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SPATIAL ELECTRON DENSITY AND ELECTRIC FIELD STRENGTH MEASUREMENTS IN MICROWAVE CAVITY EXPERIMENTS*

by

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Abstract

Measurements of electron density and electric field strength have been made in an argon plasma contained in a resonant microwave cavity at 2.45 GHz. Spatial measurements of electron density, n_e , are correlated with fluorescence observations of the discharge. Measurements of n_e were made with Stark broadening and compared with n_e calculated from measured plasma conductivity. Additional measurements of n_e as a function of pressure in mixtures of argon and oxygen are presented for pressures from 10 Torr to 1 atm. Measurements in flowing gases and in static systems are presented. In addition, limitations of these measurements are identified.

Introduction

In an earlier study Rogers¹ measured properties of microwave filamentary argon discharges created inside microwave cavities. The general properties, such as electron density, effective collision frequency, etc., of these discharges were investigated as a function of cw microwave power (10-150W) at 2.45 GHz, argon gas pressure (40-1,200 Torr) and discharge geometry. Photographic and electromagnetic probing measurements were combined with conventional microwave circuit measurements to yield average discharge complex conductivity from which discharge average electron density and effective collision frequency could be calculated. Brake et al.² have measured the electron density using the Stark broadening technique and compared it with the work of Rogers^{1,3} for surface wave plasmas. Following this work, the goal of the present study has been to perform point measurements of the electron density using Stark broadening and to correlate these measurements with the observations of Rogers¹ in order to gain insight into the coupling of electromagnetic energy to such plasmas with an ultimate goal of coupling electromagnetic energy more effectively into solids and liquids in microwave systems as well.

Experimental Apparatus

The experimental cavity, shown in Figure 1, consists of a 17.8 cm i.d., brass cylinder, a sliding short and adjustable excitation probe to provide tuning required to minimize reflected power. The argon gas was contained inside a 4 mm i.d. quartz tube that passed axially through the cavity.

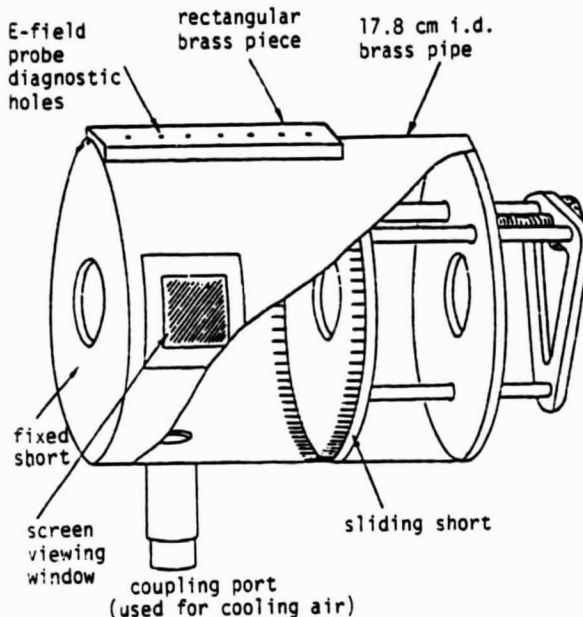


Figure 1. Cylindrical microwave cavity (from ref. [1]).

The cavity was oriented so that its axis was vertical and was ignited with 2.45 GHz microwave power in the TM₀₁₂ mode for all the experiments. A detailed description of the cavity and the expected resulting electromagnetic field distributions are given by Rogers¹. A schematic diagram of the cavity and the microwave circuit are shown in Figure 2. The input system consisted of a continuously variable 0-500 W cw 2.45 GHz oscillator, three port circulator, matched load, and directional couplers leading to two power meters which measure incident power, P_i , and reflected power, P_r . Thus, power coupled into the cavity is given by $P_i - P_r = P_a$. Earlier measurements¹ have shown that under the experimental conditions discussed here, 97% or more of the power coupled into the cavity is actually absorbed by the discharge.

Microcoaxial (0.08 in. o.d.) E field probes were either inserted through small, tightly fitting holes drilled in the cavity side walls as shown in Figures 1 and 3 or were placed through a long narrow slot cut axially in the outer cavity cylinder. This slot allowed continuous sampling of the cavity electric field vs axial position.

