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MICROWAVE ION SOURCE

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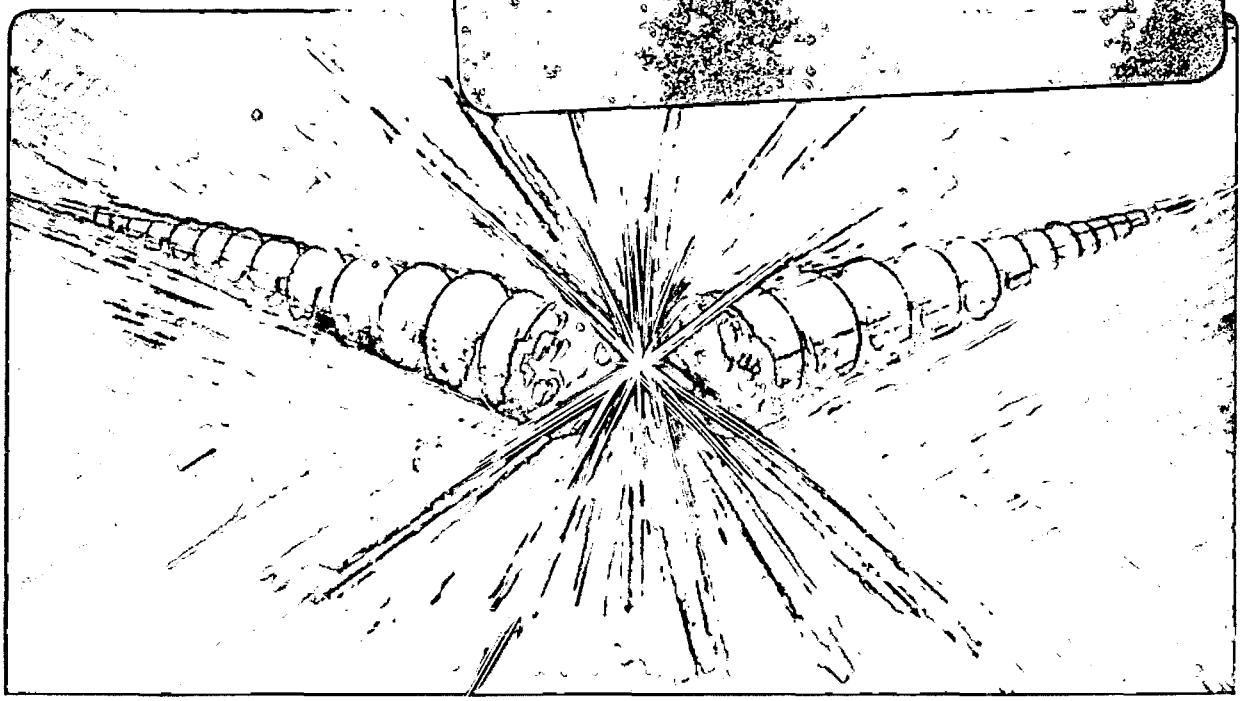

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CHARACTERISTICS OF A COMPACT MICROWAVE ION SOURCE*

S. R. Walther, K. N. Leung, and W. B. Kunkel

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

A small microwave ion source has been fabricated from a quartz tube with one end enclosed by a two grid accelerator. The source is also enclosed by a cavity operated at a frequency of 2.45 GHz. Microwave power as high as 500 W can be coupled to the source plasma. The source has been operated with different geometries and for various gases in a cw mode. For hydrogen, ion current density of 200 mA/cm^2 with atomic ion species concentration as high as 80% has been extracted from the source. It has been demonstrated that low energy oxygen ion beams can also be extracted from the source. Beam energy spread has been measured to be less than 1 eV.

* This work is supported by the Air Force Office of Scientific Research and the U.S. DOE under Contract No. DE-AC03-76SF00098.

I. Introduction

During the last decade, there has been extensive research and development of ion sources for neutral beam heating in fusion research and other applications. Positive and negative ion sources using different gases, different principles of operation, and with various ion extraction methods have been developed and tested. In virtually all of these cases, direct current discharge from a cathode to an anode are normally employed. For long pulse or cw source operation, the life-time of the cathode or filament is always limited. In some cases, it is even difficult to generate a stable plasma (for example oxygen) by using hot tungsten filaments. Therefore, it is obviously desirable to develop an ion source that operates without filaments. A microwave ion source probably can provide part of the solution. Such a source can be made quite small, and requires only one power supply for the whole source operation. In this paper, we present the characteristics of a compact microwave source[1] when it is operated with different gases to generate positive or negative ion beams. The source has been operated with two different geometries. It is shown that permanent magnet multicusp fields can be incorporated with this kind of source to provide plasma confinement.

II. Experimental Setup

The small ion source is fabricated from a quartz tube with a two-grid extractor at one end and gas inlet at the other end. The source has been operated with two different quartz tube configurations, the straight tube geometry and the expansion cup geometry. The straight quartz tube (Fig. 1)

has an outside diameter of 10 mm while the expansion cup (Fig. 2) uses a section of 10 mm tube joined to a section of a larger tube with an outside diameter of 27 mm. In both cases the quartz tube is enclosed by an Evanson microwave cavity[2] and operated at a fixed frequency of 2.45 GHz. It should be noted that this "cavity" is not a resonator in the usual sense of the word but is better described as a tunable quarter-wave stub termination for the coaxial feed line, that can be "tuned" for the minimum reflection. Microwave power as high as 500 watts can be coupled to the cavity from a Micro-Now Model 420B generator by means of a coaxial cable. Cooling air is directed at the discharge through a tube located in the body of the cavity. Additional cooling of the source is provided by an air blower. The removable end cap of the cavity allows the unit to be positioned without breaking the vacuum system.

Ionization of the gas in the tube is initiated by a hand-held Tesla coil. When properly adjusted, the cavity will maintain a discharge in various gases at pressures ranging from a few milli-torr to several hundred torr. A tuning stub and a coupling slider are provided in the cavity to properly match the impedance of the discharge to that of the generator, and once adjusted no further adjustments are necessary unless the flow conditions are changed. The reflected, as well as the incident microwave power, were measured using a bi-directional power meter located at the output of the microwave power generator. Reflected microwave power is typically 10% of the incident microwave power when the cavity is properly tuned.

The open end of the quartz tube is enclosed by a two-electrode accelerator system. The first or plasma electrode has a 0.8-mm-diam extraction aperture. This electrode is water-cooled, and is biased at a potential either positive or negative relative to the ground potential for the extraction of a positive

or a negative ion beam from the source. The second electrode is connected to ground. Since the quartz tube is electrically floating, the potential of the source plasma is "tied" to that of the plasma electrode. Thus the energy acquired by the extracted ions is equal to the potential applied on the plasma electrode plus (or minus) the plasma potential. A compact magnetic-deflection spectrometer[3] located just outside the extractor is used to determine the plasma potential as well as the positive and negative ion species of the small extracted beam.

The expansion cup source has also been operated with permanent magnets mounted longitudinally to provide multi-dipole fields for plasma confinement. In this arrangement 16 (3.5 mm x 3.5 mm cross section and 25 mm long) ceramic bar magnets are employed. An enlarged view of the quartz tube, the bar magnets, and the calculated B-field distribution[4] are illustrated in Fig. 3. Substantial improvements in current density have been obtained with the use of the confining magnets. The data presented in the following sections are obtained without the use of bar magnets unless specified otherwise.

