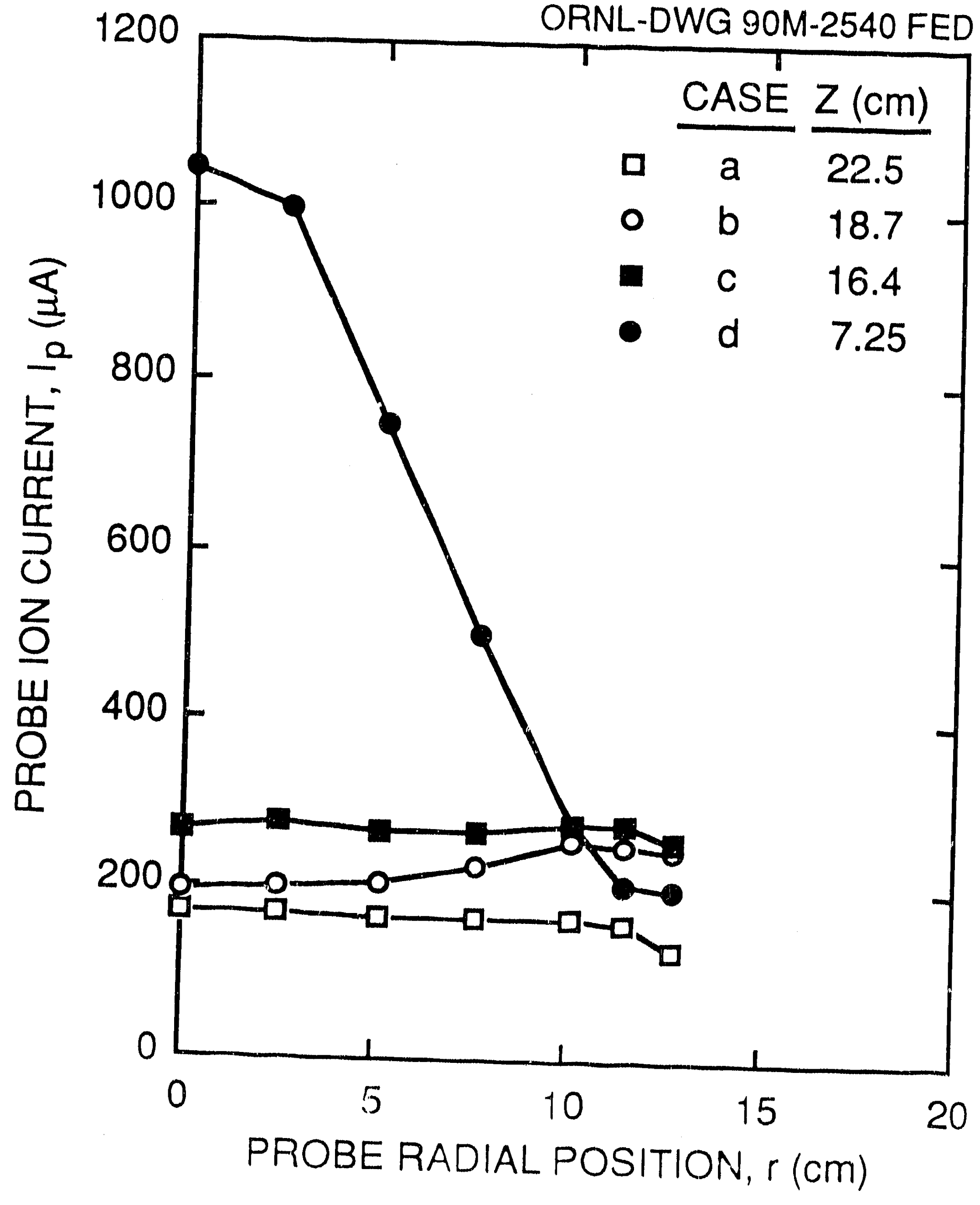


FIGURE 8

Effect of Substrate Electrical Property on