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DIAGNOSTICS OF A SUPERSONIC PLASMA STREAM USING AN IMMERSED MICROWAVE PROBE

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16. Abstract

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SYMBOLS

c	speed of light, 3.0×10^{8} m/sec
e	electron charge, 1.60×10^{19} C
E_i	incident signal, V/m
E_t	transmitted signal, V/m
H_{av}	mass average enthalpy, MJ/kg
I	relative incident power, W
$\bar{k}$	averaged wave number
$k = (\omega/c)\sqrt{\epsilon/\epsilon_o}$	complex wave number
k_i	Im (k)
$k_o = \omega/c = 2\pi/\lambda_o$	free space wave number
k_r	Re (k)
l	thickness of plasma slab under test, m
m	electron mass, 9.11×10^{-31} kg
$\dot{m}$	mass flow rate of the plasma stream, kg/sec
n_e	electron density, m^{-3}
P_I	electrical power input, W
P_L	power loss due to heat conduction to the cooling water, W
P_t	interference signal
T^2	relative transmitted power
$\Delta\phi$	phase shift, radians
ϵ_o	free space permittivity, 8.85×10^{-12} F/m
ϵ/ϵ_o	relative dielectric constant
θ	phase, radians

λ_o	free space wavelength, m
ν	collision frequency, collisions/sec
$\omega/2\pi$	operating frequency, Hz
$\omega_p/2\pi$	plasma frequency, Hz

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SUMMARY

A microwave interferometer to measure electron density and collision frequency profiles in a superonic plasma jet is described in this report.

Unlike most plasma diagnostic interferometers, both the transmitting and receiving horns were immersed in the plasma stream. Advantages and disadvantages of the immersed horn technique are discussed. The measurements were made primarily by a 70 GHz system; another system operating at around 35 GHz was used to check the results at certain points. The measured densities ranged from 10^{12} to 6×10^{13} cm^{-3}, and the collision frequency was nominally 10^{10} sec^{-1}. Despite the formation of shock waves around the horns, the measured densities compared well with the results obtained from a different microwave measuring technique which is described.

INTRODUCTION

The purpose of the investigation was to develop a microwave interferometer system that could be used to measure the radial profiles of the electron number density and collision frequency in a supersonic plasma jet. Normally, microwave interferometry is used to measure the average electron number density and the collision frequency across the width of a plasma by placing probing horns outside of the plasma. Such a technique was used, for example, by Waller (ref. 1) in the study of supersonic plasma streams. In the current investigation, however, the microwave probes (horns) were immersed into the plasma so that localized measurements could be made. Other than having the probes immersed in the plasma stream, the technique used was the standard interferometric technique of deducing the electron number density and collision frequency from the amplitude and phase of the transmitted signal. There is little documentation of previous experience with immersed probe techniques.

Kelley, et al. (ref. 2) compared measurements from immersed microwave probes with those from Langmuir probes. They reported agreement of the results to within a factor of 2. Their measurements were made on the exhaust of an MPD source with electron densities ranging from 2×10^{12} cm^{-3} to 7×10^{12} cm^{-3} and the flow velocity at about a Mach number of 1.

Two microwave systems were used in the current study, one capable of operating between 68 and 72 GHz and the other between 27 and 40 GHz. The higher frequency system was used to obtain most of the data, while the lower frequency system provided a means to check the results at lower densities. The measurable electron density range of the 68-72 GHz system was from 1×10^{12}

to 6×10^{13} cm^{-3}, and the 27-40 GHz system could measure densities to about 1.5×10^{13} cm^{-3}. The measurements were made using argon and nitrogen gases in a constricted-arc supersonic jet facility at Ames Research Center (ref. 3).

THEORETICAL BASIS

For an electromagnetic wave of frequency $\omega/2\pi$ propagating through a plasma slab with no external fields applied, the effect of the plasma can be described by a complex dielectric constant given by reference 4.

$$\frac{\varepsilon}{\varepsilon_o} = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2} - i \frac{\omega_p^2}{\omega^2 + \nu^2} \frac{\nu}{\omega} \tag{1}$$

Plasma frequency is related to the electron number density by the equation

$$n_e = \frac{\varepsilon_o m \omega_p^2}{e^2} \tag{2}$$

Ignoring the boundary effect and the multiple reflections, a plane electromagnetic wave going through a uniform plasma slab of thickness l undergoes a phase and amplitude change approximated by the following relation

$$\frac{E_t}{E_i} = \exp(-ikl) \tag{3}$$

Equation (3) is found to be a very good approximation to the exact solution whenever $\nu/\omega \geqslant 0.01$ (ref. 5) and $l/\lambda > 3$ (ref. 6). From equation (3) the phase shift and attenuation of the transmitted signal relative to the case of no plasma are given by

$$\Delta\phi = (k_o - k_r)l \tag{4}$$

$$T^2 = \exp(-2k_i l) \tag{5}$$

Equations (4) and (5) relate k_r and k_i to the measurable parameters T^2 and $\Delta\phi$. From k_i and k_r, the relative dielectric constant of the plasma can be obtained from the relation

$$\frac{\varepsilon}{\varepsilon_o} = \frac{1}{k_o^2} (k_r - ik_i)^2 \tag{6}$$

which in turn can be related to the density and collision frequency. Given in terms of k_i and k_r, the electron density and collision frequency are as follows:

$$n_e = \frac{\varepsilon_o m}{e^2}\left(1 - \frac{k_r^2}{k_o^2} + \frac{k_i^2}{k_o^2}\right)(\omega^2 + \nu^2) \tag{7}$$

$$\nu = \frac{2\omega k_i k_r}{k_o^2 - k_r^2 + k_i^2} \tag{8}$$

Equations (7) and (8) were obtained under the assumption of a homogeneous plasma: In a practical plasma, the density is never exactly uniform. However, as long as the distance over which the parameters vary is much larger than the wavelength of the microwave signal, equation (3) can be modified as follows (ref. 7):

$$\frac{E_t}{E_i} = \exp\left(-i \int_o^l k(z)dz\right) \tag{9}$$

and if an averaged wave number is defined so that

$$\bar{k} = \frac{1}{l} \int_o^l k(z)dz \tag{10}$$

then equation (9) becomes

$$\frac{E_t}{E_i} = \exp(-\bar{k}l) \tag{11}$$

In practice equation (10) is used to compute the density and collision frequency because of the lack of knowledge regarding the uniformity of the plasma. By measuring the phase and the attenuation of the signal, an averaged wave number $\bar{k}$ is obtained from which the "averaged" electron density and collision frequency are computed.

