CONF-901116--9

DE91 000707

POTENTIAL APPLICATIONS OF A NEW MICROWAVE ECR MULTICUSP PLASMA ION SOURCE*

C. C. TSAI

Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

A new microwave electron cyclotron resonance (ECR) multicusp plasma ion source using two ECR plasma production regions and 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. The plasma source has been operated with continuous argon gas feed and pulsed microwave power. The discharge initiation phenomena and plasma properties have been investigated and studied as functions of discharge parameters. Together with the discharge characteristics observed, a hypothetical discharge mechanism for this plasma source is reported and discussed. Potential applications, including plasma and ion-beam processing for manufacturing advanced microelectronics and for space electric propulsion, 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.

1. Introduction

Following the discovery of ions from "canal rays," plasma sources have been developed 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 each 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 heating fusion plasmas, beginning in the 1960s. In the 1970s [1,2], 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 is used to confine hot electrons and source plasma particles. 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.

For applications to plasma and ion-beam processing for manufacturing microelectronics, large plasma sources are needed [3]. 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 [4–6] 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 and space propulsion are also discussed.

2. Experimental arrangement

The microwave ECR plasma source (Fig. 1) 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 for 2.45-GHz microwaves. The ECR zone can be adjusted from the exit end of the launcher 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. A secondary ECR zone established in the multicusp field region could heat up the electrons and enhance plasma production there.

Under normal operations, the operating pressure (or gas flow rate) was kept constant. A matching network (3-stub tuner) in the waveguide pipe between the microwave supply and the plasma source was not readjusted. The plasma density and spatial uniformity were measured by scanning an electrical probe in a plane at the downstream end of the plasma chamber or along the surface of a probe position platform in Fig. 1. 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, and gas pressure.

3. Preliminary results

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 2 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 2 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 magnetic field as shown in Fig. 3. Plasma uniformity is very sensitive to gas pressure (Fig. 4). At high pressures, the plasmas produced had peaked profiles; at low pressures, they had hollow profiles.

We observed insignificant density variations in the azimuthal direction but significant effects in the axial direction. Figure 5 shows the difficulty in initiating discharges at some axial positions. This feature, which we call the "cavity effect" of the plasma chamber, indicates that the microwave electric field in the ECR zones is too weak to create sufficient hot (energetic) electrons for initiating discharges. For z = 16.4–22.5 cm, the plasma density is lower, but uniformity is fairly good. However, for z approaching 7.25 cm, the plasma is dense but not uniform. This cavity effect on plasma density and uniformity is clearly shown in Fig. 6.

4. Hypothetical discharge mechanisms

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 in terms of simple 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 in the primary ECR zone near the exit end of the launcher but are transmitted to the secondary ECR zone next to the chamber walls. The RHCP waves are absorbed in the primary ECR zone and create 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. 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. However, the electric field in the secondary ECR zone may be too weak to initiate a plasma discharge, as discussed below. Thus, the primary ECR zone is essential for reliable discharges.

Before the discharge is established, the electric field that couples to electrons in the primary ECR zone is the sum of field components of the forward-traveling RHCP and the reflected LHCP microwaves. When the length of the plasma chamber is changed (by scanning the probe position platform up or down), the field component of the reflected LHCP microwaves varies. At some axial positions, the resultant electric field in the primary ECR zone may be too weak to initiate discharges and produce plasmas, as shown in Fig. 6. Under these conditions, the reflected voltage (or power) is slightly lower than the forward voltage (or power). However, this simple problem can be solved by adjusting the plasma chamber length slightly.

At relatively high pressures, a dense plasma above the cutoff of 7.5×10^{10} cm^{-3} can be created in the primary ECR zone. The LHCP microwaves will be reflected back to the power generator. Insufficient hot electrons in the secondary ECR zone, caused by the weak ECR electric field and low fraction of the hot electrons arriving from the primary ECR zone, produce insignificant plasma there. The plasma particles near the primary ECR zone diffuse radially out and axially down to the substrate or the probe platform. Consequently, a peaked radial profile in the probe plane (Fig. 4) is expected with high reflected voltage or power. Similar phenomena (Fig. 3) are also expected to occur for plasmas created at relatively low applied magnetic fields, under which a large fraction of the hot electrons is lost to the launcher walls, since the primary ECR zone will be deeper in the launcher throat.

