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Edge effect correction for small planar Langmuir probes

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One problem inherent in the use of small planar Langmuir probes to analyze low-density plasma is expansion of the space-charge sheath with increased probe potential due to the departure from planarity caused by a nonnegligible sheath edge. Experimental evidence showing the existence of significant edge effects in the ion saturation region of the characteristic obtained from such probes is presented. The extra ion current ΔI_+ collected as a result is shown to depend on the (negative) probe potential V according to the empirical relation $\Delta I_+ \propto V^{0.75}$. A theoretical justification for this is obtained. Finally, the effectiveness of the technique in eliminating the edge effect for this type of probe is demonstrated by the equivalence of ion and electron densities measured in a helium discharge.

I. INTRODUCTION

Langmuir probes have long been used as a simple and inexpensive diagnostic technique for studying plasmas with a low energy density. They offer the advantages of a simple and rapid experimental technique, together with a spatially resolved result. However, by way of balance, accurate analysis of the characteristic trace is complex and lengthy. The form of this analysis differs with the probe geometry, being at its simplest in the case of an infinite plane probe.[1,2] For this most simple case alone, theories allowing estimation of the density of negative as well as positive ions have been generated.[3,4] This makes the ability to use planar probes in certain types of plasma highly desirable.

By definition, the effects of the probe edges on the characteristic are ignored, the planar probe being assumed infinite. For probes of a large enough area, this appears to cause little problem,[5] since the edge effects are proportionally small. However, probes of this size ($\sim$2 cm diam) draw a considerable current from the plasma when biased to plasma potential, and their use is thus restricted to large plasmas where the perturbation so caused is minimal. In smaller devices, plane probes of a smaller area are necessary, introducing the possibility of a significant edge effect.[6,7] In this article, the existence of such an effect is demonstrated, and a corrective term obtained.

As is well known, the characteristic obtained from a Langmuir probe may be explained in terms of the space-charge sheath that surrounds any conductor immersed in and biased relative to a plasma. Effectively, it is the area of this sheath, and not that of the probe itself which determines the current collected by the probe. The effect of the edge on a finite planar probe causes this sheath to be distorted from the ideal infinite case, where the sheath has the same area as the probe. In the case of a single-sided disk probe, the sheath forms the distorted hemisphere shown in Fig. 1. This causes an increase in current over and above that predicted by planar probe theory. Since the distance of the sheath edge from the probe increases with the probe potential, the sheath area and thus the collected current also increase with the probe potential. This sheath expansion distorts the probe characteristic, as shown in Fig. 2.

When obtaining a probe characteristic for analysis, it is seldom necessary to venture far beyond plasma potential into the electron saturation region, as values at the plasma potential itself are all that is required. Hence the increase in electron current due to sheath expansion is relatively unimportant. However, in the case of ion collection, the presence of high-energy electrons in the discharge often requires the ion collection region to be obtained at strongly negative probe potentials ($V\sim -100$ V). These high potentials render the ion saturation current value sensitive to the effects of sheath expansion. Determining the true value of the ion saturation current is therefore difficult, and exacerbated by the very small values of I_+. To identify the form of this expansion, a series of experiments were carried out on a small planar probe immersed in a low-density plasma.

II. THEORETICAL TREATMENT

The gap between the edge of the ion sheath and the probe face may be considered as a plane diode, in which the sheath edge emits ions and the probe face absorbs them. In this situation, the Child–Langmuir law for current transport across the gap is

$$J_+ = \frac{4\epsilon_0}{9}\sqrt{\frac{2e}{M_+}}\frac{V^{3/2}}{d^2}, \tag{1}$$

where d is the gap separation, M_+ the ionic mass, V the sheath potential, and ϵ_0 the permittivity of free space. If the sheath expands with voltage, this gap may be conveniently expressed in terms of a number κ of Debye lengths:

$$d^2 = (\kappa\lambda_D)^2. \tag{2}$$

The Debye length may be expressed in the form

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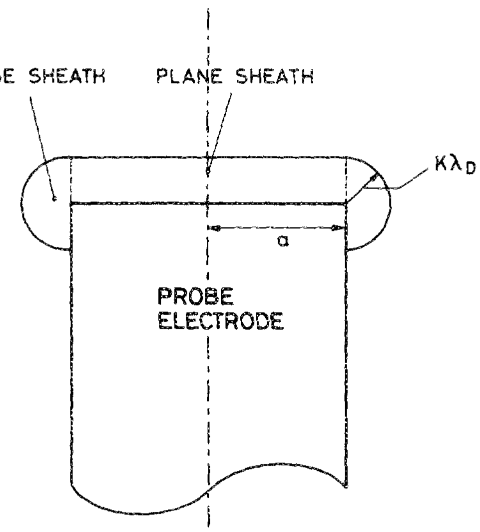

FIG. 1. Sheath geometry for the planar Langmuir probe.

$$\lambda_D = \sqrt{\frac{\epsilon_0 T}{eN_+}},$$

where T is the electron temperature in eV and N_+ the plasma density. Substituting this into Eq. (2), we may obtain for the current density J_+

$$J_+ = \frac{4}{9}\sqrt{\frac{2}{M_+}}\frac{(eV)^{3/2}}{T}\frac{N_+}{\kappa^2}. \quad (3)$$