APPARATUS

Figure 1 is a schematic diagram of the constricted-arc supersonic jet facility at Ames Research Center. The plasma was generated by a direct current electric arc from a cathode located in the plenum chamber through a 1.27-cm-diameter constrictor, or throat region, to the 23 anodes located near the exit of a 15° half-angle conical nozzle. The plasma at the exit nozzle has a 15.4-cm diameter. The test chamber into which the plasma stream flows has a volume of approximately 1 m^3 and is kept at about 0.2 mm Hg pressure when the test is being run. All the profile measurements were taken about 10 cm downstream from the nozzle, and the stream velocity was about Mach 3.

The 70 GHz interferometer system used was tunable from 68 to 72 GHz and it used a klystron source enclosed in a container, which allowed the source to be operated within the test chamber. The container had an air inlet and outlet for cooling purposes. The outlet also served as a passage for the wires to the klystron from the power supply outside the test chamber. To avoid electrical breakdown, the klystron container was kept at atmospheric pressure. The microwave plumbing, including the klystron, phase shifters, attenuators and horns, was placed on a movable carriage within the test chamber. The carriage was pneumatically controlled so that the horns could be moved laterally through the plasma stream as well as along it. Carriage speed was controlled so that the probes moved laterally through the stream and back before being excessively heated.

The Ka band system, covering the 27 to 40 GHz frequency range, used a backward wave oscillator (BWO) for a source. For this system, the source was kept outside the chamber and the microwave power was fed into the chamber by means of flexible wave guides. The rest of the equipment was on a movable carriage as in the 70 GHz system.

One of the probes used in the experiment is shown positioned in front of the nozzle in figure 2. The horns are protected by the splitter plates, and the horn opening can be seen on the bottom plate. The splitter plates are 3.5 cm wide with a 15° angle on the leading edge and are made of Invar, which has a low coefficient of thermal expansion. Asbestos board protects the microwave plumbing from the heat. The spacing between the probes can be adjusted from 0 to 18 cm, allowing measurements to be made with the probes totally outside of the stream.

Figure 3 is a schematic diagram of the microwave interferometer. Silicon crystal detectors measured the transmitted power (T^2), reference power (I^2), and the sum of the transmitted and reference signals (P_t) to give the phase shift information. The outputs from the detectors were fed into a Hewlett-Packard 415 SWR meter and from there into an oscillograph recorder. The signal from the source in both systems was modulated with a 1000 Hz square wave so that the SWR meter with ac coupling could be used to minimize the dc ground loop problems.

To prevent detuning of the microwave system as the plasma facility was pumped down to the operating pressure, a motor-driven attenuator and phase shifter were put into the 70 GHz system and remotely controlled from outside the test chamber. In this way, the system could be recalibrated under vacuum at any time. The Ka band system was not provided with the motor-driven phase shifters or attenuators, and accordingly, with the chamber evacuated, this system could only be tuned with difficulty by shifting the microwave frequency.

EXPERIMENTAL PROCEDURE

Initially, the horn assembly was positioned outside of the plasma stream. The attenuators and phase shifters were adjusted so that the phase and the power level of the transmitted signal were at predetermined values. The information on the phase of the transmitted signal was obtained from a square law detector, which squared the sum of the reference and transmitted signals. If I and T are the amplitudes of the reference and transmitted signals, respectively, the output of the square law detector gives

$$P_t = I^2 + T^2 + 2IT \cos(\theta + \Delta\phi) \tag{12}$$

where θ is the initial phase difference between the reference signal and the transmitted signal. (Refer to fig. 3 for measurements of P_t, T^2, and I^2.) The phase shift $\Delta\phi$ was caused by the presence of the plasma between the horns (see eq. (4)). To simplify the data analysis, the transmitted signal amplitude T was initially set equal to I and θ was set to π. Furthermore, since I could be held constant during the measurement, P_t was read in a normalized form such that I was arbitrarily set to unity. With these initial settings, P_t was given by

$$P_t = 1 + T^2 - 2T \cos \Delta\phi \tag{13}$$

Outside the plasma stream, $\Delta\phi = 0$ and $T = 1$; hence, $P_t = 0$. As the horns are introduced into the stream, both T and $\Delta\phi$ change. Since T^2 was measured directly by another square law detector, $\Delta\phi$ could be obtained from P_t (see eq. (13)).

As the probe went in and out of the plasma stream, P_t, T^2, I^2, and the position of the probe were recorded. The total phase shift $\Delta\phi$ could not be attained by given values of P_t and of T^2 alone, since $\Delta\phi$ can go through a multiple of 2π radians as the probe penetrates the plasma stream. However, by tracking P_t and T^2 as the probe moved across the plasma, the number of 2π radians in $\Delta\phi$ could be determined.

RESULTS AND DISCUSSION

Figure 4 shows profile plots of the electron density measured at operating frequencies of 70 GHz and 36.4 GHz for a horn spacing of approximately 2.5 cm. These measurements were taken with the same horn assembly. Argon was used as the working gas at an arc current of 60 A and a plenum chamber pressure of 5 psia. The results obtained at the two frequencies agree to within 15 percent at the centerline.

Unfortunately, it was found that under typical operating conditions of the jet, the electron density was above the cutoff density for the Ka band system. Thus, it was possible to compare the results obtained by the two systems only at very low density conditions.