At relatively low gas pressures, some hot electrons in the primary ECR zone will diffuse to the secondary ECR zone and be confined there. These electrons will efficiently ionize gas particles and create plasma. In addition, the LHCP microwaves will establish weak electric fields, heat electrons, and produce additional plasma particles in this secondary ECR zone. These plasma particles diffuse radially toward the axis of the plasma chamber and form a plasma with a hollow profile (Fig. 4), accompanied by low reflected voltage or power. The hollow profile feature is also expected 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) will reach the cusp field region and produce plasma there.

5. 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 [4–6], 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 different electrical potentials of the wafer and the substrate holder. This plasma source can be further developed for etching of large wafers (300 mm or larger). It could be also used for thin-film deposition.

Such plasma sources can supply ions 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 [7]. 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, and D. E. Schechter.

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

[4] 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).

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

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

[7] 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. Experimental arrangement with 3-D probe position platform for studying plasma properties.

Fig. 2. Increase in plasma density with input power.

Fig. 3. Magnetic field effect.

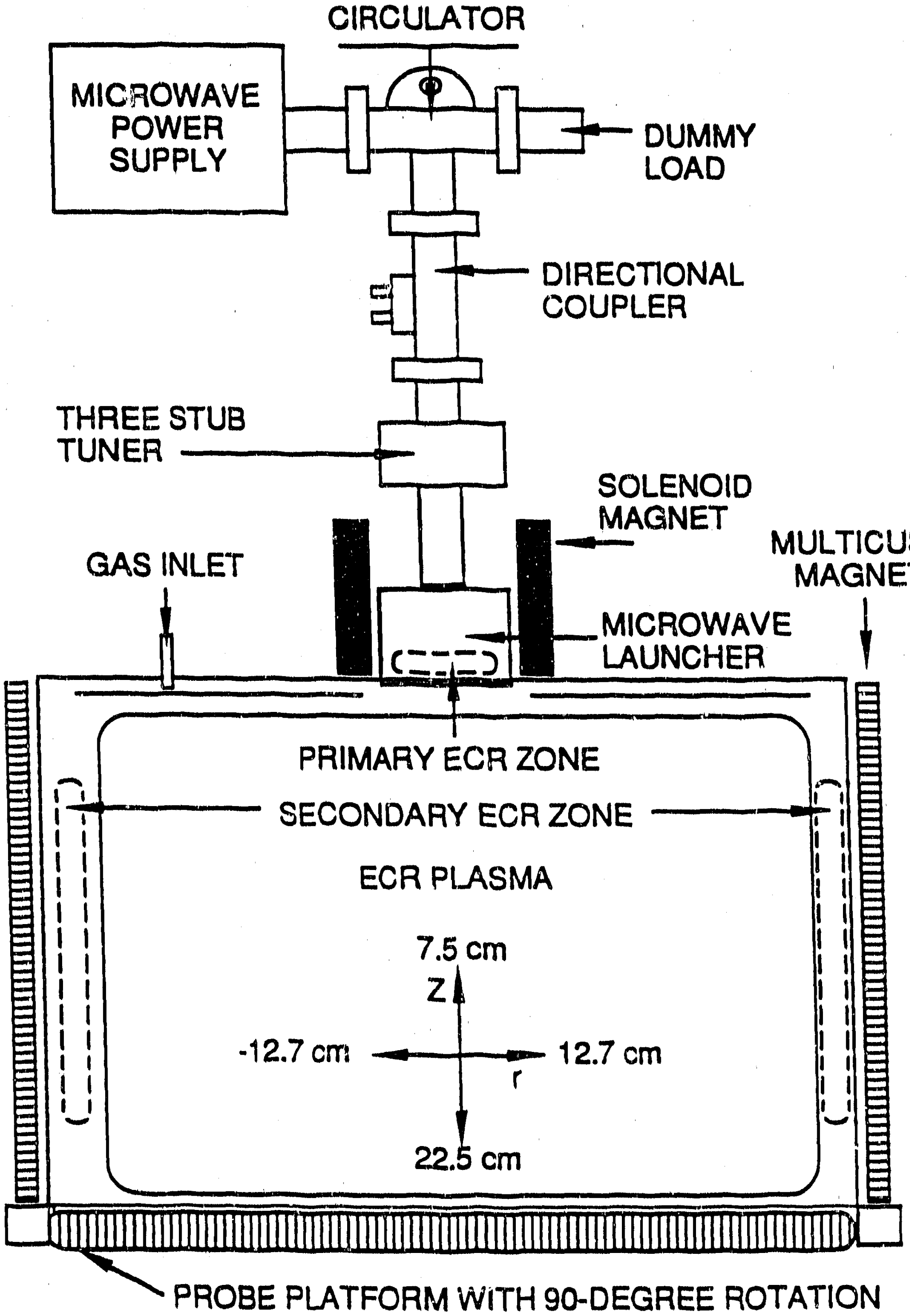
Fig. 4. Gas pressure effect.

