

An Experimental Procedure For Determining the Pertinent Parameters in a Plasma Containing Three Electron Energy Groups

John M. Peterson and Norman L. Oleson, *Member, IEEE*

Abstract—In an experimental study of the properties of a double-beam plasma device where the driver plasma was separated from the target plasma by a hemispherical separating screen, three Maxwellian energy groups of electrons appeared whenever an ion beam was sent from the driver plasma to target plasma. A method is given here for determining the densities and temperatures of these energy groups.

I. INTRODUCTION

AS early as 1930, Langmuir and Compton published information on their observation of two superimposed Maxwellian distributions of electrons in a region of intense ionization near the cathode of an electric discharge [1]. One of these groups was of relatively high mean energy, apparently consisting of primary scattered electrons from the cathode, and the other a much lower energy secondary group of electrons produced by ionization of the gas by the primary electrons. Two electron temperatures associated with moving striations were observed later by Oleson and Found [2]. By successive approximations they resolved the data into two energy groups having distinct Maxwellian distributions. The higher energy electron group was associated with the brighter portion of the striation, and the lower energy group with the dark region. Successive approximations were also used later by Jones *et al.* [3] to determine the precise electron temperatures associated with the primary and secondary electrons in a quiescent plasma. A formula was derived by them to determine the electron temperatures associated with the primary and secondary electrons. A formula was derived by Jones *et al.* [3] from the dispersion relation for ion acoustic waves which gave the effective temperature of the electrons in terms of the hot and cold groups:

$$N_0/T_{\text{eff}} = N_c/T_c + N_h/T_h \quad (1)$$

where N_0 , N_c , N_h are the total, cold, and hot electron group densities, respectively; and T_c and T_h are the cold and hot temperatures. They experimentally confirmed that T_{eff} determined the ion acoustic speed; i.e.,

$$C_s = [kT_{\text{eff}}/m_i]^{1/2} \quad (2)$$

where m_i is the ion mass.

Equation (1) tells us that T_{eff} is dominated by the cold group and that the presence of even a small amount of cold electrons can lower the effective temperature significantly.

Manuscript received March 5, 1990; revised November 29, 1990. This work was supported by the University of South Florida.

J. M. Peterson was with the Department of Physics, University of South Florida, Tampa, FL 33620. He is now with the State Department of Transportation, Juneau, AK.

N. L. Oleson is with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620.

IEEE Log Number 9042661.

We have recently completed a thorough study of the properties of a multipole double-plasma (DP) device filled with argon at 0.4 mT [4]. The inside dimensions of the stainless-steel cylindrical containing vessel was 50 cm in diameter and 150 cm in length. A hemispherical, negatively biased (−50 V) separating screen was placed between the driver plasma and target plasma to keep electrons from the driver plasma from entering the target plasma. Fig. 1 is a schematic of the apparatus. An additional electron energy group appeared whenever the driver plasma potential was made positive with respect to the target plasma, causing an ion beam to be sent from the driver plasma to the target plasma. Langmuir plots taken in the target plasma, including the focal region, revealed the presence of this additional third, very cold group whose density was found to be greatest within the focal region. In this present paper we give more details on the method of obtaining the electron temperatures and number densities of the electrons in the three energy groups.

II. EXPERIMENTAL DETAILS AND OBSERVATIONS

The magnetic multipole field boundaries containing the plasma were configured by placing ceramic bar magnets parallel to each other and running along the inside walls of the cylindrical plasma device [5]. A close study of Fig. 1 shows that the anode-cathode arrangement of the conventional DP plasma has been modified. In our case, the anode screen was placed directly in front of the filament assembly so that the potential of the plasma could be raised well above the grounded walls, resulting in a further charge density increase due to this electrostatic confinement. The presence of magnetic cusps near the walls resulted in the reflection of most of the fast electron trajectories, whereas the slower and thermal electrons and ions were lost to the walls by ambipolar diffusion [6], [7]. As previously mentioned, the hemispherical separating screen was biased strongly negative with respect to the grounded walls to insure that only ions were driven into the target plasma when the plasma potential of the driver plasma was increased over that of the target plasma.