An important parameter used often in the arc-jet studies is the mass average enthalpy of the stream. This parameter gives a measure of the energy content of the stream and is obtained by considering energy conservation for the system as follows:

$$H_{av} = \frac{P_I}{\dot{m}} - \frac{P_L}{\dot{m}} \tag{14}$$

Figure 5 shows the centerline electron densities and collision frequencies obtained from the measurements taken with the 70-GHz system as functions of H_{av} with plenum chamber pressure kept at 1 atm. Also on the abscissa are the corresponding arc currents. The working gas for this case was argon. Similar curves obtained for nitrogen are shown in figure 6. No other independent measurement was available for comparison for the above cases. The collision frequency is estimated to be only within one order of magnitude of the actual average value since it depends strongly on the transmitted signal loss through the plasma between the horns. In the calculations to determine the collision frequency, all the signal energy loss was assumed due to absorption within the plasmas, not to other loss mechanisms such as reflection or refraction. The reflected power at the transmitting horn was monitored in some of the first measurements made, and it was normally more than 10 dB down from the incident power.

The graphs of figure 7 show centerline densities as functions of the arc current for the case of 5.0 psia plenum chamber pressure using argon as the working gas. The results are compared with those obtained by another independent microwave technique, devised by Carlile, et al. (ref. 8), in which the transmitting horn stays outside the plasma stream and only the pickup probe is immersed. The pickup probe is designed to detect the microwave signal at the tip of a sharp, pyramid-shaped probe. The probe tip, made of boron nitride, is pointed against the stream. In this way, the microwave signal propagates mostly through the free stream and only through a thin shock layer attached to the probe tip. The two sets of results generally agree to within 25 percent and the Carlile probe data give lower values, since in his technique, the free-stream condition is preserved to a greater degree.

Repeatability of the measurements was checked by making the same measurement 10 times on a continuously running plasma. Argon was used with 80 A arc current and 1-atm plenum chamber pressure. The density measurement near the stream center was repeatable within 5 percent, and the collision frequency within 20 percent.

A major difficulty with any measurement technique utilizing physically immersed probes in a rapidly moving plasma is the formation of shock waves and the consequent perturbation of the free-stream conditions. It was hoped that splitter plates would cause the shock wave formed around the horns to perturb the flow only negligibly and that the condition in the area between the horns would not differ much from the free-stream condition. However, the perturbation due to the immersed probe was visibly noticeable. Figures 8(a) and 8(b) are photographs of the actual plasma stream during a test. The horn spacing in figure 8(a) is 3.04 cm; the shock layer around each splitter plate can be seen easily. In figure 8(b) the spacing is 1.9 cm. At this spacing, the region between the two horns is completely occupied by the shock layer. The effect of the horn separation was studied by taking density measurements at different horn spacings. Since the electron density behind the shock front is higher than that in the free stream, the average density between the horns decreased with increased separation.

Presumably, to obtain the free-stream density value, one needs only to increase the horn separation and thereby increase the free-stream flow between the horns. However, due to nonuniform density profiles and other factors such as density fluctuations and high collision frequencies, it is impractical to separate the horns more than about 8 free space wavelengths.

Under most of the operating conditions, the transmitted microwave signal was reduced considerably as the horns were moved through the stream edges. Presumably, the signal loss was due largely to the high collision frequency and also to the high density inhomogeneities at the stream edges. The density inhomogeneities cause a large refraction of the incident microwave signal. With a large horn separation, that is, horns outside the stream, the signal was invariably cut off as the horns moved across the edge of the stream. Although with the large horn separation the signal reappeared as the probe moved closer to the stream centerline, the information on the total phase shift was lost due to loss of the signal at the edge. Density fluctuations also tended to destroy the data for wide horn spacings. Oscilloscope and spectrum analyzer studies showed that at certain operating conditions, electron densities fluctuated as much as 10 percent with random fluctuation frequencies in the range of near 0 to 30 kHz. Since P_t is detected in the time averaged sense, a rapid density fluctuation can destroy the phase information for wide horn spacings. Thus, to obtain good measurements, it is necessary to adjust the horn spacing to minimize these detrimental effects.

CONCLUDING REMARKS

The main advantage of the immersed probe technique is the ability to make localized measurements. Its major disadvantage is the interference from shock waves altering the flow condition. Despite the visible shock formation, however, it was found that the electron density results obtained by the 70-GHz system compared well with the results from the microwave technique developed by Carlile, et al. (ref. 8). Generally, Carlile's technique yielded slightly lower densities. The collision frequency results were considered to be of little value because of the inability to account for the various loss mechanisms accurately.

It appears that better results could be obtained by using a smaller probing horn assembly to reduce the perturbation and by moving the horn opening closer to the wedge tip to reduce the thickness of the shock region through which the microwave signal passes. Usefulness of the probing scheme described in this report would be enhanced considerably if the relationships between the free-stream conditions and the conditions behind the shock wave could be established theoretically.

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Moffett Field, Calif., 94035, April 24, 1970