Fig. 5. Resonance cavity effect of chamber length.

Fig. 6. Plasma radial profiles at different axial planes.

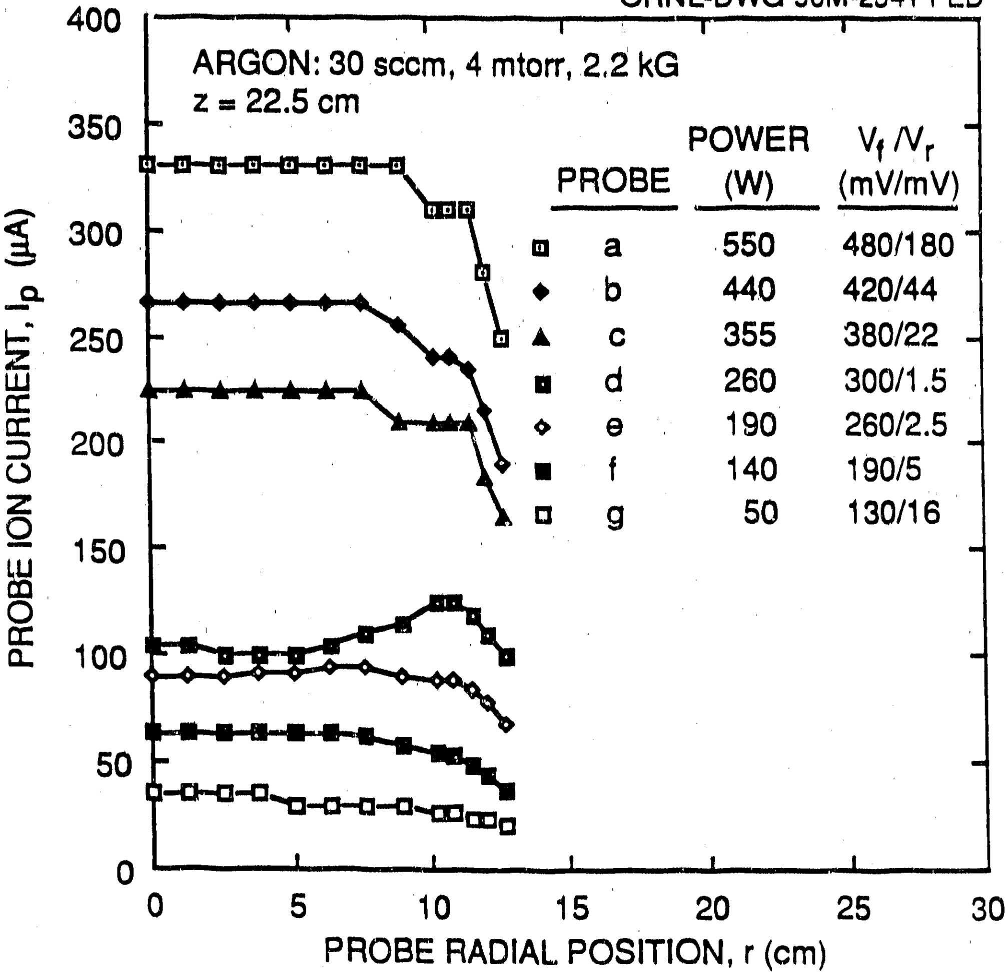
EXPERIMENTAL ARRANGEMENT WITH 3-D PROBE POSITION PLATFORM FOR STUDYING PLASMA PROPERTIES