The background target plasma was generated from hot filaments located at the far end of the target chamber. Electrons coming from these filaments were the source of primary electrons in the target plasma. These electrons were detected in all Langmuir characteristics taken throughout the target plasma. They formed the hottest, most tenuous group of electrons: Their high energy caused the background argon gas to ionize, thus forming the plasma and, accordingly, a second group of electrons we call the secondary electrons. The presence of these two groups was detected as the two straight line segments in Fig. 2(c). The method of successive approximation revealed Maxwellian temperatures of 12–15 eV associated with the primary electron group, and 4–6 eV for the secondary

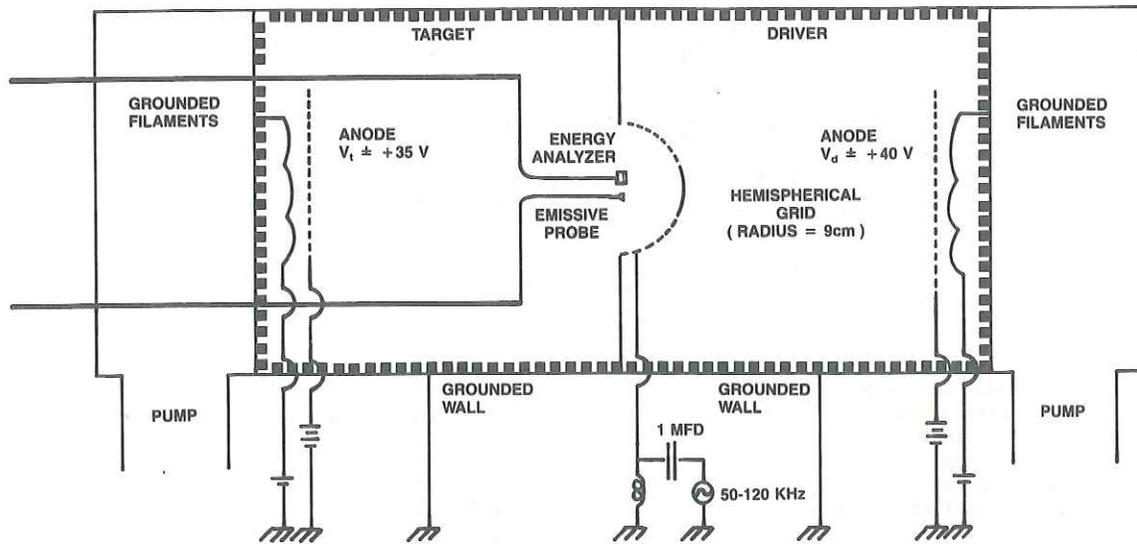


Fig. 1. The multipole double plasma device; ceramic magnets are shown by the shaded areas.

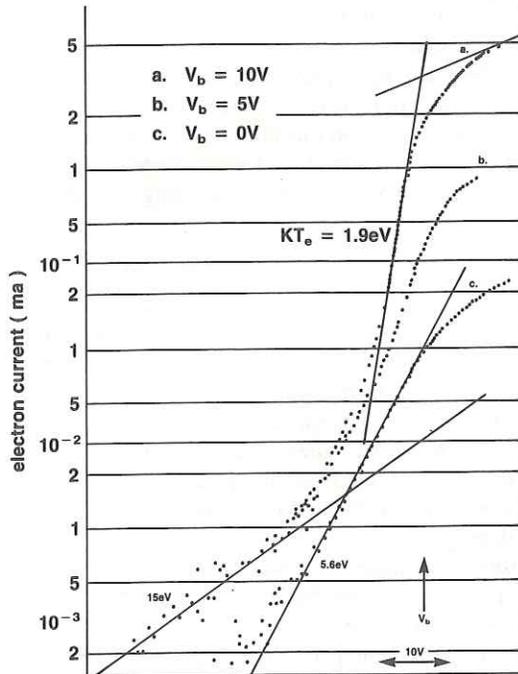


Fig. 2. Three Langmuir plots taking at the focus for various beam energies. A third cold-temperature component occurs only in the presence of an ion beam. The hotter components are due to the primary and secondary electrons.

electrons [4]. Their influence remained relatively unchanged throughout the target plasma, even in the presence of the beam. The presence of a third straight line was detected only when an ion beam passed through the screen from the driver side to the target side.