The spectral and optical measurements were made through a screened viewing port soldered into the cylindrical wall of the cavity. This viewing port is different from the one shown in the cavity

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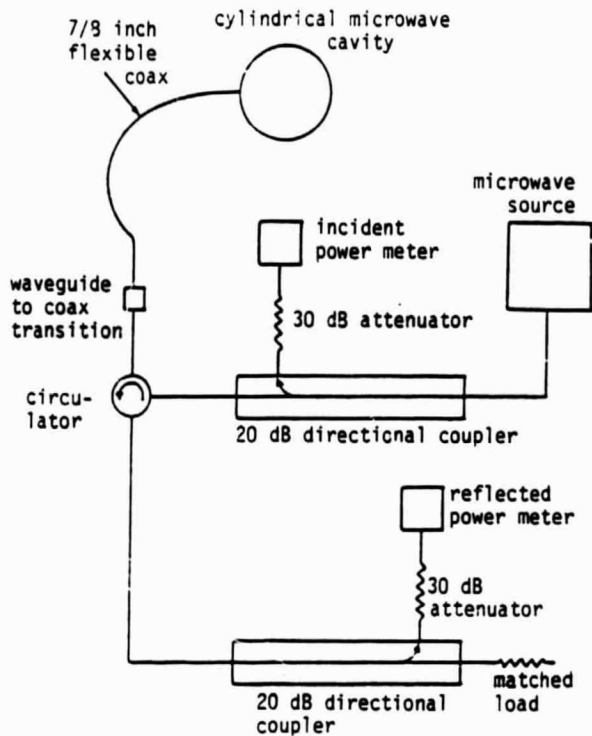


Figure 2. Experimental microwave circuit (from ref. [1]).

in Figure 1. It consisted of a 3cm by 7cm screened slot cut axially in the outer cavity cylinder. Thus, during experimental runs, the microwave filamentary discharges could be viewed axially, and optical point measurements could be performed through this window axially along and radially through the discharge.

The light emitted from the plasma was gathered with two 3.7 cm diameter lenses with focal lengths of 25 cm. The first lens was placed 25 cm from the discharge, and the second lens was placed 25 cm from the entrance slit of the spectrometer leaving approximately 50 cm between the lenses. At the exit slit of the grating spectrometer (Spex, No. 1704, f9, 1 meter, Czerny Turner) was a high quantum efficiency photomultiplier tube, PMT (EMI 9658R). The output of the PMT was read on a digital pico-ammeter (Kiethley 480) and a strip chart recorder (Bristol 71A-4PG). The spectrometer, lenses and microwave cavity were aligned with a $H_e - N_e$ laser at the exit slit of the spectrometer. The hydrogen H_β line at 4861 Å was used to determine the electron density. There was enough residual H_2 in the argon bottle (99.8%) to measure the linewidth. The full width at half height (fwhh) was measured and the contribution of the Doppler and instrument broadening to the line were used to "deconvolute" the measured linewidth using tables of the Voigt profiles⁴. From earlier studies, the translational temperature was assumed to be 1000°K for determination of the Doppler width⁵. The instrument broadening was determined during each set of experiments by measuring the width of the argon line at 4200 Å which has negligible Doppler and Stark broadening. The electron density was determined from the expression

$$n_e = C(n_e, T_e) \Delta \lambda_s^{3/2} \quad (1)$$

where the values of $C(n_e, T_e)$ were taken from Griem⁶. The electron temperature, T_e was assumed to be 10,000°K from previous studies⁵; however, the value of $C(n_e, T_e)$ and the resulting value of n_e are very insensitive to these assumptions made with regard to T and T_e . A more detailed description of this apparatus, the calibration technique and the significance of these assumptions is given by Brake⁵.

Results

Results of the measurement of the electron density as a function of axial position are shown in Figure 4 along with the plasma fluorescence as recorded by the camera. The electron density is constant vs length at a value of $\sim 10^{14}/\text{cm}^3$. The electron density clearly dips at the node of the field; however, the existing apparatus did not permit sufficient spatial resolution to follow it through the node. Experimental measurements with the E-field probes shown in Figures 1 and 2 indicate that maintaining a discharge filament in the cavity reduces the TM_{012} loaded cavity Q from $\sim 3,000$ - $6,000$ without a filament to 50-100 in the presence of a filamentary discharge. Thus, for a given cavity input power the square of the electric field strength inside the cavity decreases by ~ 50 - 100 times when the plasma filament is loading the cavity. Slotted cavity experiments also yielded similar results. However, they also indicated that coupling from TM_{012} mode to surface filamentary modes is possible.