ORNL-DWG 90M-2538A FED

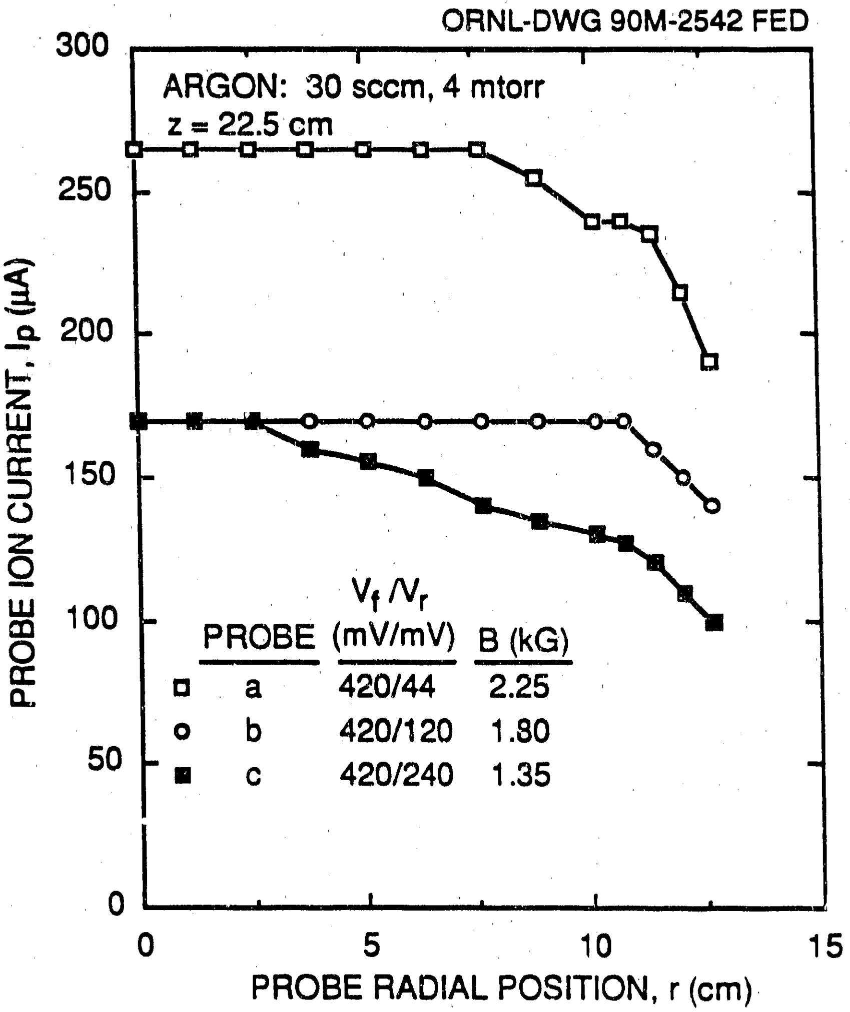


PLASMA DENSITY INCREASES WITH INPUT POWER

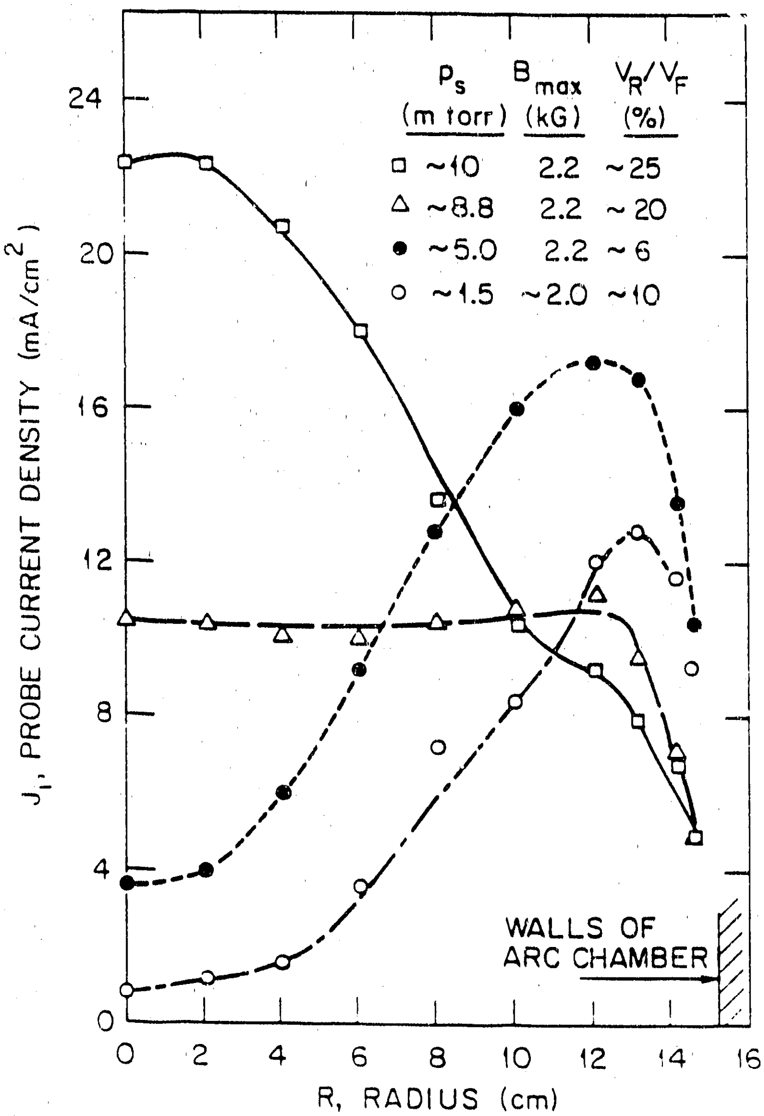