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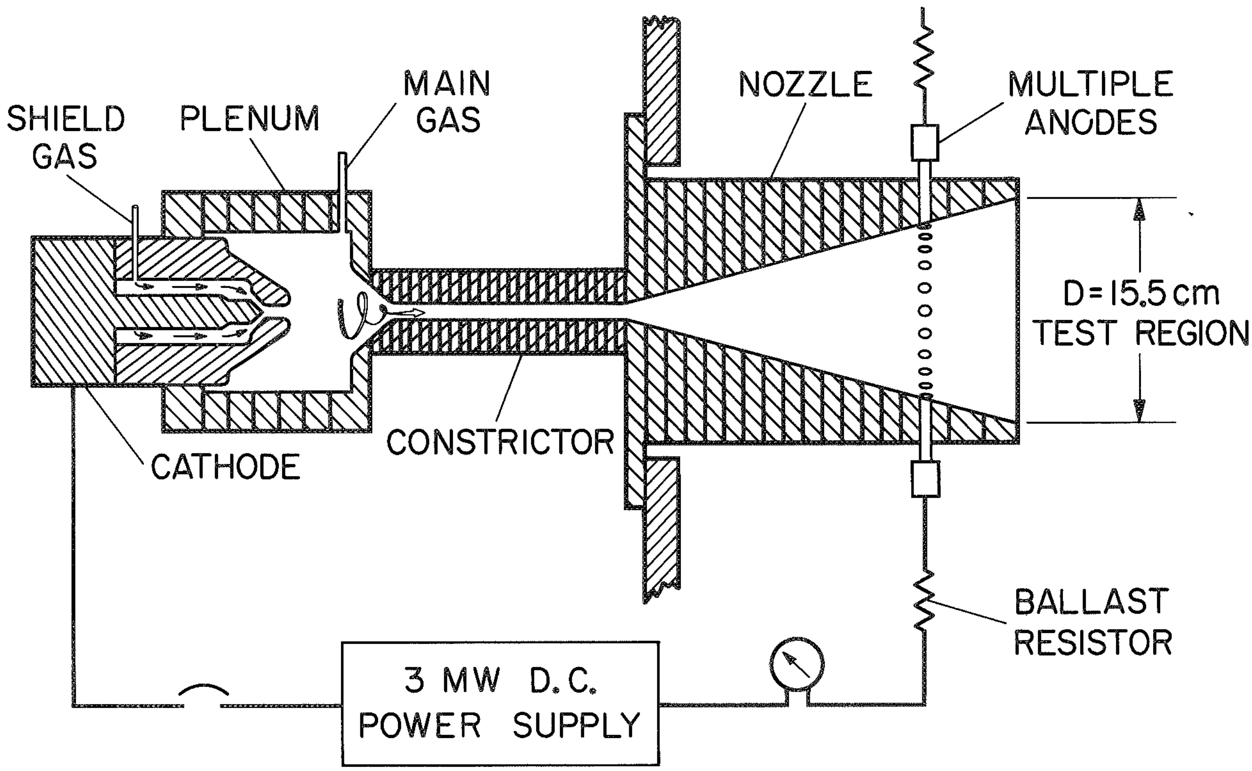

Figure 1.- Schematic drawing of the 1.27-cm-diameter throat low-density constricted-arc supersonic jet.

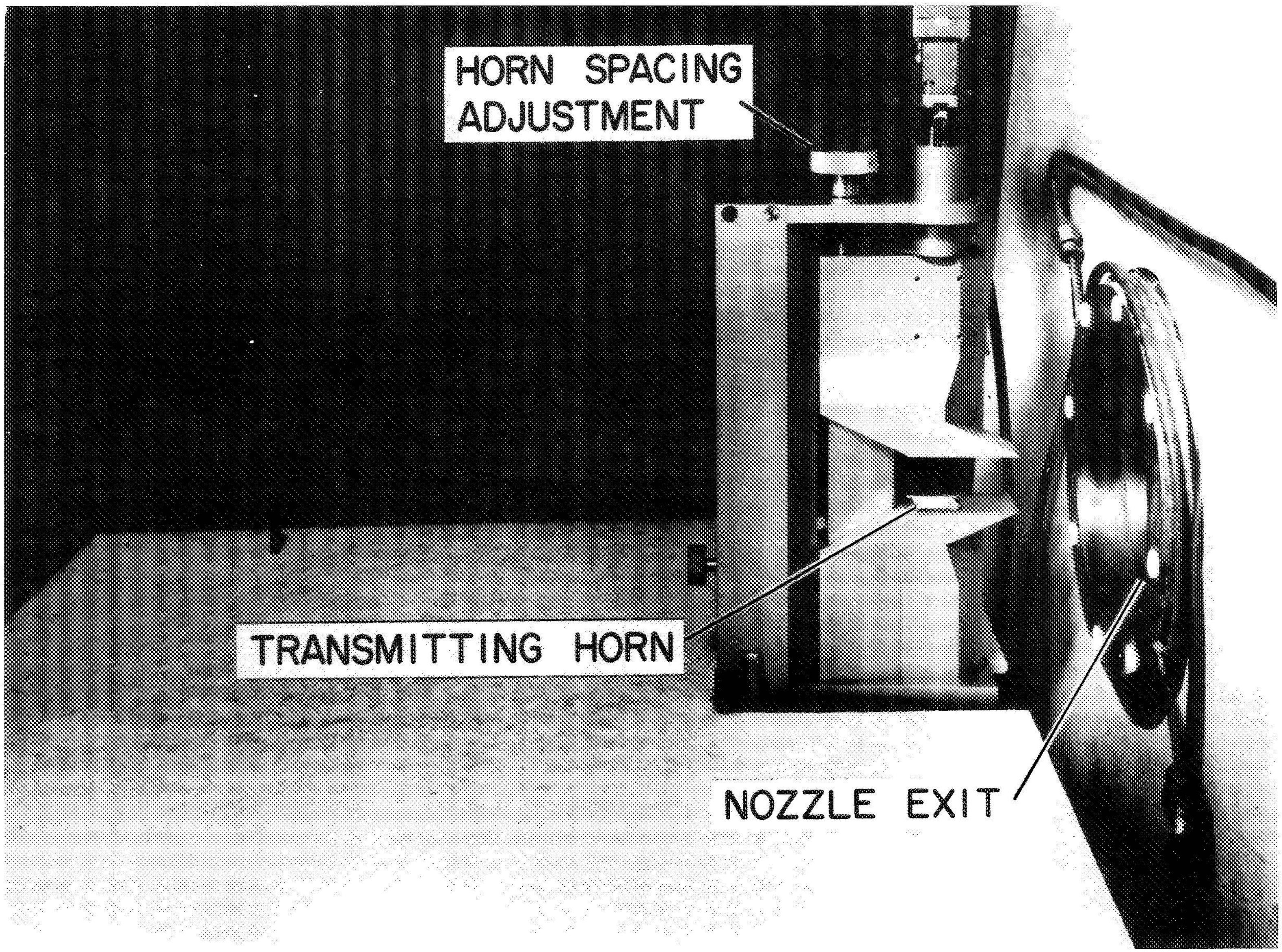

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Figure 2.- Microwave plasma diagnostic probe.