Presently, we define the ion beam energy as the difference in potential between the driver and target plasmas. This definition was found to be consistent with the beam energy as determined by a moveable electrostatic energy analyzer placed inside the target plasma [4]. Fig. 2 shows the action of a bare spherical probe placed at the center of curvature of the hemispherical grid. The outstanding feature in these figures is the appearance of a third group of relatively very cold electrons whose density

increased rapidly for stronger beam energies. We concluded from this that this cold group of electrons came from the background plasma on the target side in an effort to neutralize the ion beam. The fact that this group of electrons was relatively very cold led us to believe that the ion beam density was locally much higher at the center of curvature of the dividing screen than elsewhere.

The quasi-neutral property of the plasma implies that an ion is neutralized on the average by its neighboring electrons. If this were so, then any localized "lump" of ions would naturally tend to gather lower energy electrons, as they would have a tendency to "stay-put." Soon the region of high ion density would reach a state of dynamic equilibrium whereby enough low-energy electrons have convened to neutralize the region. This is what we believe was happening at the center of curvature. The presence of this very high density, low-temperature group of electrons found at the center of curvature of the hemispherical separating screen further led us to investigate the possibility of a focusing of the ion beam by the hemispherical grid. This investigation was carried out using probe designed to move in and out of the center of curvature along the axis of the plasma.

Fig. 3 shows the Langmuir probe curves at constant beam energy at three different positions along the axis of the plasma: A, at the focus; B, half-way between the focus and grid; and C, within one-half centimeter of the grid. These graphs clearly show an increased density due to the focusing of the beam at the center of curvature of the grid. They also reveal that the local beam density of the cold electrons at a given point on the axis between the hemispherical separating grid and focal point depends on the ion beam cross section at that point; that is, the smaller the beam cross section, the greater the charge number density of the axis. The electron temperature, which is a property of the plasma characteristic, remains the same for each energy group. The primary and secondary electrons are shown in the figure as the 12 and 4.5 eV groups, respectively. The current due to the primary electrons from the target plasma filaments constitute the primary current. It is constant throughout the target plasma except near the borders and the sheath region of the hemispherical dividing grid. On the other hand, many of these primary electrons give rise to the secondary electrons and current in collisions with neutral atoms in the plasma. This secondary current is found to decrease slowly with distance from the target

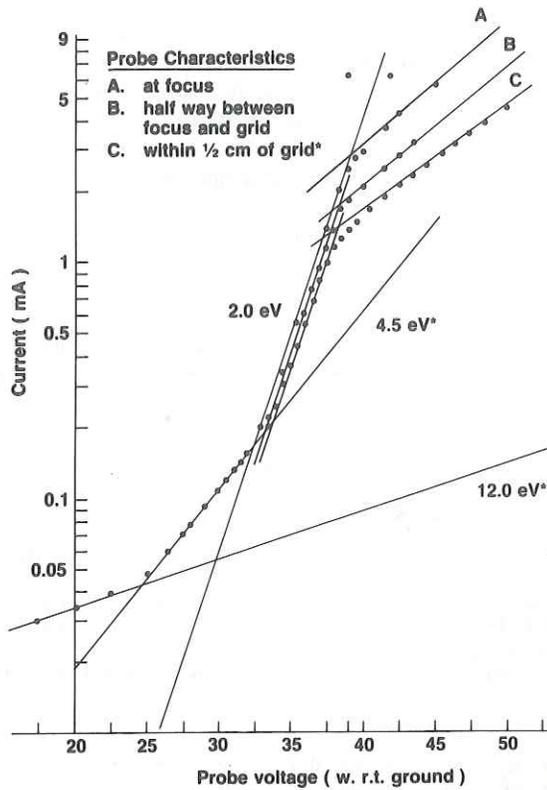


Fig. 3. Three Langmuir plots taken at various positions with constant ion beam energy: $eV = 10 eV$. For position C the hotter electron temperature components are each reduced by one third, and the current scale has been multiplied by a factor of ten.