III. Experimental Results for Straight Tube Geometry

(a) Source operation with hydrogen

When the source is operated with hydrogen, the extracted positive ion current increases almost linearly with the absorbed microwave power (which is defined as: forward power - reflected power). Figure 4 shows a plot of the current density versus the absorbed power for an extraction voltage of 2 kV and a flow rate of ~ 9 standard cubic centimeters per minute (sccm). It can be seen that the current density exceeds 200 mA/cm^2 when the microwave power is about 400 W.

The hydrogen ion species are measured by the mass spectrometer. Figure 5(a) shows a typical mass spectrum of the extracted positive ion beam. The evolution of the ion positive species distribution as a function of the absorbed microwave power (Fig. 6) is similar to those of dc discharge ion sources.[5] At low microwave power, the ion species is dominated by H_3^+. As the power increases, the percentage of H_3^+ decreases while the concentration of H^+ increases. The percentage of the H_2^+ ions varies only between 5% and 8% throughout the range of power tested. Higher atomic ion percentage (> 80%) can be obtained if the wall of the quartz tube is kept very cold so that the recombination rate for atoms on the wall is low.[6]

The potential of the source plasma can be estimated from the energy of the ions when the extraction voltage is adjusted to zero. The spectrometer output signal shows that the ions left the source with energies as high as 70 eV. This result suggests that the electron temperature of the source plasma can be very high. The data presented in section (c) for other gases support this observation.

(b) Extraction of H^- ions

In order to extract a negative ion beam from the microwave source, the plasma electrode is biased at -500 V relative to ground. The magnitude of the H^- output signal is extremely small. Since the electron temperature is high and the plasma potential ~ +70 V, very few H^- ions are available for extraction near the plasma electrode. A pair of ceramic magnets is then used as a filter[7] to provide a transverse B-field near the extractor. This arrangement lowers the plasma potential and the electron temperature near plasma electrode. As a result, a much larger H^- signal is observed

[Fig. 5(b)]. Compared to the positive ion species, the H^- signal is about two orders smaller in magnitude.

(c) Source operation with other gases

The straight tube microwave source has also been operated with other gases such as O_2, Ne and Ar. The gas flow rate required for optimum operation ranges from 1 sccm for O_2 to 5 sccm for Ar. The plasma formed from each of these gases produces a characteristic color which is red for Ne, white for O_2, and light blue for Ar. Figure 7 shows the current density extracted from these plasmas as a function of the absorbed microwave power for an extraction voltage of 1 kV. In all cases, current density higher than 35 mA/cm^2 can be achieved by employing 300 W of power.

For O_2, both O^+ and O_2^+ ions are present in the extracted beam. When the source is operated with low microwave power, the spectrometer signal in Fig. 8(a) shows that the majority of the ions are O_2^+. When higher power is used, Fig. 8(b) shows that O^+ becomes the dominant species. For Ne and Ar gases, ions with higher charge state are present in the plasma. In the case of Ne, the spectrometer shows that Ne^+, Ne^{2+} and Ne^{3+} are all present in the extracted beam. Since the production of Ne^{3+} ions requires electrons with energies greater than 64 eV, the electron temperature of the source plasma is indeed very high. Although the plasma potential in this source is higher than that of a dc discharge plasma, the energy spread of a xenon ion beam has been measured to be less than 1 eV in a separate experiment.[8] This result indicates that this source is suitable for applications which require high quality ion beams.

IV. Experimental Results for Expansion Cup Geometry

(a) Single hole extraction system

The expansion cup source geometry provides a larger usable extraction area when a large diameter beam is needed. Figure 9 shows the extracted current density versus absorbed microwave power for optimum gas flow rates. It can be seen that the current density increases with power for all gases. As expected, the current density is typically lower (40 to 60%) for this geometry as compared to that of the straight tube configuration. The lower current density is due to the increased volume of the expansion cup geometry and the increased distance from cavity to extraction grid. However, the useful extraction area has increased from 0.5 cm^2 to over 3 cm^2 with the expansion cup geometry.

Figure 10 is a photograph of the expansion cup geometry when it is operated as a small multicusp ion source. It is difficult to measure the magnetic field distribution inside the source. However computer calculation shows a larger area (diameter = 1.8 cm) with magnetic field less than 20 gauss can be obtained, if 16 or more magnet columns are employed.

The effect of mounting magnets columns around the expansion cup is shown in Fig. 11 when neon gas is used. The effect of the magnets is most notable at lower power levels. It is observed that a 100% increase in current density occurs at 100 W for neon, tapering off to a 36% increase at 400 W of absorbed microwave power. For other gases, this multicusp source geometry improves the extracted current density by 10 to 40% at high power levels.

(b) 25 - hole extraction grid

In order to increase the beam current, an extractor with 25 holes was fabricated for the expansion cup source geometry. These holes (each 0.8 mm

diam) were distributed uniformly within a circle of 1 cm diameter. Oxygen gas with an optimum flow rate of 5 sccm and an extraction voltage of 3 kV were used for this experiment.

Figure 12 shows a plot of oxygen beam current versus absorbed microwave power. It can be seen that the extractable current increases with microwave power. A total beam current of 4.6 mA was achieved at an absorbed power of 385 W.

The source plasma potential for the expansion cup geometry is a function of microwave power and gas flow. With proper adjustments, plasma potentials less than 8 V have been observed with the mass spectrometer. This result suggests that the microwave source is very useful for generating low energy oxygen ion beams which can be used to simulate the low earth orbit environment encountered by the space shuttle and many of the payloads.

In conclusion, we have presented some of the characteristics of a small microwave ion source. The source operation is simple and it has only a few components. Limited lifetime elements such as filaments and cathodes are eliminated, allowing stable long life operation even for reactive gases such as oxygen. Future plans for this source include the production of metallic ion beams as well as further measurements of the ion source characteristics.

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8. E. Chamberlin, LANL (private communication).

Figure Captions

Fig. 1 Schematic diagram of the straight tube microwave ion source.

Fig. 2 Schematic diagram of the expansion cup microwave ion source with confining magnets.

Fig. 3 A computer plot of the magnetic field and field lines inside the expansion cup ion source. Upper half plot shows field lines from 2.5 gauss-cm to 100 gauss-cm, while the lower half plot shows constant magnetic field contours from 10 gauss to 500 gauss.

Fig. 4 A plot of extracted hydrogen current density as a function of absorbed microwave power.

Fig. 5 Spectrometer output signal showing the typical mass spectrum of (a) the positive hydrogen ion beam and (b) the negative hydrogen ion beam.

Fig. 6 A plot of the extracted positive hydrogen ion species distribution as a function of absorbed microwave power.

Fig. 7 A plot of the extracted current density as a function of absorbed microwave power for oxygen, neon, and argon.

Fig. 8 Spectrometer output signal showing the distribution of the extracted positive oxygen ion species using (a) 100 watts and (b) 200 watts of absorbed microwave power.

Fig. 9 A plot of the extracted positive ion current density as a function of absorbed microwave power for oxygen, neon and argon using the expansion cup ion source.

Fig. 10 A plotograph of the expansion cup ion source utilizing confining magnets.