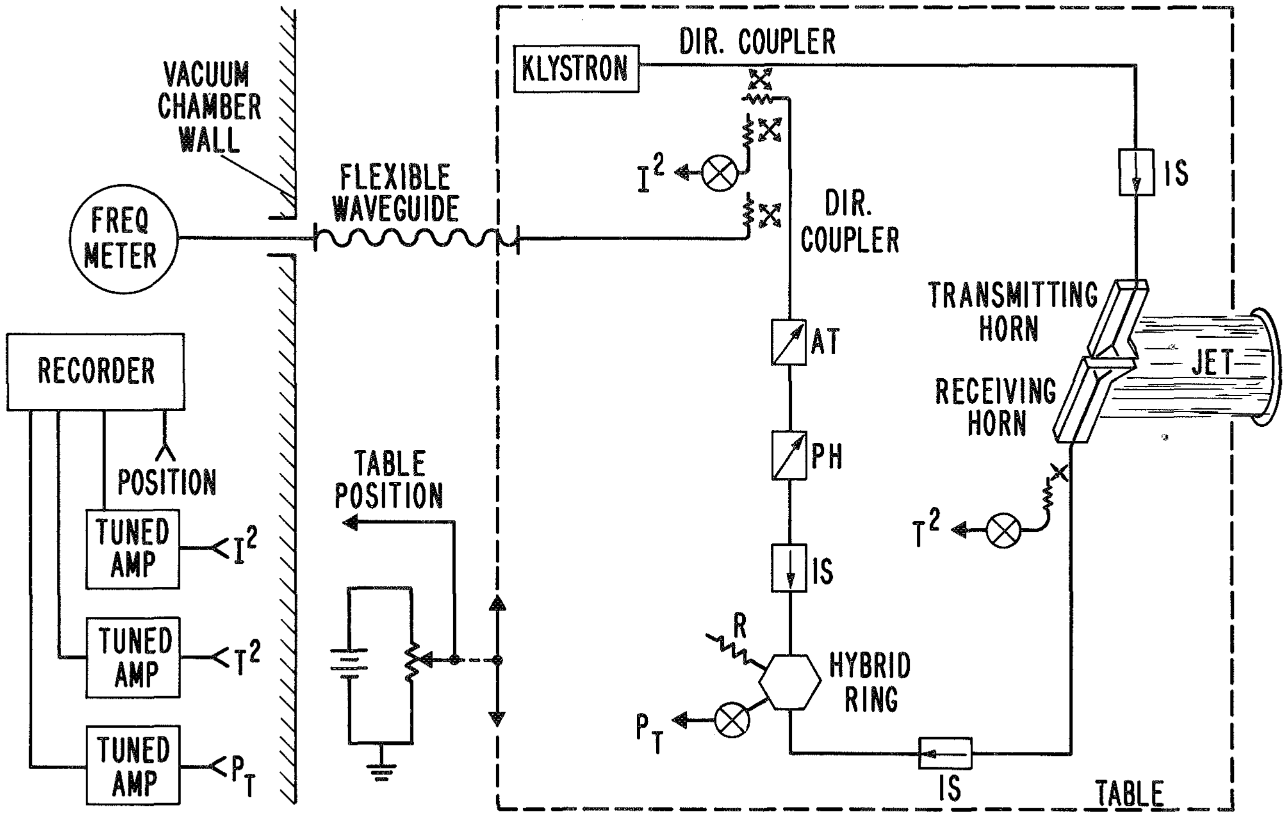


Figure 3.- Microwave circuit. At, motor driven attenuator; PH, motor driven phase shifter; T^2, transmitted power; I^2, incident power; R, matched load; P_T, interference signal; IS, ferrite isolator; X, tuned crystal detector.