anode, indicating that their reflection from the chamber walls is not as uniform as that of the primary electrons. Recall that neither the primary nor the secondary electrons pass through the hemispherical dividing grid and consequently are not focused. Position C, being close to the grid, has diminishing currents due to the primary and secondary electrons (not shown in the figure). In spite of the probe's close proximity to the grid, the saturation current remained relatively strong at position C. For this position the probe current was mainly due to the cold electrons associated with the beam. This is illustrated by the presence of the cold 2 eV (uncorrected) group of electrons at all three positions within the target plasma in the presence of a 10-V beam.

III. METHOD OF ANALYSIS OF DATA

By using the method of successive approximations in the following sections of this paper, we will draw some quantitative information about the third group of electrons and the ion beam itself. Fig. 4 is a typical Langmuir plot taken in the focal region in the presence of a 10-V ion beam. The plasma potential V_p was determined by the breakpoint in the curve at the electron saturation current. A vertical line was drawn at this potential. The straight line portions of the Langmuir plot indicate the presence of three electron groups. Let us assume that the total saturation current is the sum of three smaller plenary currents due to each of the three energy groups. The plenary current associated with the primary (hottest) group was found by extending the line AB in Fig. 4 until it crossed the vertical line drawn at the plasma potential. The current at this point is the primary electron plenary current i_p . The current found by extending the line CD until it crossed the plasma potential

gives a current which is the sum of the primary and secondary currents. This current, minus the primary electron current i_p , gives the secondary plenary current i_s . Similarly, the coldest electron plenary current i_t is the total electron saturation current minus the sum of the primary and secondary plenary currents. Accordingly, line AB was caused by the collision of electrons from the hottest distribution. The inverse slope of this line being proportional to the primary electron temperature T_p . The second line, CD, was due to collection of both the hot primary electrons and the cooler secondary electrons. The inverse slope of this line being proportional to the secondary electron temperature T_s . The corrected secondary electron temperature was found by subtracting the line AB from the line CD. The inverse slope of the line formed after this subtraction, line (cd), gives the true or corrected secondary electron temperature T_s^* . This is essentially the method of successive approximation, and here we extend it to a third group. The temperature of the coldest group of electrons T_t is found from line EF. It must first be corrected by subtracting out line AB, resulting in the line (ef) yielding line T_t^* . Line (ef) is corrected once again by subtracting out the secondary electrons, line (cd), from line (ef). The slope of the resulting line (e¹f¹) yields the temperature T_t^{**} of the coldest group of electrons, corrected twice. The various temperatures found in this way for a 6.5-V beam are tabulated in Table I. The number density of each energy group was calculated in the usual manner from the plenary current and corrected electron temperature. The floating potential V_f and beam energy V_b are also listed in Table I. The diminished number density of the colder electrons on the axis beyond the focus is a result of the beam diverging in this region.

Finally, the effective electron temperature T_{eff} was found from the relative group densities and temperature, in a fashion similar as for the two electron temperatures plasma [3], [4]; thus,

$$N_0/T_{\text{eff}} = N_p/T_p + N_s/T_s^* + N_t/T_t^{**} \quad (3)$$

where N_0 , N_p , N_s , and N_t are the total number density, primary number density, the secondary density, and the tertiary number density, respectively. The various values of T_{eff} are recorded in Table I.