Fig. 11 A plot of the extracted neon ion current density as a function of the absorbed microwave power using the expansion cup ion source with and without the confining magnets.

Fig. 12 A plot of total oxygen ion current as a function of absorbed microwave power using the expansion cup ion source with 25 extraction holes.

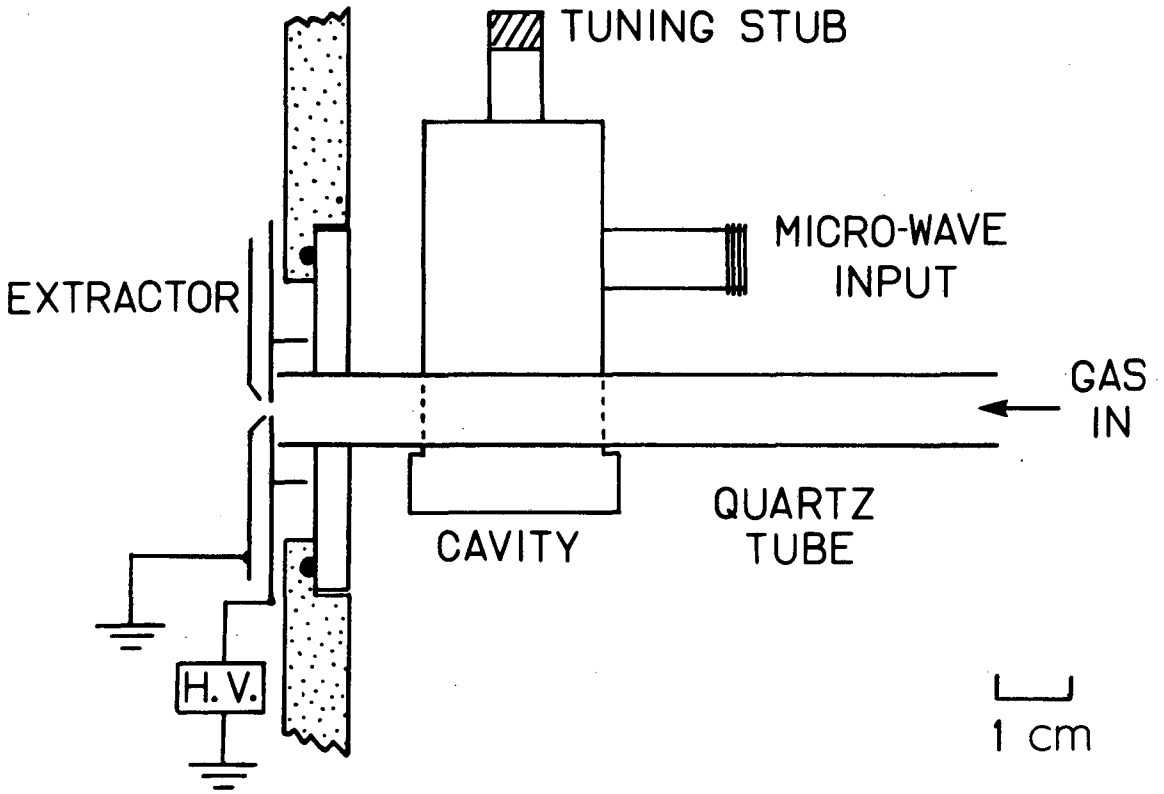

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Fig. 1