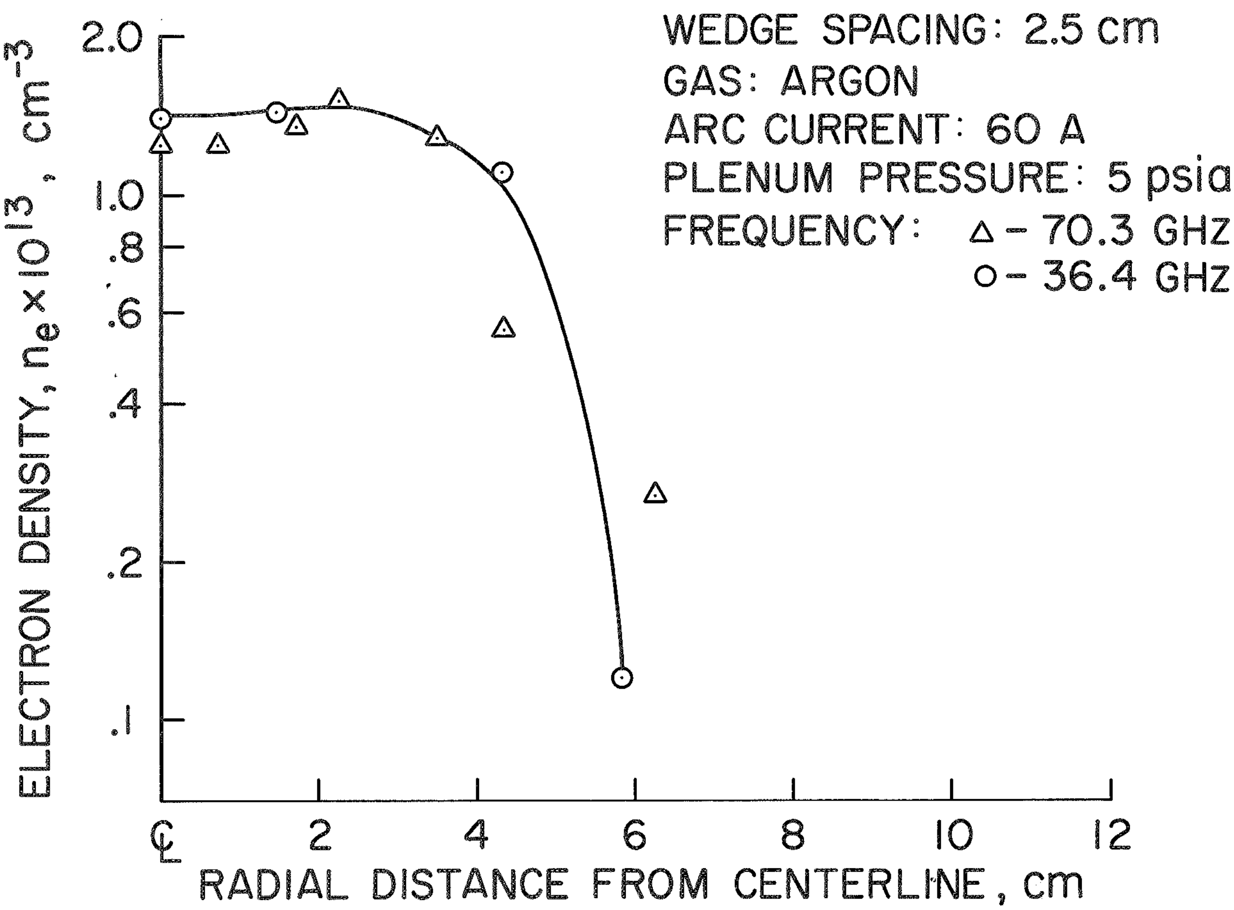


Figure 4.- Electron density profile on diameter of plasma stream.

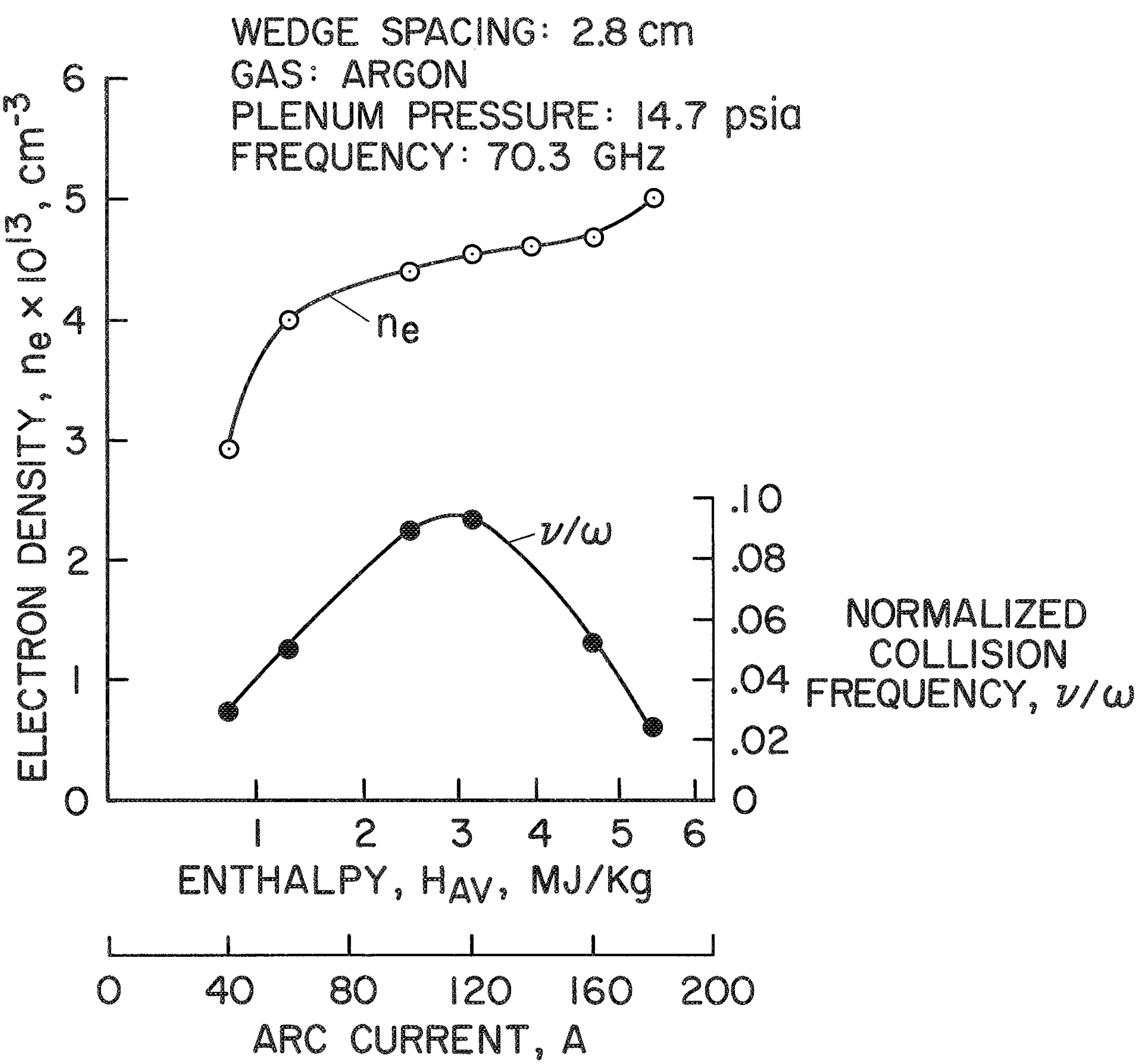


Figure 5.- Electron density and collision frequency on stream centerline as a function of average enthalpy and arc current.