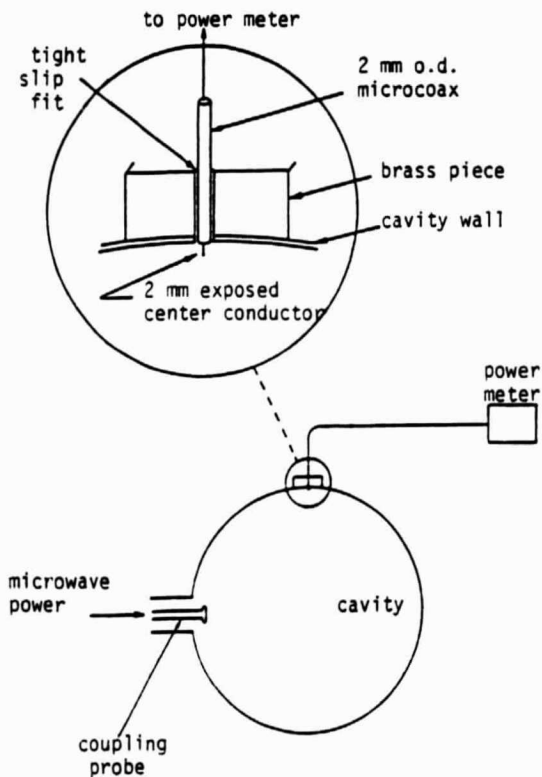


Figure 3. E-field probes and circuit (from ref. [1]).

The radial distribution of the electron density was also measured with Stark broadening and the value again appeared to remain nearly constant in the plasma region. However, it is strongly suspected that internal reflections produced this result; and, hence, we were not actually measuring the value of n_e as a function of radius but rather an average value. In viewing the onset of signal as a function of position, the spatial resolution appeared to be approximately 1 mm in the axial direction.

Since the constant value of n_e was counter to our intuition, several other measurements were made to check sensitivity of the measurements to various parameters. First, the value of electron density was measured as a function of pressure and compared with the measurements of Rogers¹. This comparison, shown in Figure 5, indicates that the Stark broadening values are a factor of 2 to 6 larger than the "average" electron densities measured by the conductivity method. For these measurements, the gas flow rate was lcc/sec and the power was tuned to the point of lowest reflected power in the TM₀₁₂ mode. The tuned absorbed power, P_a , ranged from 50-70 watts. A subsequent measurement of n_e showed that n_e was relatively insensitive to power, (see Figure 6). This insensitivity was also observed by Rogers¹. The optically observable variation in spatial dimensions of the plasma fluorescence is the most noticeable parameter to change during tuning.

Since these measurements take several minutes, the value of n_e was measured with Stark broadening under constant conditions over a period of time. For times less than 90 minutes, which is typically twice the length of most experiments, there was no change in the observed value of n_e . This is displayed graphically in Figure 7. After 90 minutes, the power supply would often overheat and shut off.

Finally, measurements of n_e using the Stark technique were made while the flow rate and the Ar/O₂ ratio were varied. As shown in Figures 8 and 9, these results indicate that over the parametric range shown, n_e is insensitive to flow rate and Ar/O₂ ratio. For smaller ratios of Ar/O₂, the plasma could not be sustained under these conditions.

Conclusions

An experimental study has been performed to examine the relative spatial distribution of electron density and electromagnetic fields in a resonant cavity. At a constant discharge pressure the electron density and electric field strength were observed to be nearly constant inside the discharge region. The electron densities measured with the Stark broadening method were 2-6 times larger than those inferred from the plasma conductivity. This difference can be explained in part by noting the difference between the two measurement techniques. The electromagnetic method of Rogers¹ measures the electron density averaged over the entire plasma volume. The plasma volume, determined from calibrated photography, was defined as that volume that emitted intense visible light. A more detailed knowledge of the actual plasma volume may resolve this difference in density measurements. The initial slotted cavity experiments also indicated that further, more detailed,

measurements and analysis is required to identify and understand the coupling of TM₀₁₂ mode power to other plasma cavity modes.

Using Stark broadening the measured electron density was found to be insensitive to the absorbed microwave power, Ar/O₂ ratios from 5 to ∞, and spatial position within the plasma. The electron density was a strong function of the gas pressure, and the physical size of the plasma was dependent on most parameters studied.