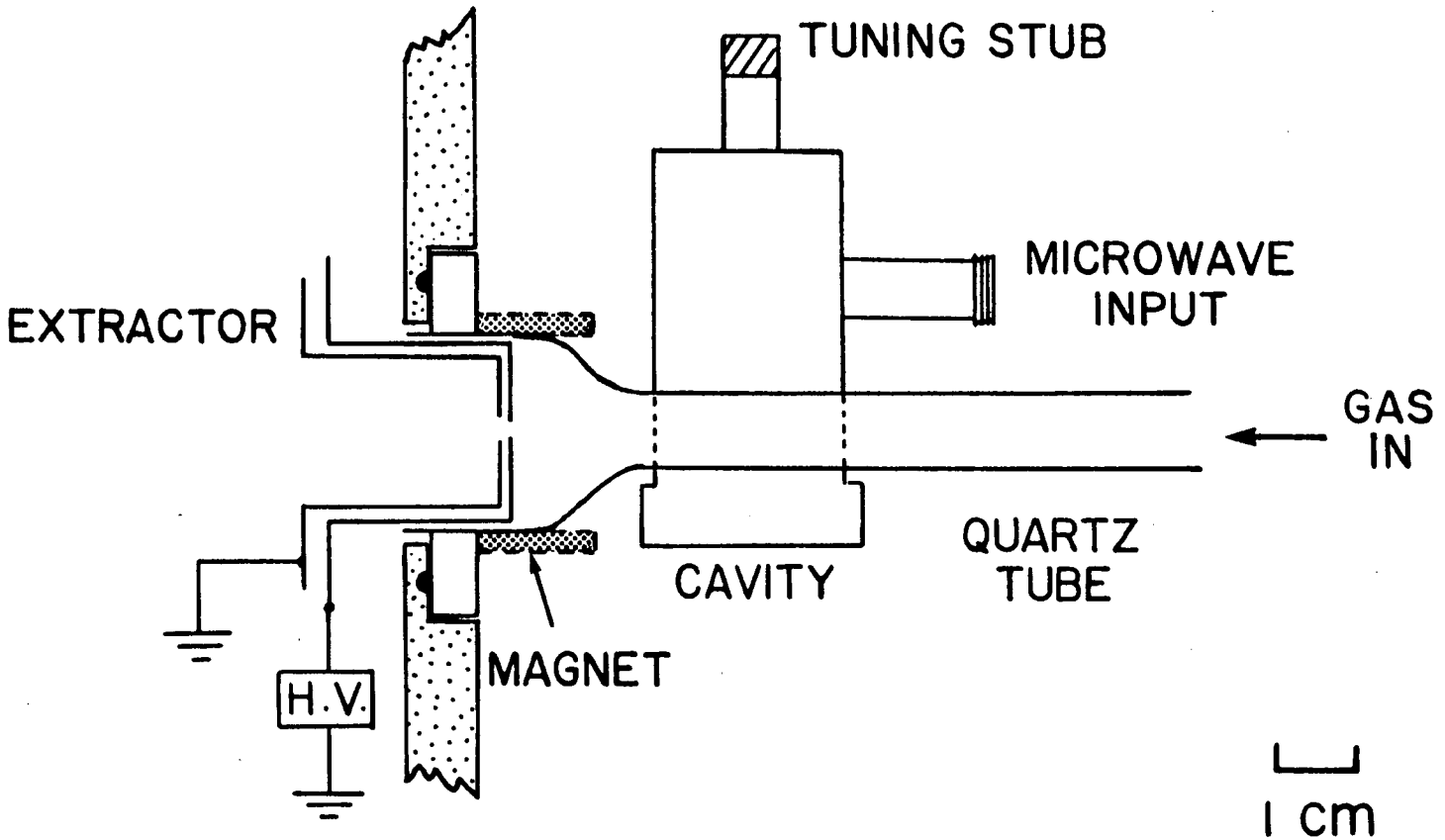

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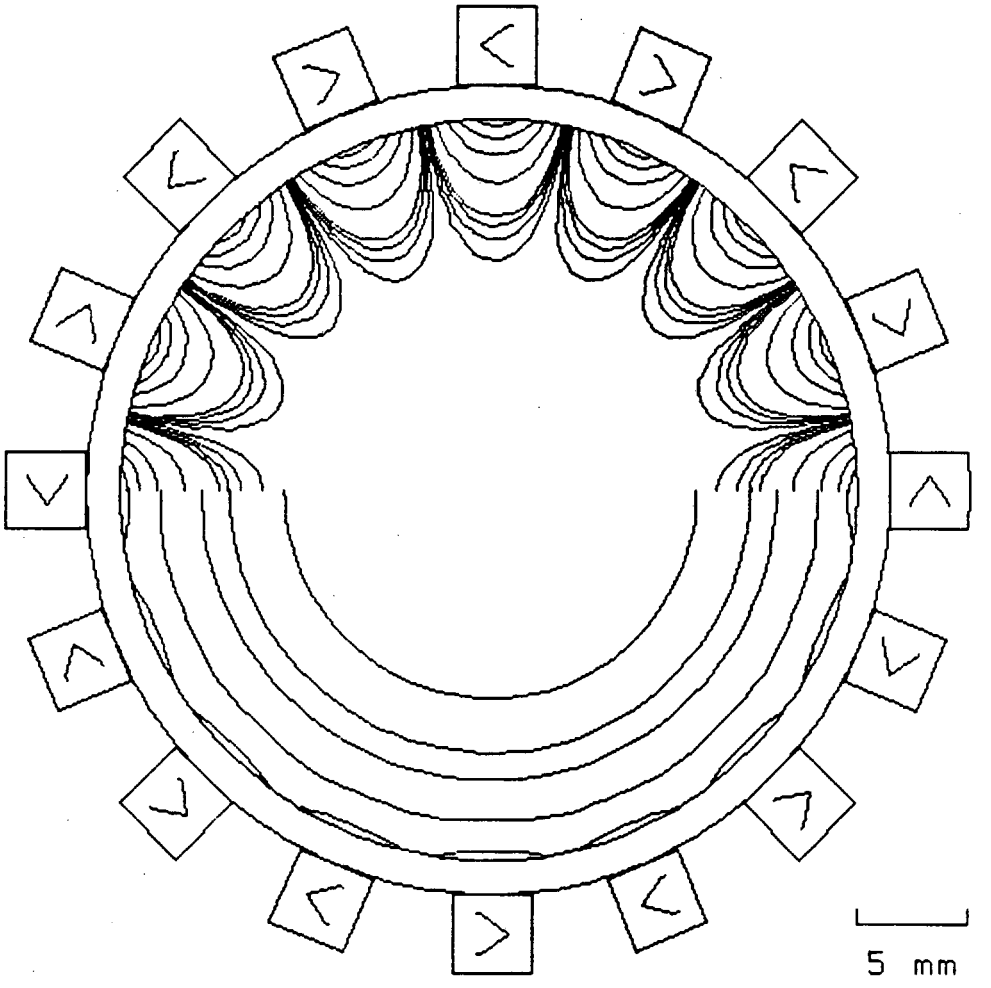
Fig. 2

B rem = 3.0 A=0.35(0.14) B=0.35(0.14)

Magnet Periods= 8 Magnets per Period= 2



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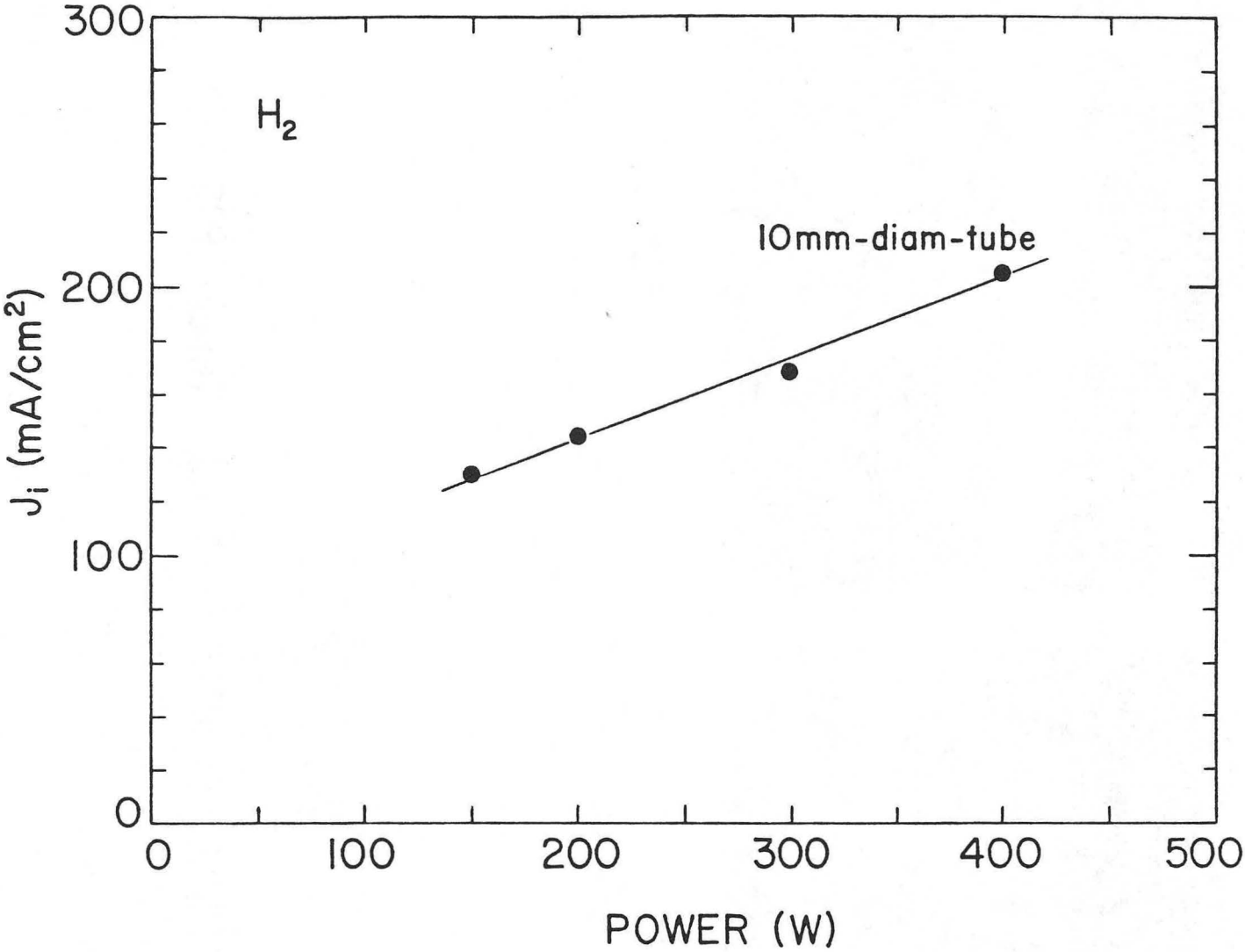
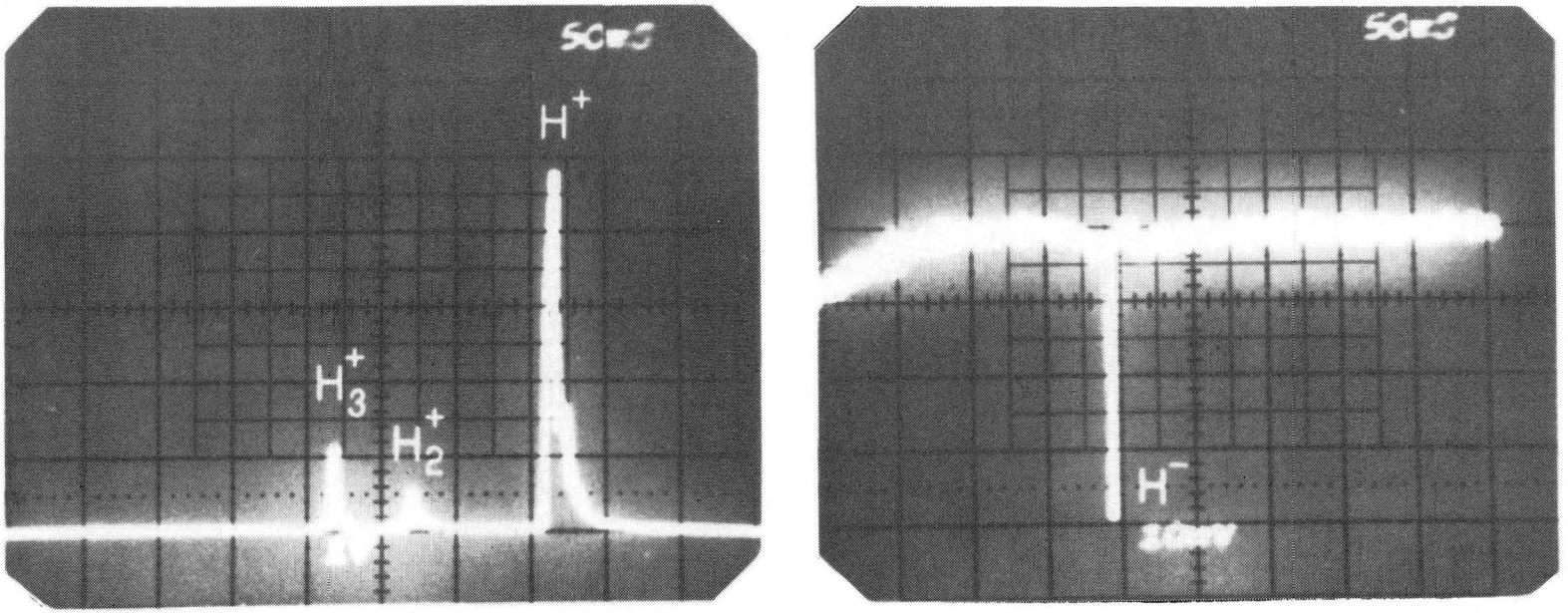
FIELD LINES.0(025,05,075,1,25,5,75),.1KG-CM FIELD INTENSITY .01,.05,.1,.25,.5KG

