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LANGMUIR PROBE IN A SUPERSONIC HIGH TEMPERATURE PLASMA

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Time-resolved electron density of relatively high velocity, high temperature plasma, generated in an electric shock tube is measured by single Langmuir probe. The results are compared with electron density inferred from plasma electronic conductivity measured by filament electrodes. This comparison shows that Langmuir probe has successfully determined the local electron density of the flowing plasma.

I. INTRODUCTION

The Langmuir probe is one of the most widely used diagnostic tools in laboratory [1-5] and space plasmas [6], largely because of its apparent simplicity and the extensive documentation of its operational characteristics. It is often desirable to relate the ion current to a probe immersed in a plasma to the electron number density, ionic mobility, probe radius and probe bias. However, anomalies have been shown to exist when Langmuir probe is placed in flowing plasmas. Langmuir [7] was the first who analysed the signal from a probe in a low density, low velocity flowing plasma. Clements et al. [8] dealing with spherical probes in a flame plasma have shown that their results were in agreement with theory corrected for the finite residence time of the probe in the plasma; their basic theory follows thick sheath and diffusion-convection models for the probe current. Segall and Koopman [9], dealing with cylindrical probes in a high velocity collisionless plasma, and Huggins [10], dealing with spherical probes in a room temperature flowing after-glow plasma, have shown that the measured electron characteristics were in good agreement with their analysis. Fucks and Theenhaus [11] have shown that Langmuir probes can be used in non-stationary processes, if the reproducibility of the process is adequate. Maclatchy and Didsbury [12] have reported that the probes used in a flame plasma were operated in the sheathconvection regime and exhibited a systematic variation between thin and thick sheath behaviour. Most of the foregoing measurements were made with Langmuir probes immersed in relatively low temperature, low velocity plasma flows.

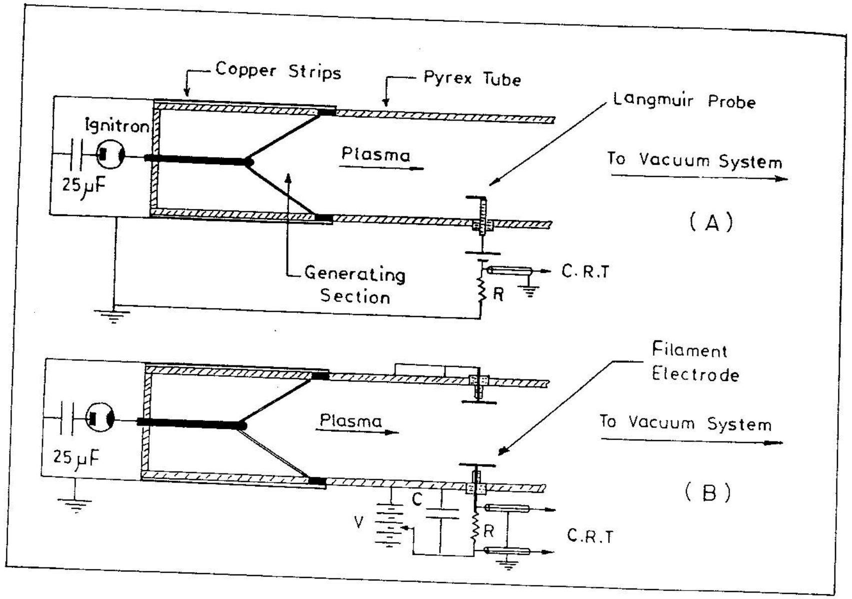

Fig. 1. Electrode assembly and shock tube, together with: (*a*) Langmuir probe circuit. (*b*) Filament electrodes circuit.

In this paper we are interested to use single Langmuir probe to measure the electron density in a relatively high velocity, high temperature plasma.

II. EXPERIMENTAL WORK

The 5-cm. inside diameter electric shock tube, used in this experiment, has been described elsewhere [13], and is illustrated in Figure 1*a*. A cylindrical tungsten wire of 0.038 cm. diameter, and 0.42 cm. in length was projected inside the shock tube, at a measuring station situated 21.6 cm. downstream of the generating section, Figure 1*a*, with its axis made parallel to and at a distance of 1.6 cm. from the shock tube axis.