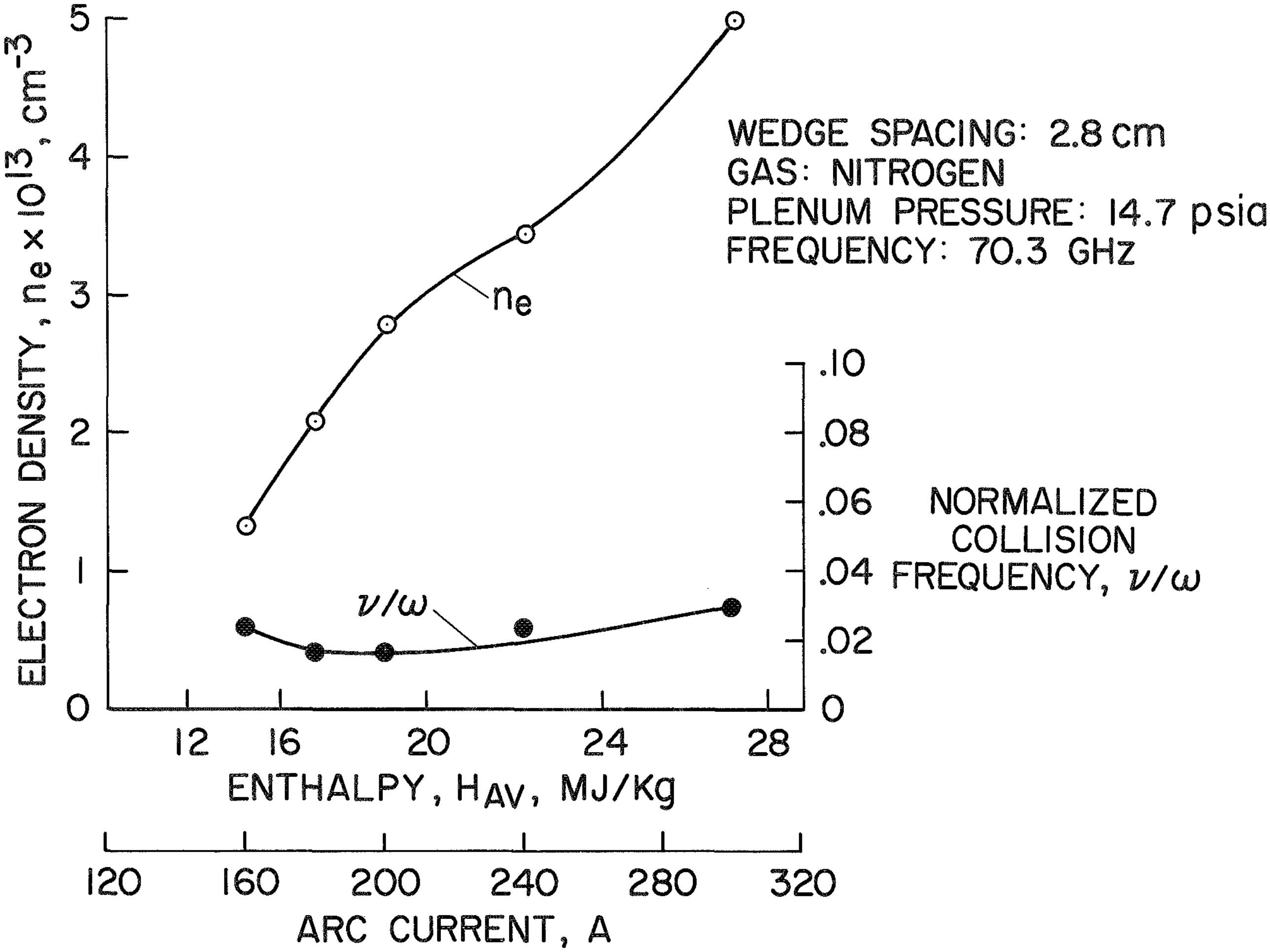


Figure 6.- Electron density and collision frequency on stream centerline as a function of average enthalpy and arc current.