IV. CONCLUSIONS

The well-established method of successive approximations [2], [3] for determining the electron number densities and temperatures in a quiescent two-electron temperature plasma was previously confirmed by experiments designed to measure the speed of the ion acoustic wave in the same type of plasma [3]. In the present study we extend the method of successive approximations to an ion beam plasma apparently having three electron temperatures. (The coldest electron temperature group appeared only when an ion beam was present.) Electron number densities and temperatures found in this way are tabulated for three different local position within the plasma. (It so happens that our beam is a converging ion beam caused by a hemispherical separation grid in a double plasma device.) Effective electron temperatures were calculated by extending the formula derived previously [3] to include a third electron group. Attempts to determine the effective electron temperature via the ion acoustic wave speed have met with difficulty in our experiment. In order to produce waves in the test plasma, one must superimpose a pulse (or a continuous wave) on the beam which results in the appearance of the so-called ion beam modes in the test plasma [8], [9]. They consist of a mixture of several waves, including the

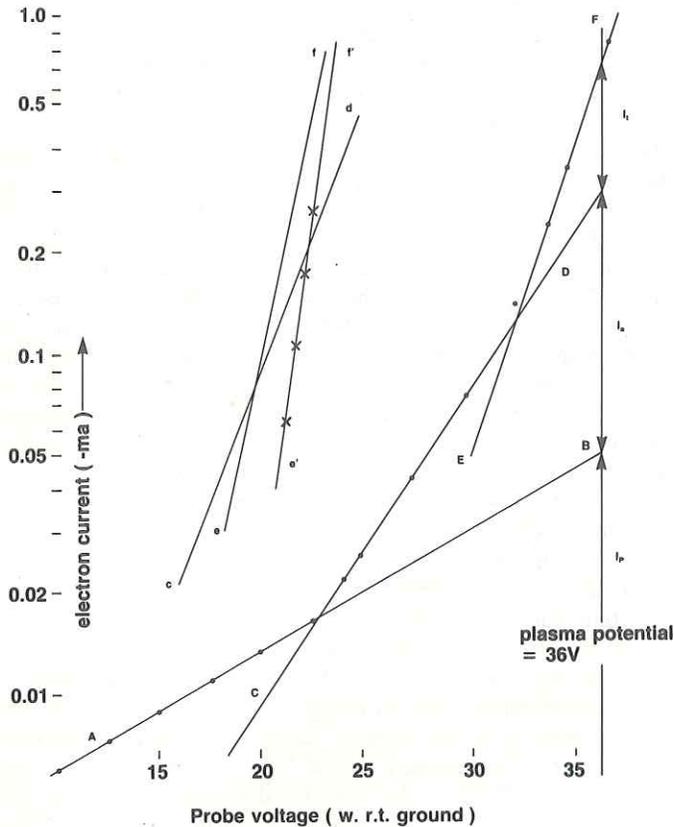


Fig. 4. Probe curves taken within the focal region for a 10 eV beam, illustrating the method of successive approximations for three electron groups. Line *cd* and *ef* give the secondary and tertiary electron temperatures corrected once. Line *e'f'* gives the tertiary temperature corrected twice.

TABLE I

PLASMA PARAMETERS IN AND AROUND THE FOCAL REGION FOR A 6.5-V BEAM

	5-cm in Front of Focus	At Focus	10-cm Behind Focus
V_b (V)	6.5	6.5	6.5
V_p (V)	38.0	38.0	38.0
V_f (V)	26.0	29.0	24.0
i_p (ma)	0.05	0.05	0.05
i_s (ma)	0.10	0.12	0.15
i_t (ma)	0.75	0.83	0.20
T_p (eV)	12.0	12.0	12.0
T_s (eV)	4.5	4.5	4.5
T_s^* (eV)	2.8	2.8	2.8
T_t (eV)	2.0	1.9	2.0
T_t^* (eV)	1.5	1.5	1.5
T_t^{**} (eV)	0.8	0.8	0.8
$N_p/10^8 \text{ cm}^{-3}$	0.11	0.11	0.11
$N_s/10^8 \text{ cm}^{-3}$	0.45	0.54	0.67
$N_t/10^8 \text{ cm}^{-3}$	6.29	6.96	1.68
$N_0/10^8 \text{ cm}^{-3}$	6.85	7.60	2.45
N_p/N_0	0.016	0.014	0.055
N_s/N_0	0.065	0.071	0.339
N_t/N_0	0.919	0.915	0.606
T_{eff} (successive approx.) (eV)	0.85	0.85	1.13