Two identical filament electrodes were used to measure the electronic conductivity of the flowing plasma. These filament electrodes were from tungsten wire 0.038 cm. in diameter and mounted in opposite station, at the same measuring position so as to project 1 cm. from the tube wall. Fig. 1*b*. shows the electrode arrangement, where each electrode was made from 12 straight sections, each about 2.12 cm. long; this gives an overall electrode surface area of 3.04 cm^2. Each filament was welded on two molybdenum wire supports which were covered by a thin layer of glass for insulation. The 12-wire sections were made parallel to the tube axis.

The present measurements were carried out with a shock velocity of Mach 6, a driver-gas velocity of 0.13 cm/μs., a maximum driver-gas temperature of 7000 K

and at a basic pressure of 1 torr of high purity argon. The input electrical energy into the generating section was fixed at 450 joules.

The Langmuir probe and the filament electrodes were loaded by non-inductive resistors, in the range from 0.6 to 500 Ω and the voltage drop across these loads, which is a measure of Langmuir and electrode currents, was displayed on a double-beam oscilloscope. To maintain reproducibility it was necessary to clean Lagmuir probe surface periodically, as well as the filaments, between successive discharges, were flashed to white heat for a period of about 3 seconds to clean them. A slight argon flow was allowed within the shock tube system during the measurements, while the pressure was maintained constant at the required value.

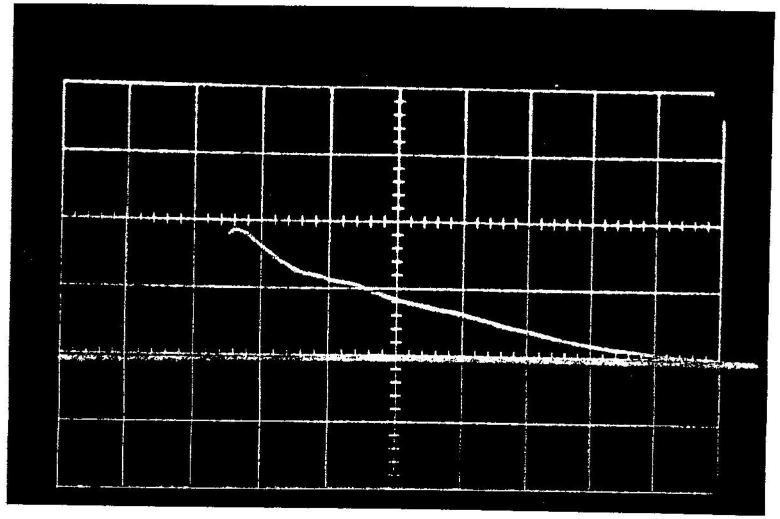

Fig. 2. Voltage oscilogram with Langmuir probe. Voltage scale = 20 V/div; load resistor = 500 Ω; T.B. = 20 μs/div.

III. RESULTS AND DISCUSSION

Fig.2. shows a typical oscillogram obtained for the response of the Langmuir to the flowing plasma, while Fig.3. shows a typical oscillogram obtained from the cold filament electrodes.

A single Langmuir probe current-voltage characteristic, made up of a group of measurements, for typical conditions, is shown in Fig.4., where each experimental point represents the average of at least three oscillograms taken under identical initial conditions.

The interpretation of Langmuir probe characteristics, is a subject which is far from closed [14]. However, Fig.4. shows that the saturation of ion current, for negative probe voltage relative to ground, is clearly evident. It is interesting to see that with the probe at a certain positive voltage, relative to ground, the characteristic