Plasma Uniformity

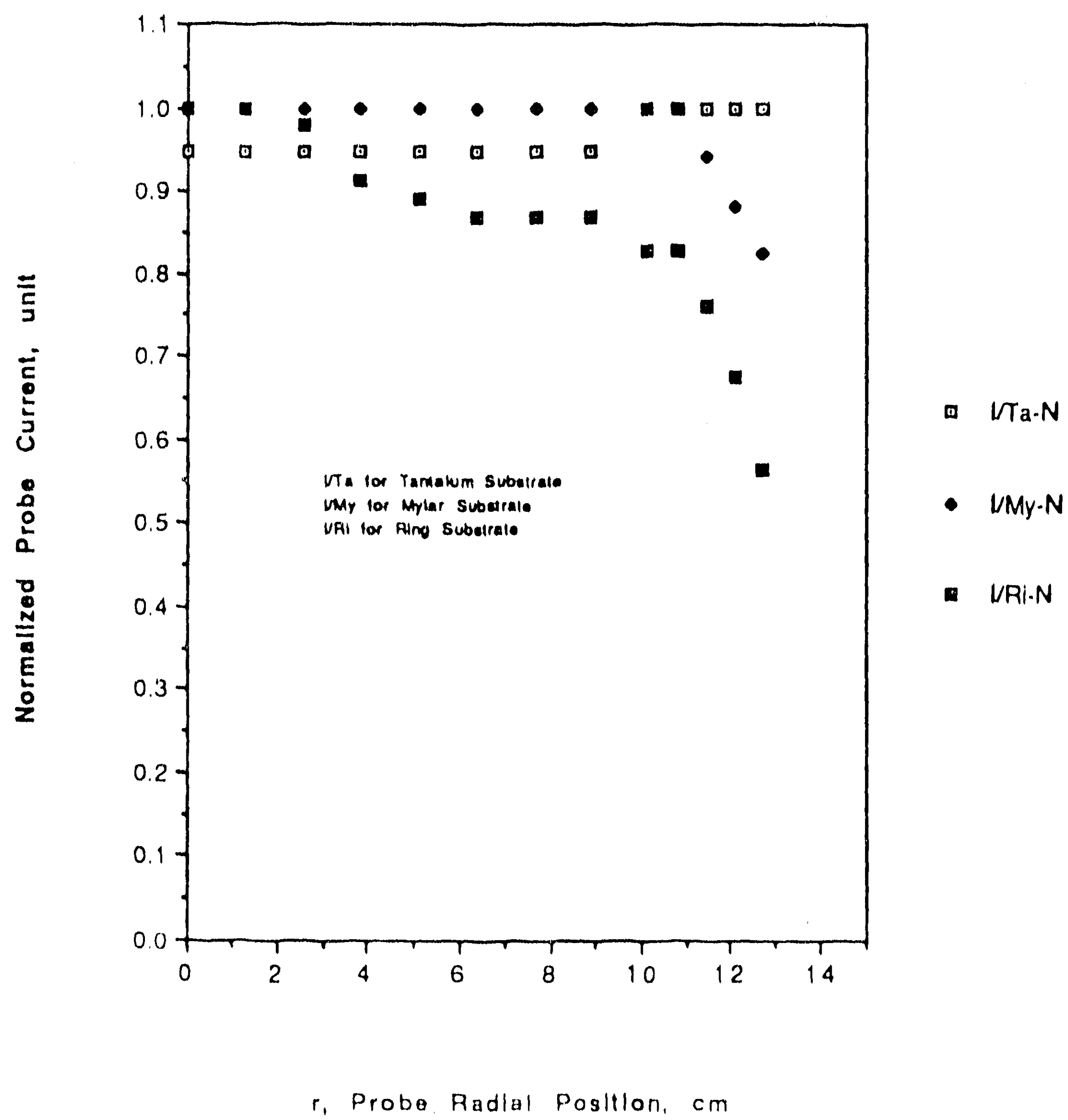


FIGURE 9

Effect of Ring Biasing on Plasma