fast beam mode, the slow beam mode, and the ion acoustic mode. Garner and Oleson [10], using a hemispherical separating screen,

found, for the range of parameters used in their experiments, that the predominate mode was the fast mode, the other modes being severely damped. However, by changing the experimental parameters it might be possible to decrease the damping of the ion acoustic wave so that its speed can be measured and use be made of (3) to verify the effective temperature in this case. If T_{eff} is defined by (3), then it can be calculated from the data listed in Table I. Values of T_{eff} so obtained are listed in Table I.

ACKNOWLEDGMENT

The authors are grateful to G. Pidick for maintaining the equipment. They also appreciate the constructive comments of the referee.

REFERENCES

- [1] I. Langmuir and K. T. Compton, *Rev. Mod. Phys.*, vol. 2, p. 2, 1930.
- [2] N. L. Oleson and C. G. Found, *J. Appl. Phys.*, vol. 20, p. 416, 1949.
- [3] W. D. Jones, A. Lee, S. M. Gleman, and H. J. Doucet, *Phys. Rev. Lett.*, vol. 35, p. 1349, 1975.
- [4] J. M. Peterson and N. L. Oleson, *Phys. Fluids B*, to be published.
- [5] R. J. Taylor, K. R. MacKenzie, and H. Ikezi, *Rev. Sci. Instrum.*, vol. 43, p. 1675, 1972.
- [6] C. Chan, T. Intrator, and N. Hershkovitz, *Phys. Lett.*, vol. 91A, p. 167, 1982.
- [7] M. H. Cho, N. Hershkovitz, and T. Intrator, *J. Appl. Phys.*, vol. 67, p. 3255, 1990.
- [8] D. Gresillon and F. Doveil, *Phys. Rev. Lett.*, vol. 34, p. 77, 1975.
- [9] H. Akiyama, T. Yamada, and S. Takeda, *Japan. J. Appl. Phys.*, vol. 18, p. 1543, 1979.
- [10] C. E. Garner and N. L. Oleson, presented at the 31st Ann. Meet. Div. Plasma Phys., Anaheim, CA, Nov. 13-17, 1989, paper IE-14.



John M. Peterson was born on May 21, 1949 in Fargo, ND. He received the B.S. degree in physics from the University of Alaska in Fairbanks in 1976. He became interested in plasma physics while working as an assistant at the Poker Flats Rocket Research Range near Fairbanks. He went on to study plasma physics at the University of South Florida in Tampa, where he received the M.A. degree in natural science with a major in physics.

Presently, he teaches geometry at Community Christian High School in Juneau, AK, and is a Computer Programmer for the State Department of Transportation.

Mr. Peterson was elected an associate member of the Sigma Xi Society in 1982 for excellence in experimental research.



Norman L. Oleson (M'89) was born in Detroit, MI, and obtained the B.S., M.S., and Ph.D. degrees at the University of Michigan, Ann Arbor.

Following military service, he joined the Lamp Research Group at the General Electric Company. Afterwards he became a member of the faculty of the Department of Physics at the Naval Postgraduate School in Monterey, CA, where he remained until 1969 when he was elected Chairman of the Department of Physics at the University of South Florida in Tampa. In 1978 he returned to teaching and research and in 1990 moved over to the Department of Electrical Engineering. He has been doing research in gaseous electronics and waves in plasmas, including moving striations, ion acoustic waves and solitons. He and F. Coengen organized the first meeting of the Division of Plasma Physics, which was held in Monterey, CA, in 1959.

Dr. Oleson is a Fellow of the American Physical Society.