ORNL-DWG 90M-2541 FED



MAGNETIC FIELD EFFECT

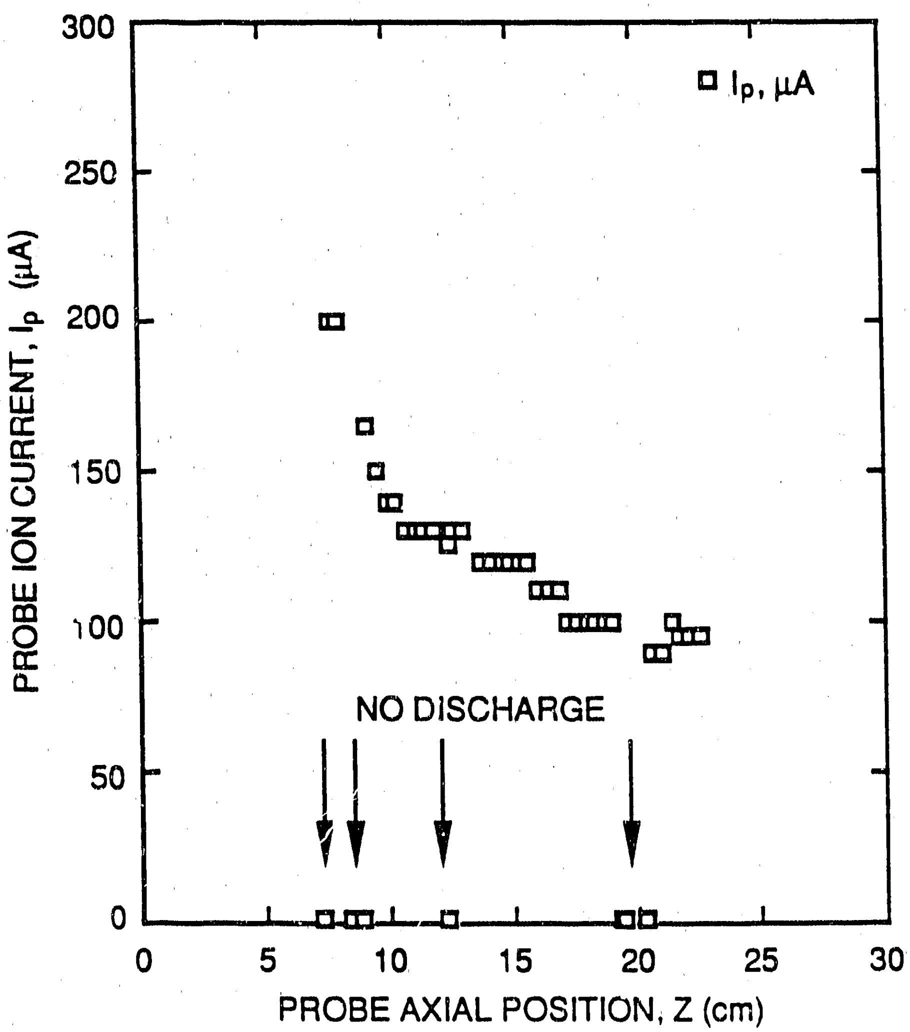


ORNL-DWG 88-3029 FED

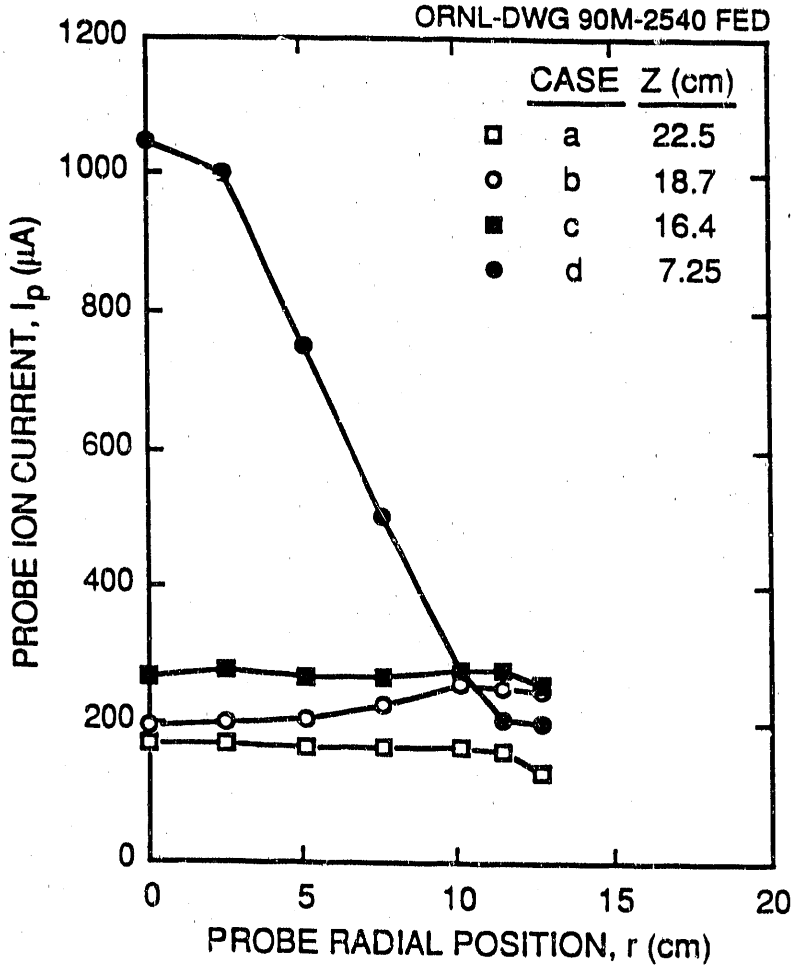


RESONANCE CAVITY EFFECT OF PLASMA CHAMBER LENGTH

ORNL-DWG 90M-2543 FED



PLASMA RADIAL PROFILES AT DIFFERENT AXIAL PLANES



END

DATE FILMED

10 / 29 / 90