Uniformity

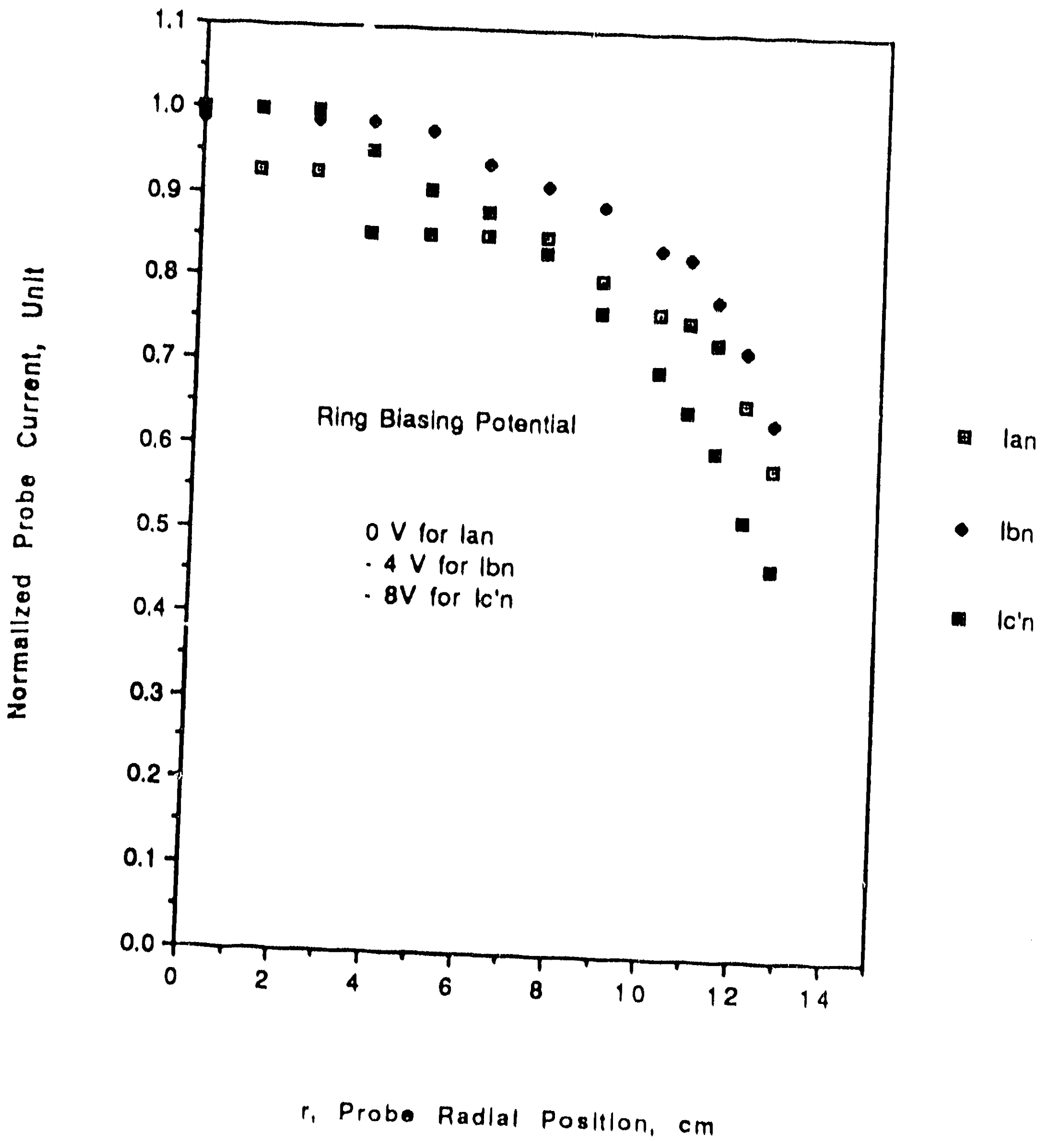


FIGURE 10

END

DATE FILMED

12 / 05 / 90