Fig. 3



XBL 855-2392 A

Fig. 4



(a) (b)

XBB 855-3671A

SPECTROMETER OUTPUT SIGNAL SHOWING (A) THE THREE POSITIVE HYDROGEN ION SPECIES, AND (B) THE H^- IONS

Fig. 5

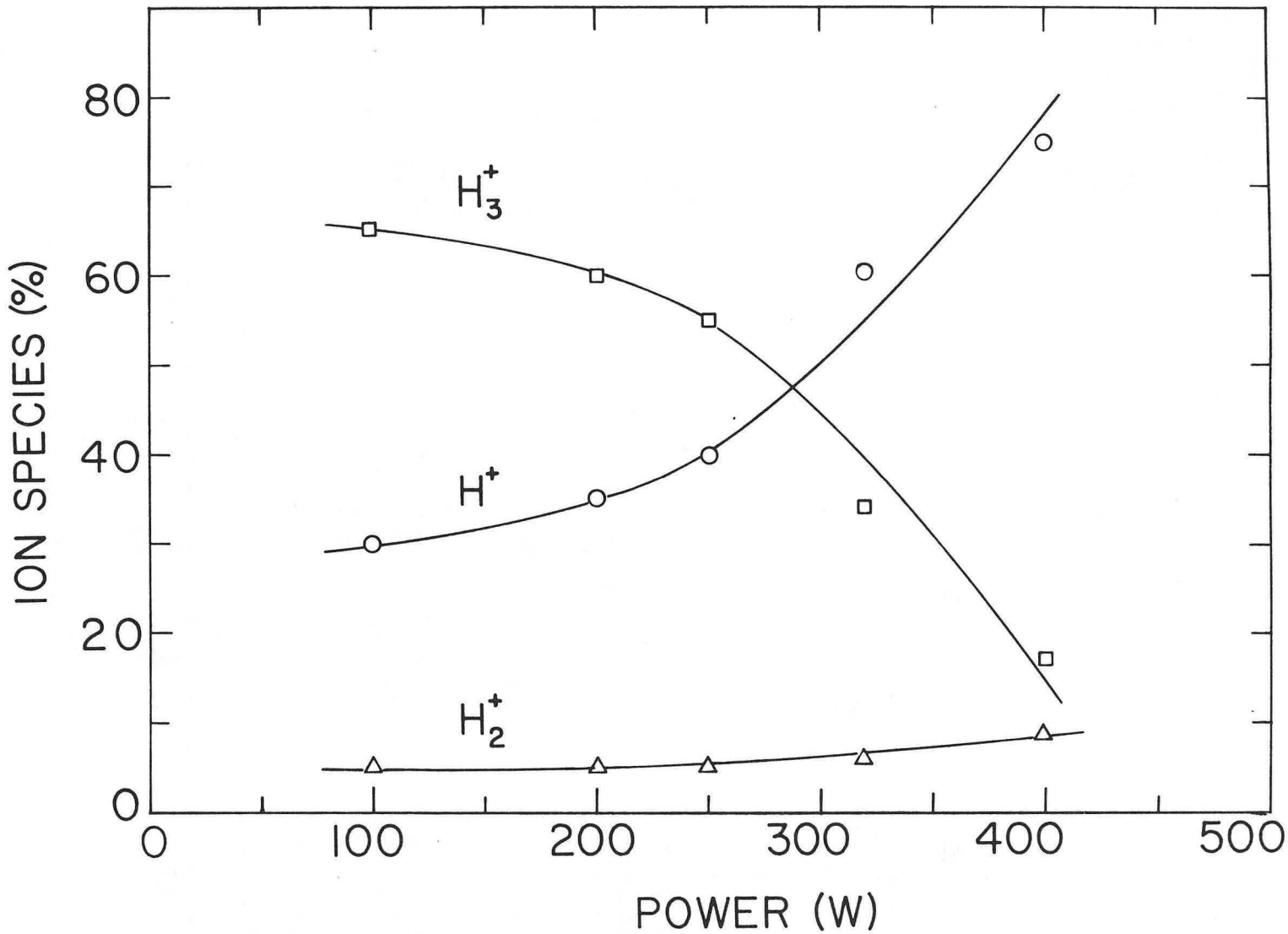