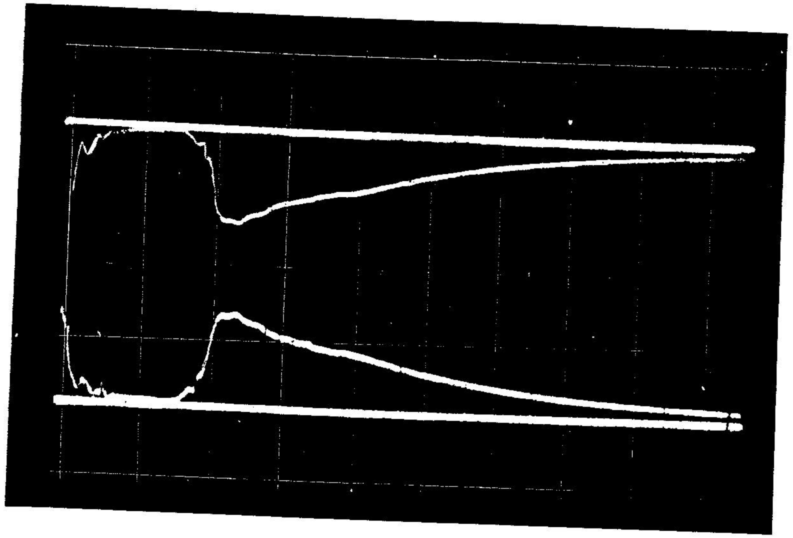

Fig. 3. Voltage and current oscillogram with cold filament electrodes. Upper trace represents the voltage signal (inverted) across the filaments; voltage scale 10 V/div.; the lower trace represents the current signal across a load resistance of 1.1 Ω ; current scale 9.1 A/div.; T.B. = 20 μs/div.

of Langmuir probe appears to level off. This successful detection of probe saturation currents, indicates that we are operating in a density regime where $r_p >> \lambda_d$, where r_p is the probe radius and λ_d is the electron Debye length. Other reporters [9,14], dealing with electrostatic probes, in flowing plasmas, have demonstrated a failure of plasma shielding of probe voltage, in the electron attracting region, even when $r_p >> \lambda_d$. Accordingly we have used Bohm formula [15], as our principal method for determining the ion density. Thus

$$i_{psat} = 0.566\, n_i\, e\, (k\, T_e\, m_i)^{1/2}\, A \qquad (1)$$

where i_{psat} is the saturation positive current to the probe, n_i and m_i are the positive ion density and mass respectively, and A is the probe area. We have evaluated i_{psat} at the space potential V_s as shown in Fig.4.

On the assumption that postulated Maxwell-Boltzmann distribution to apply [7], we get

$$\ln i_e = \ln i_{ep} - (eV_{pp}/kT_e) \qquad (2)$$

where i_e is electron current to probe, i_{ep} is the random electron current and V_{pp} is the probe voltage relative to the plasma. The electron temperature T_e was calculated for typical conditions and is shown in Fig.5. The linearity of this relationship indicates that the electrons, in the present flowing plasma, have a Maxwellain velocity distribution, and hence the use of equations (1) and (2) is valid in the present case.

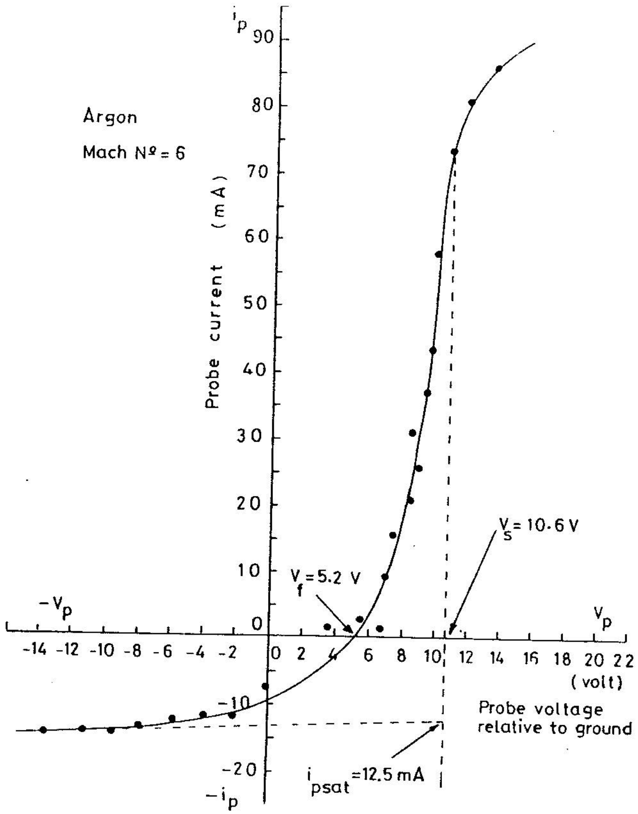

Fig. 4. Current- Voltage characteristic curve of Langmuir probe, after the response of the threshold by 25 μs.

For a plasma with $n_e \simeq n_i$, Fig.6. shows the variation of n_e, given by equation (1), with time behind the threshold of the ionized driver gas measured in the present case.

The filament electronic current-voltage characteristic, made up of a group of measurements, for typical conditions, is shown in Fig.7., where each experimental point represents the average of at least three oscillograms taken under identical experimental conditions.