Acknowledgements

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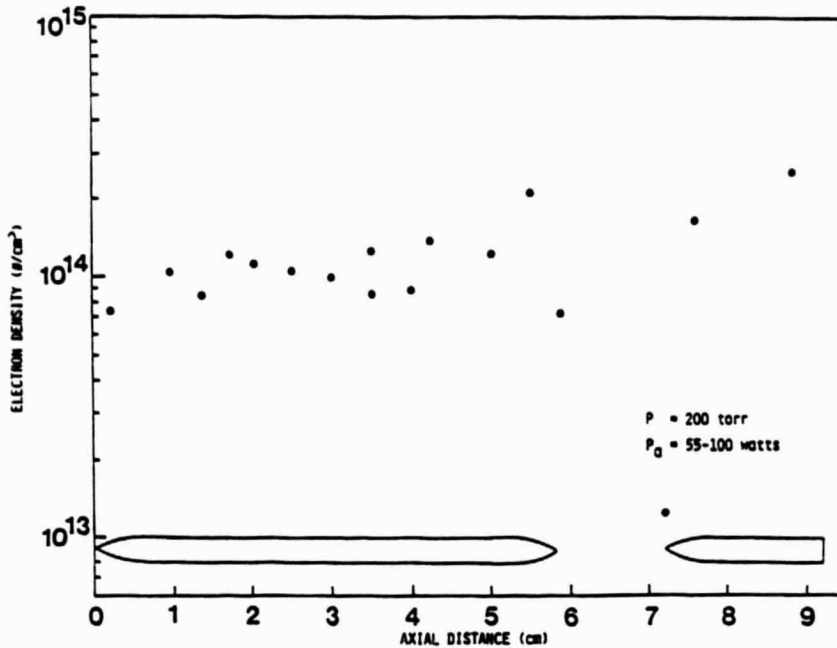


Figure 4. (a) Electron density vs. axial position as measured by Stark broadening at 200 torr. (b) A sketch of plasma fluorescence vs. length of the upper two parts of the plasma filament as it appears along the cavity axis. The absorbed power was tuned to 55-100 watts during the Stark broadening measurements.

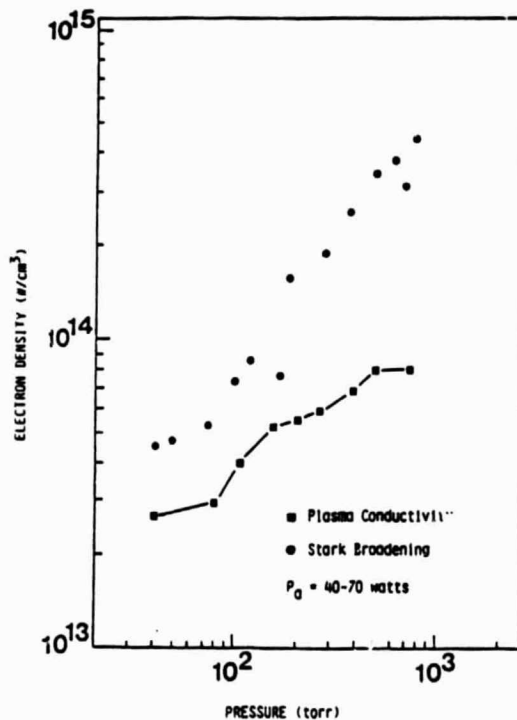


Figure 5. A comparison between measured electron density by the conductivity method [1] and Stark broadening. The argon flow rate was $1 \text{ cm}^3/\text{sec}$ in a 4 mm i.d. quartz tube with 40-70 watts absorbed power tuned to minimum reflection.

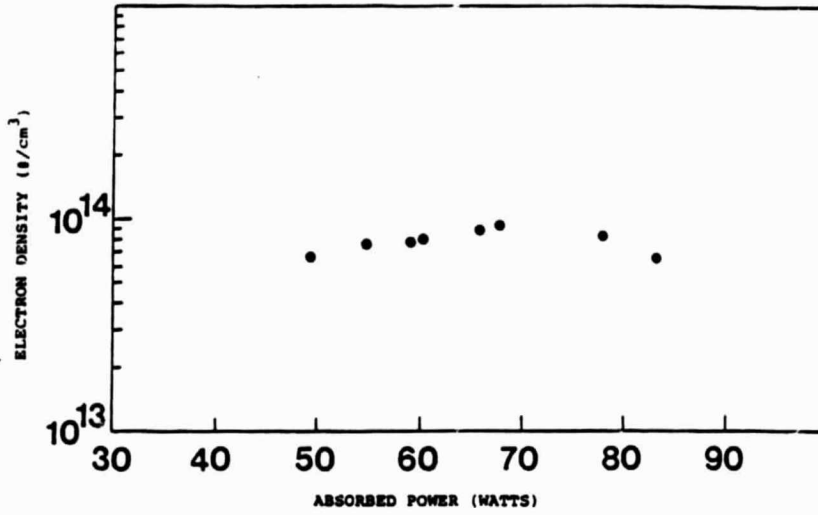


Figure 6. Effect of absorbed power on electron density.
The argon pressure was 150 torr with no flow.