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Fig. 6

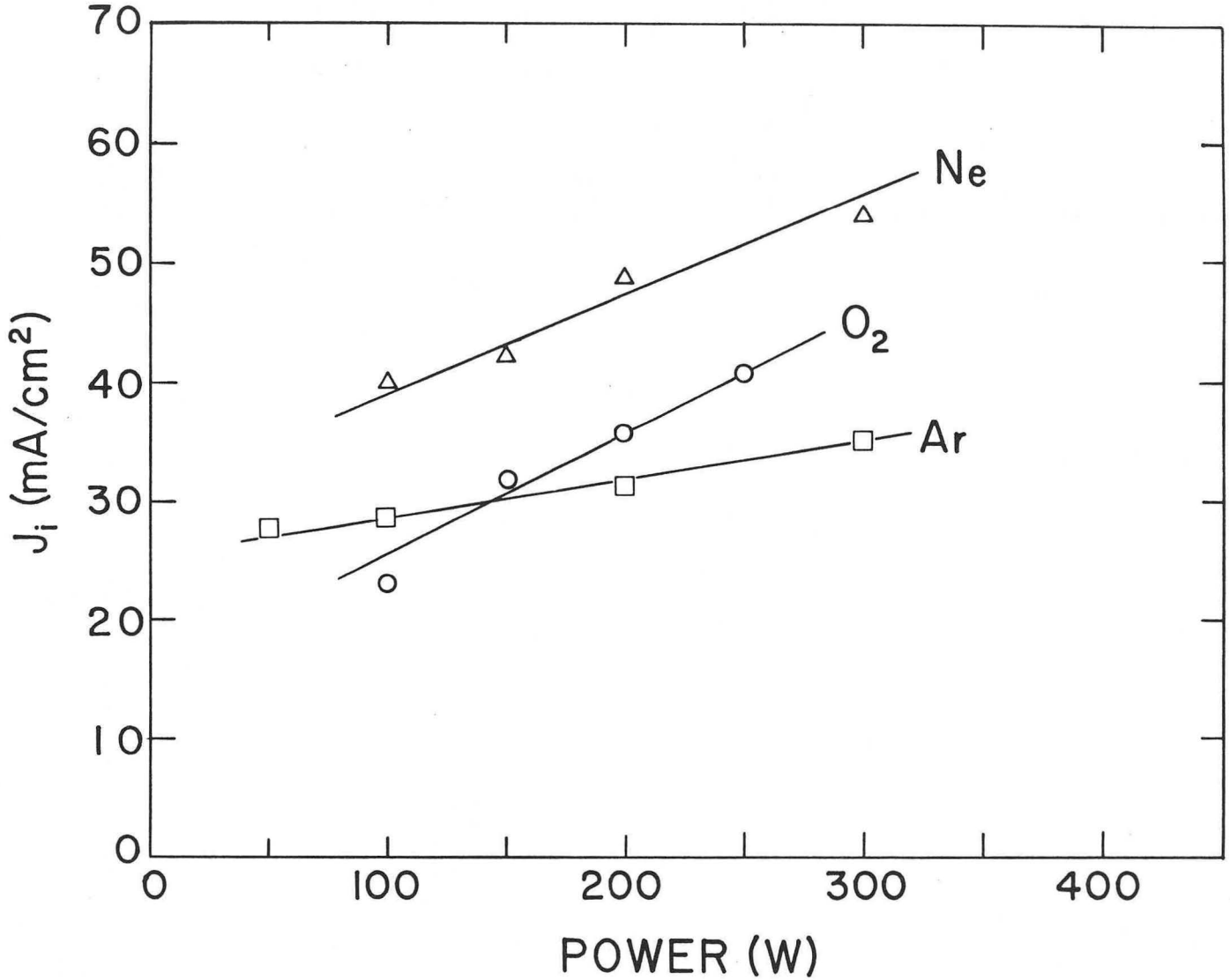

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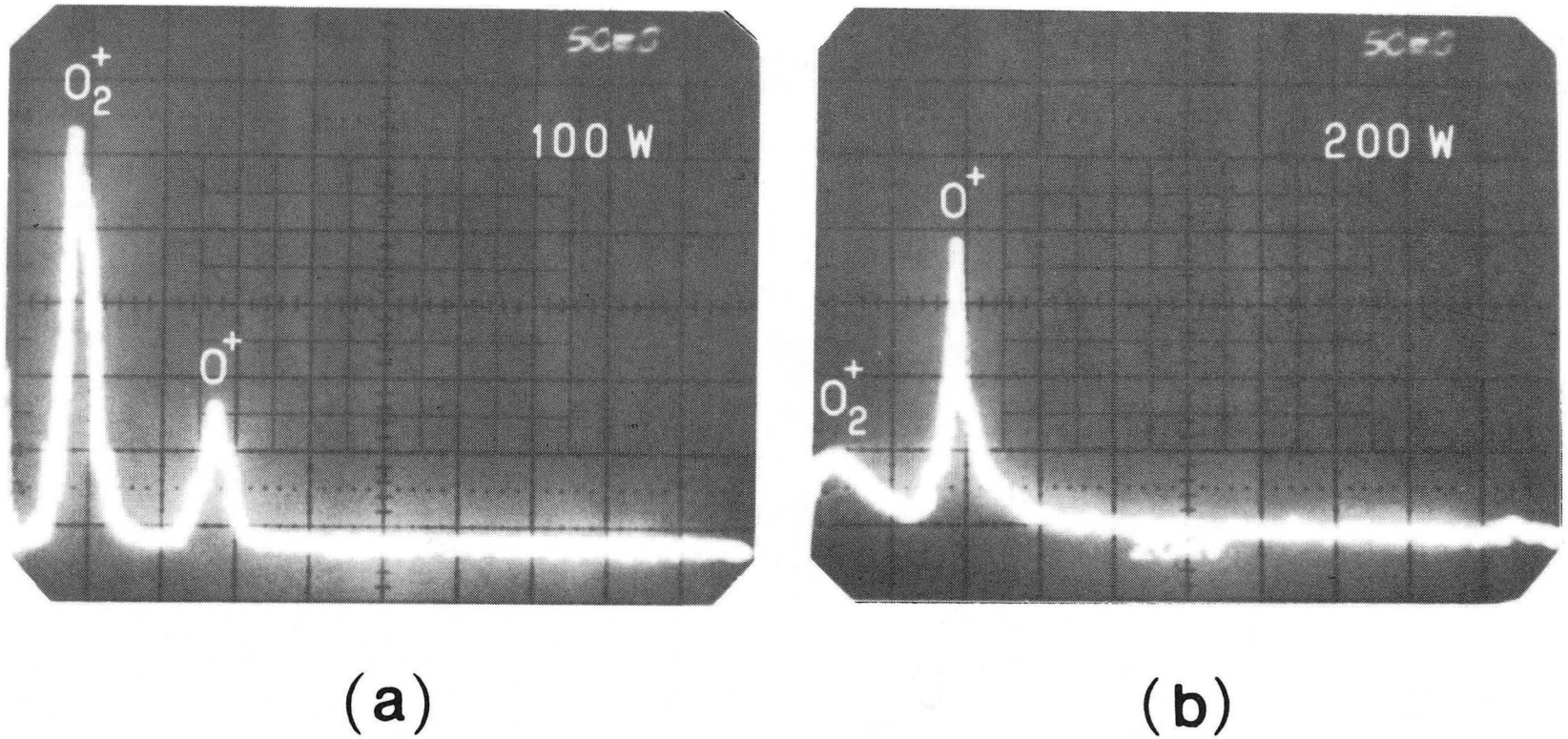
Fig. 7