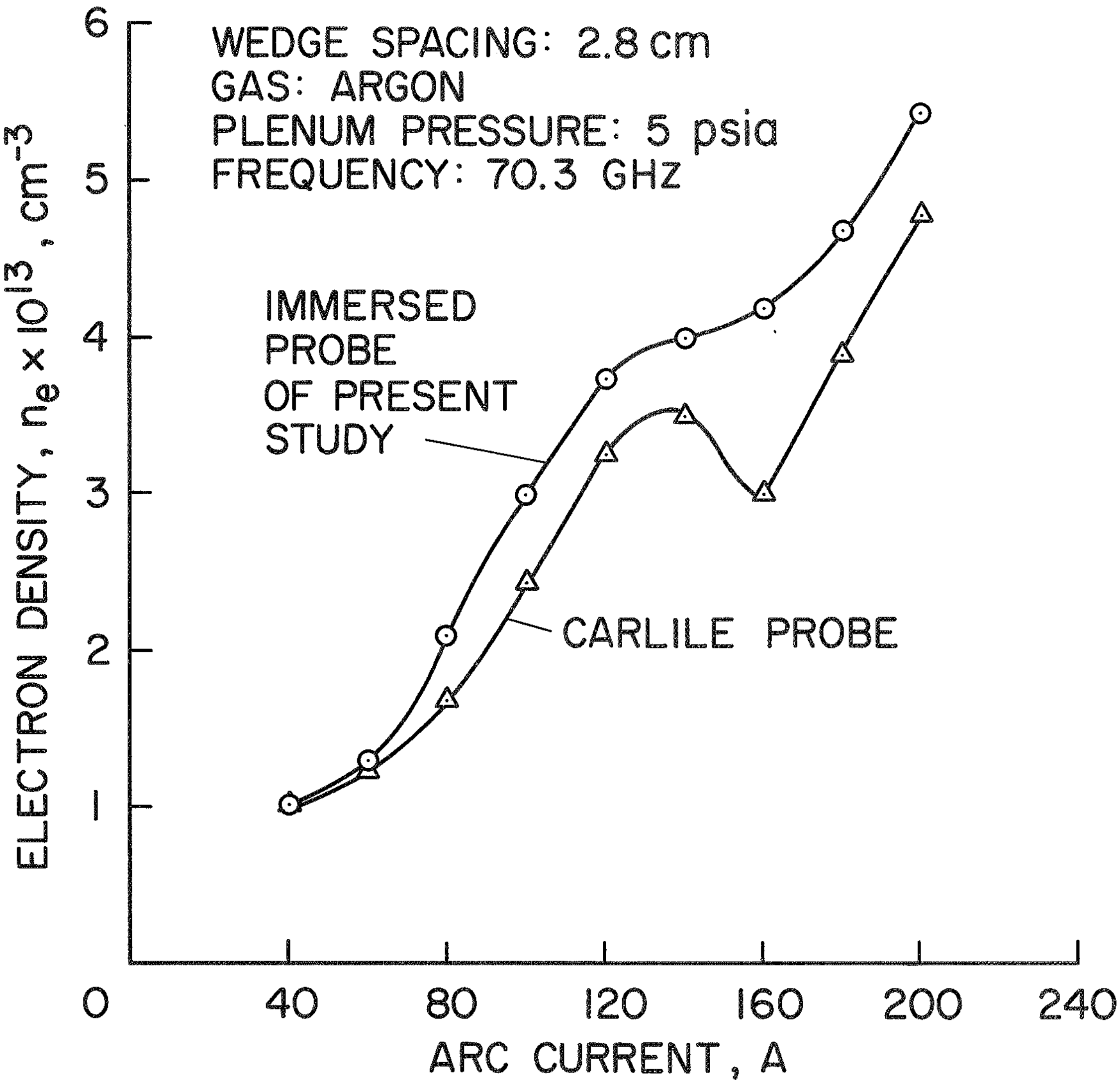
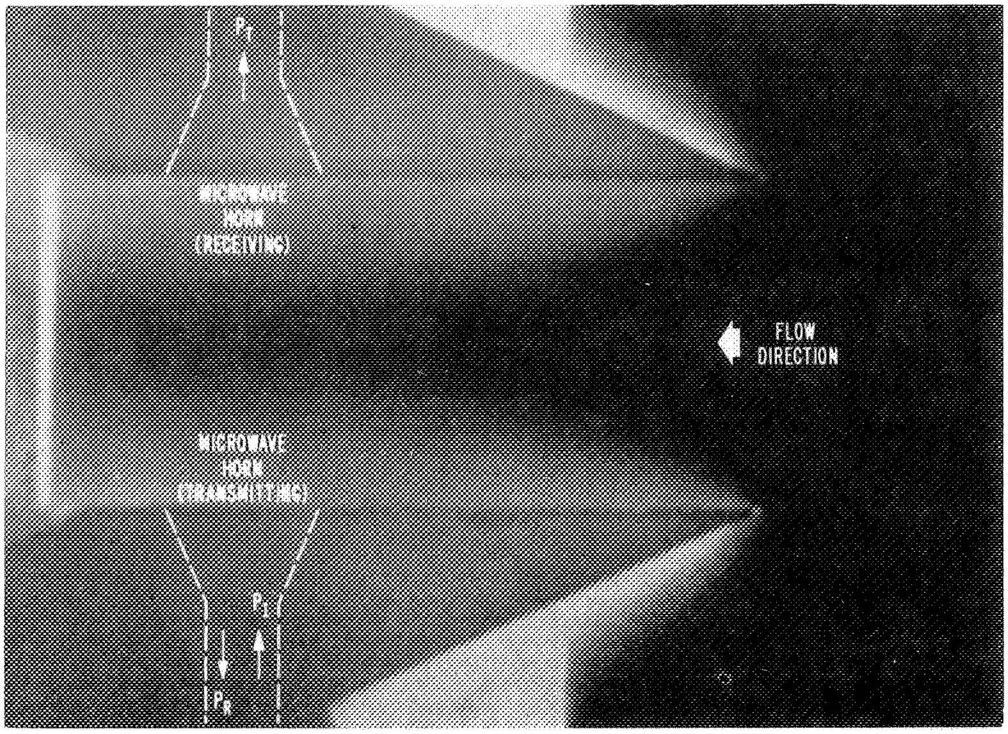


Figure 7.- Electron density on stream centerline as a function of arc current.



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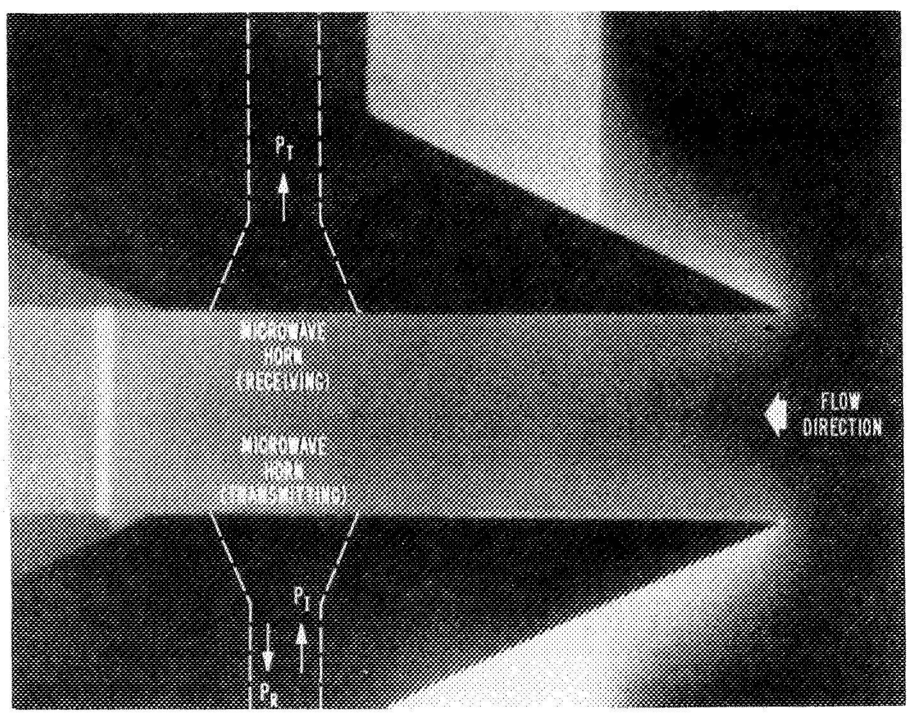
(a) Horn spacing, 3.04 cm.



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(b) Horn spacing, 1.91 cm.

Figure 8.- Plasma flow.

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