The plasma resistance R_p between the interelectrodes regions, in the steady state, may be written in the form

$$R_p = \frac{I}{A}\left(\frac{l}{\sigma_e} + \frac{V_{sh}}{J_E}\right) \qquad (3)$$

where A is the filament electrode current-collecting area, l is the filament electrodes separation, σ_e is the electronic conductivity of the plasma, V_{sh} is the total poten-

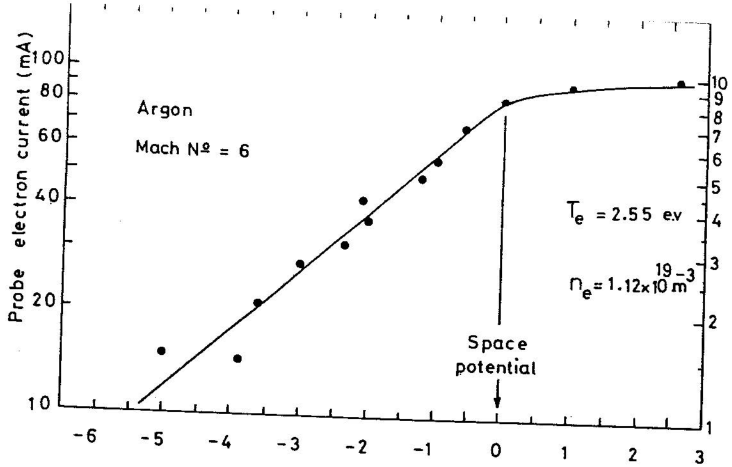

Fig. 5. Langmuir probe electron current vs adjusted probe voltage for typical conditions.

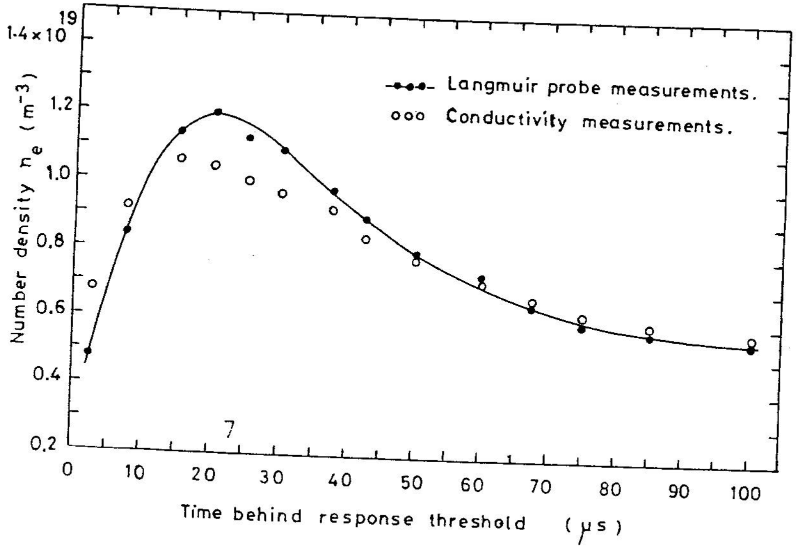

Fig. 6. Variation of number density with time behind response threshold.

tial drop across the sheath and J_E is the external load current per unit area of filament electrodes. Equation (3) shows that the plasma resistance R_p is supposed to approach that correspondig to electronic current flow either for a constant voltage drop across the sheath and increasing current density or, for reduced sheath voltage drop by an emitting cathode for example. It is clear that for very small current with cold electrodes, almost the applied voltage will fall across the sheath.

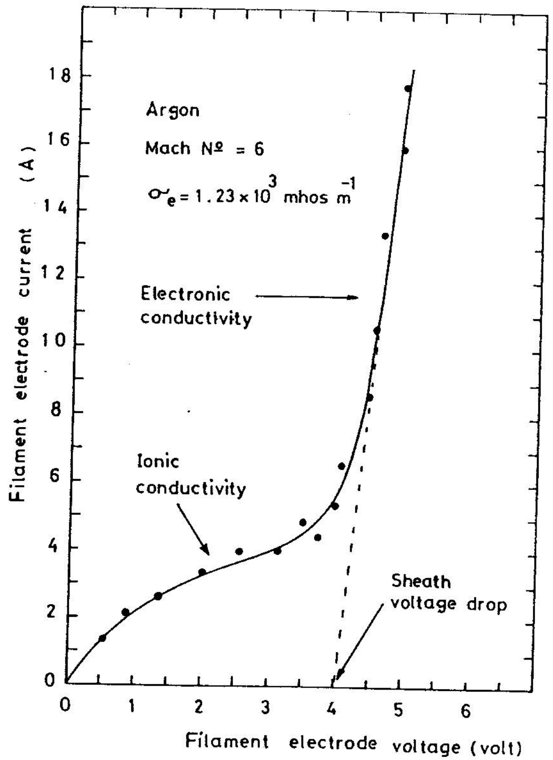

Fig. 7. Filament-electrode current vs Filament-electrode voltage, after the response of the threshold by 25 μs.