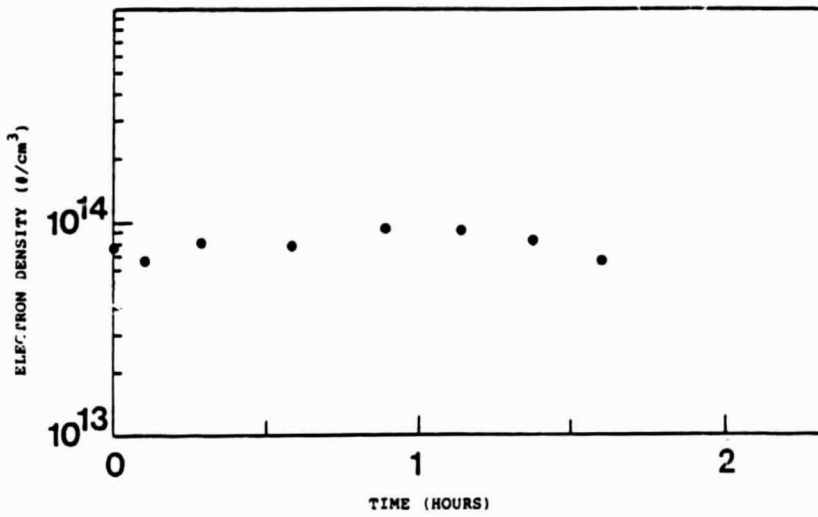


Figure 7. Effect of discharge time on electron density.
The argon pressure was 150 torr with no flow.

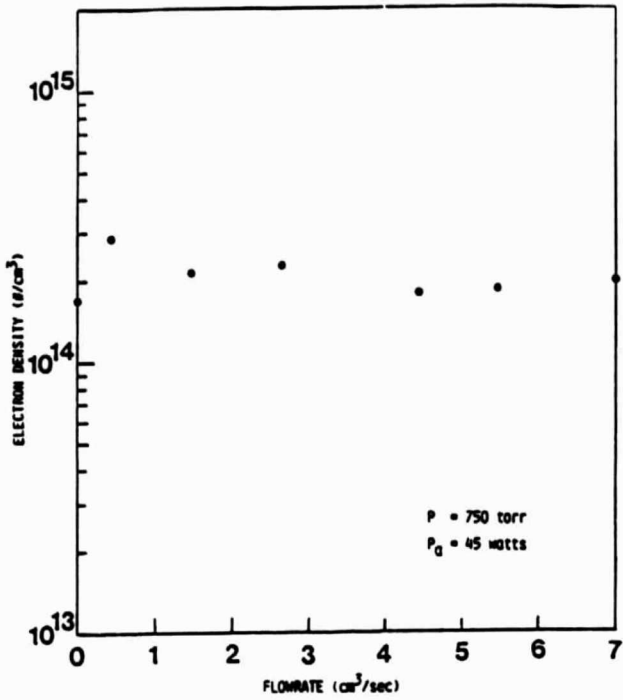


Figure 8. Effect of flow rate on electron density. The argon pressure was 750 torr with 45 watts absorbed power.

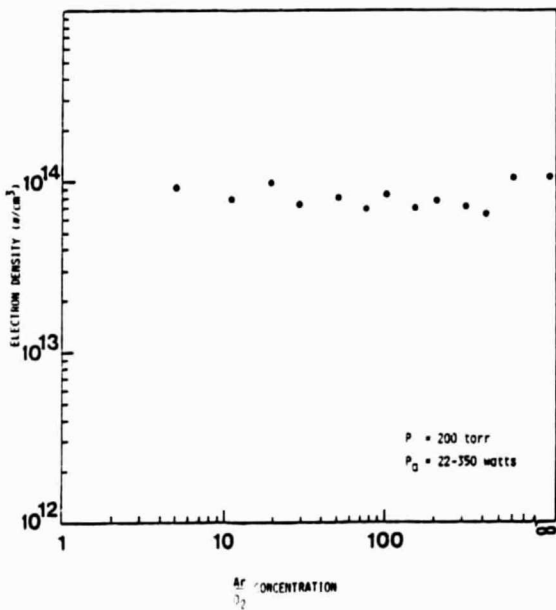


Figure 9. Effect of Ar/O_2 ratio on electron density. The gas mixture was held at 200 torr with no flow. The absorbed power was 22-350 watts.