XBB 855-3672A

THE DISTRIBUTION OF THE OXYGEN ION SPECIES WHEN THE SOURCE IS OPERATED AT (A) LOW, AND (B) HIGH MICROWAVE POWER LEVELS

Fig. 8

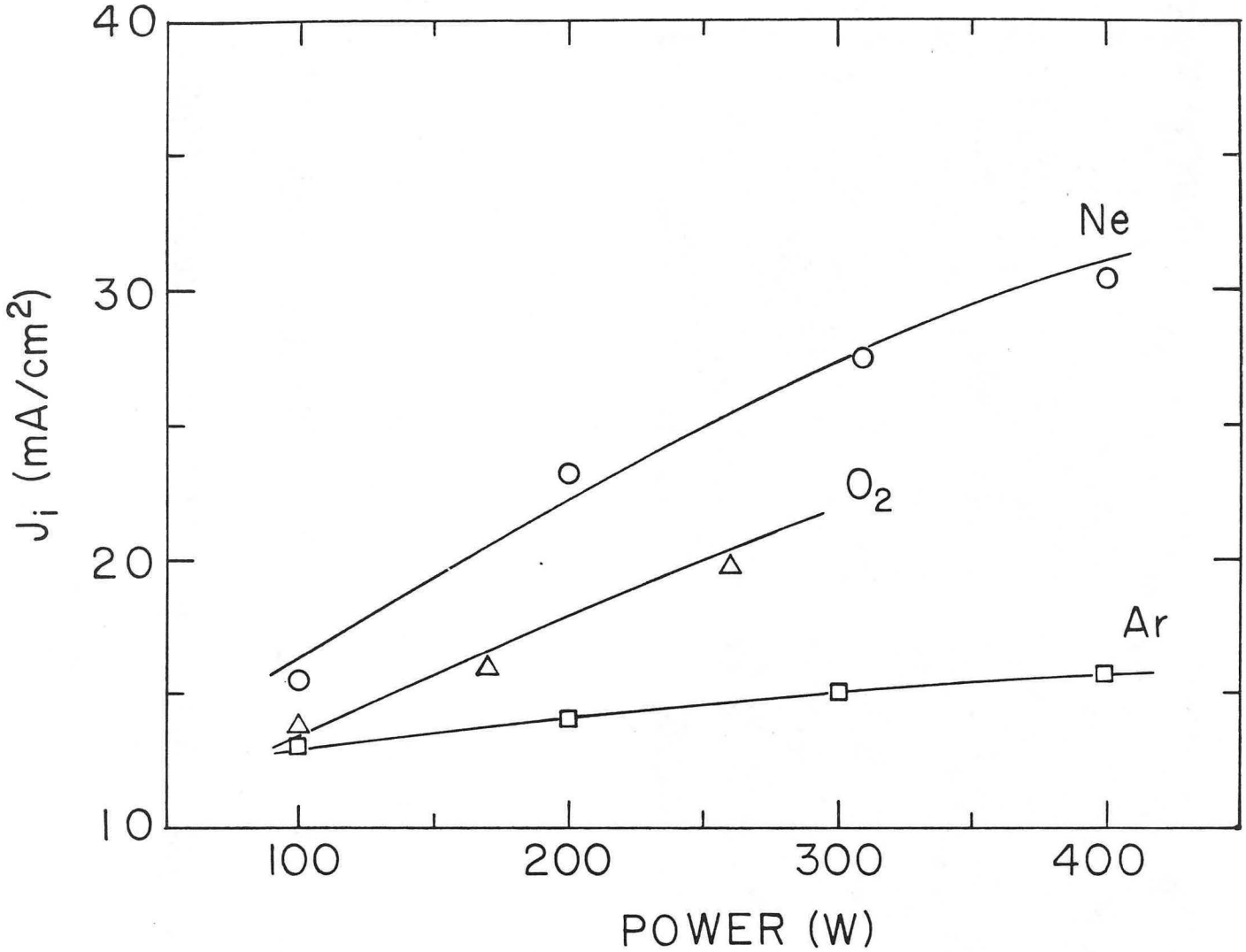


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Fig. 9

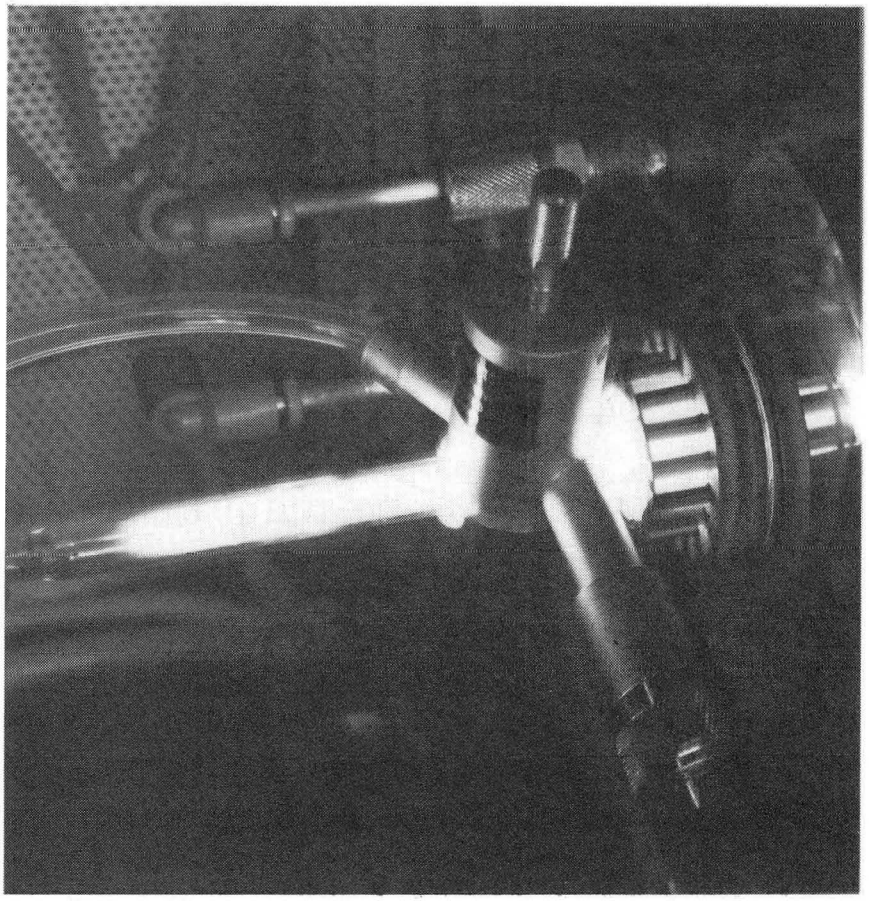