In the present experiment, it is clear that the linear increase of the flowing current with increasing the filament electrode voltage was obtained after an observable electrode voltage drop which is supposed to be the sheath voltage drop in this case. Such linear inrease of electrode current with increasing electrode voltage indicates the emission of electrodes from the cold filament cathode. The short duration of the ionized-driver gas precludes the possibility of the filament electrodes becoming heated. We believe, therefore, that the electric field at the cathode surface was sufficient to accelerate the positive ions to a high velocity, and as they strike the cathode surface electron emission will result.

Consequently, from the linear part of the I-V characteristics and by taking into consideration the fringing factor for these electrodes, the plasma electronic conductivity σ_e was calculated according to equation (3) and hence the electron density, using the expression [16],

$$\sigma_e = \left\{ 4.8 \times 10^{11} \frac{T^{1/2} Q_0 N_0}{n_e} + \frac{66.67}{T^{3/2}} \ln \left(\frac{8.7 \times 10^6 T^{3/2}}{n_e^{1/2}} \right) \right\}^{-1} \tag{4}$$

where all quantities are given in units of SI. σ_e represents in this case the electronic conductivity for gas with an intermediate degree of ionization, Q_0 denotes the particle cross-section for momentum transfer for electron-atom collision (values of Q_0 were taken from the results of Ref.17), N_0 is the initial particle density and T is the gas temperature.

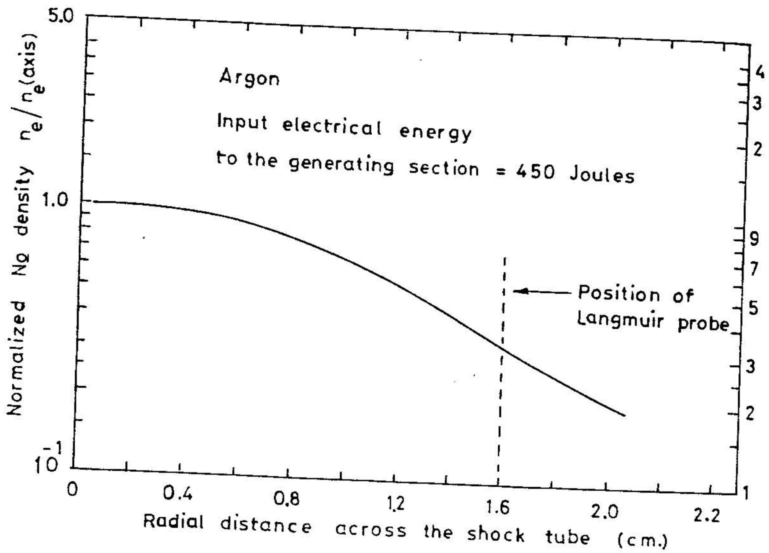

Fig. 8. Normalized number density of electrons versus radial distance of the shock tube, (Ref. 18).

Abbas [18], using a Lin-type magnetic probe [19], mounted inside the shock tube, has confirmed experimentally that the electron density distribution varies in a nearly parabolic manner, with the shock tube radius as shown in Fig.8. It can be seen that the electron density at a radial distance of 1.6 cm from the shock tube axis was about 34% of n_e (axis) measured at the tube axis. Taking this fact into consideration, the variation of the corrected number density n_e (estimated by equation (4)) with time behind the threshold of the ionized driver gas is plotted in Fig.6. We can see that the number density n_e obtained from the Langmuir probe is approximately of the same magnitude as the corrected values from Lin-type magnetic probe measurements.

The approximate similarity between the time-resolved electron density, inferred from Langmuir probe and conductivity measurements indicates that the experimental results were obtained with good reproducibility.

IV. CONCLUSION.

Judging from the good reproducibility of the experimental results and from the relative small amount of scatter of the experimental points, it is safe to conclude

that Langmuir probe has successfully determined the local electron density of the present high velocity, high temperature plasma.

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