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Fig. 10

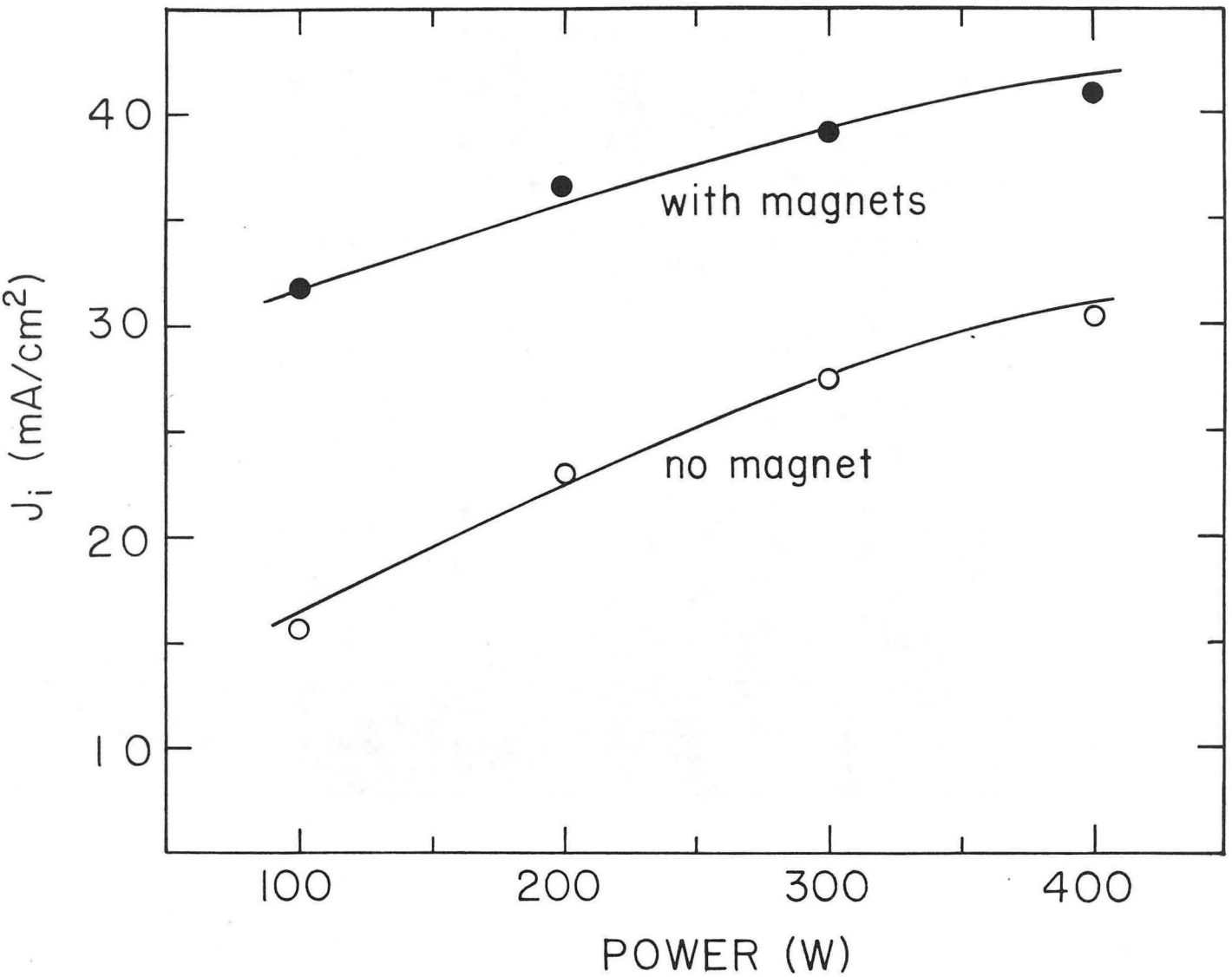

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Fig. 11

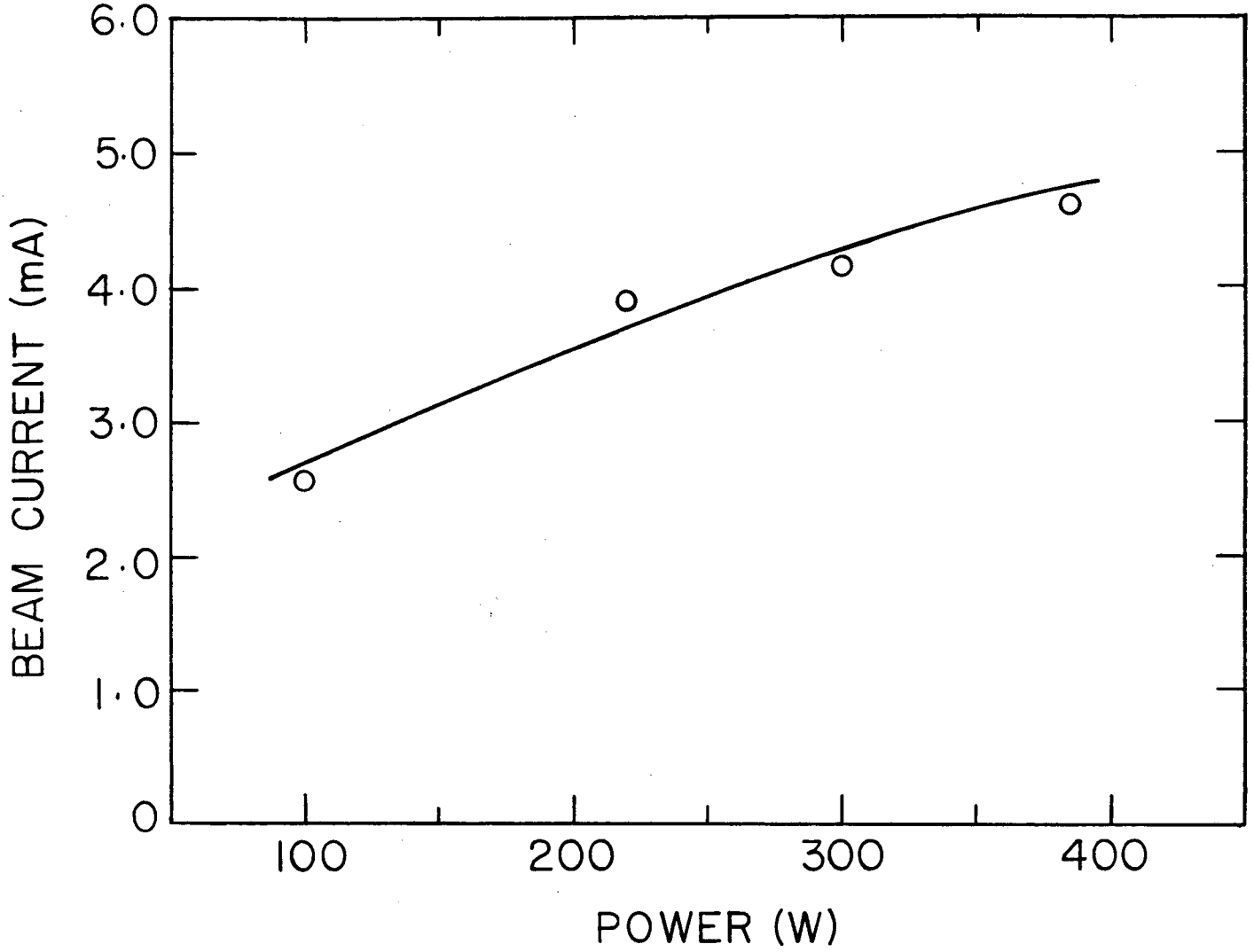

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Fig. 12

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