From planar probe theory,[2] the ion current density collected by the probe is also given by

$$J_+ = 0.6eN_+\sqrt{\frac{eT}{M_+}}. \quad (4)$$

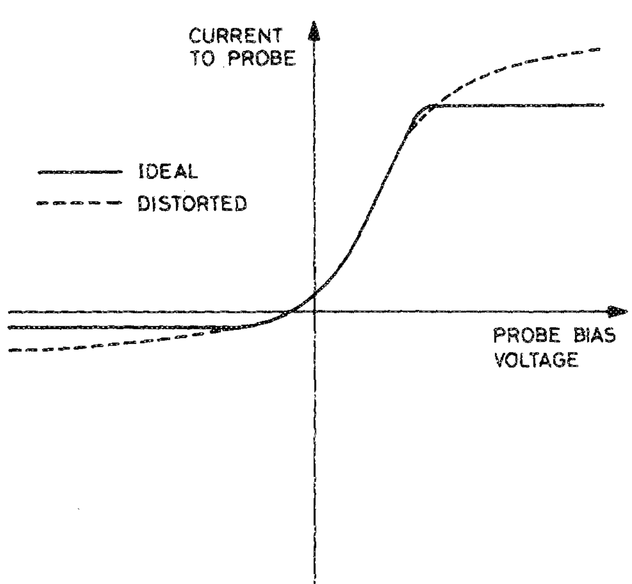

FIG. 2. Distortion of probe characteristic due to sheath expansion.

Equating these two expressions [(3) and (4)] and rearranging for κ yields

$$\kappa = 1.018(V/T)^{3/4}. \quad (5)$$

Having obtained an expression for κ, we may return to the probe. The total collected positive ion current will be given by the current flowing into the sheath area. The latter may be expressed as the sum of the probe area itself, plus that of the hemispherical ring comprising the sheath edge (the outer portion of a torus vertically cut along its median circumference), as shown in Fig. 1. Assuming terms in $(\kappa\lambda_D)^2$ are comparatively small, the measured ion current I_m is given by:

$$I_m = J_+\pi a^2 + J_+ 2\pi^2 a(\lambda_D\kappa),$$

where J_+ is the ion current density in the absence of a probe. Defining J_m, the *apparent* current density "seen" by the probe, as $J_m = I_m/\pi a^2$, it is possible to write

$$J_m = J_+ + J_+(2\pi\lambda_D\kappa/a).$$

Substituting in the expressions obtained for κ and λ_D, this becomes

$$J_m = J_+\left(1 + \frac{2\pi}{a}\sqrt{\frac{\epsilon_0 T}{eN_+}}\,1.018\frac{V^{3/4}}{T^{3/4}}\right). \quad (6)$$

Rearranging, and using the probe-theory expression for J_+ [Eq. (4)], this may be written for ions of atomic mass number A as

$$J_m = J_+\left(1 + \frac{1.45\times 10^{-3}}{a\sqrt{J_+}A^{1/4}}V^{0.75}\right). \quad (7)$$

III. EXPERIMENTAL STUDY

A number of experiments were performed using a small planar probe with a single disk surface 3 mm in diameter. This was formed from a shielded cylindrical electrode mounted on a watercooled shaft, as shown in the inset to Fig. 3. A gap of $\sim$0.6 mm separated the electrode from the shielding tube. The probe was placed in the plasma generated by a hydrogen arc discharge in a small multipole ion source, described elsewhere,[8] capable of generating plasma densities of up to $\sim 10^{11}$ cm^{-3}. A high-stability dc power supply was connected between this and the source body (discharge anode) as reference electrode. The experimental arrangement is shown in Fig. 3. The voltage applied to the probe was scanned between 0 and -400 V, and the I-V characteristic monitored using a chart recorder. This sequence was repeated over a wide range of arc discharge conditions for probes situated in various different regions of the source plasma. Discharge current was altered in order to vary the plasma density, and source filling pressure to vary electron temperature. A typical family of "ion saturation" I-V traces obtained from this experiment is shown in Fig. 4. Rigorously, the sheath potential differs from the probe-to-ground voltage by the plasma potential; however, in this ion source, the plasma potential was small (around 1 V), and the sheath potential could thus be safely approximated to the probe voltage.

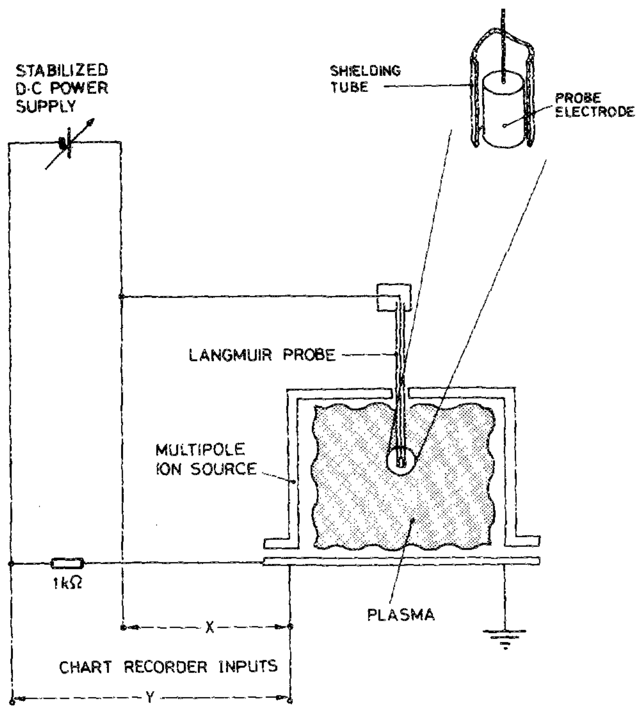

FIG. 3. Experimental arrangement used to study sheath expansion.

The data showed that the ion current increased in a nonlinear fashion with probe voltage. To reliably fit a line to this region, it was necessary to identify the index of expansion, here denoted γ. Assuming that I_m may be expressed in terms of a constant saturation current I_+ and a voltage-dependent term;

$$I_m = I_+ + \beta I_+ V^\gamma,$$

where β is a constant. Differentiating this yields

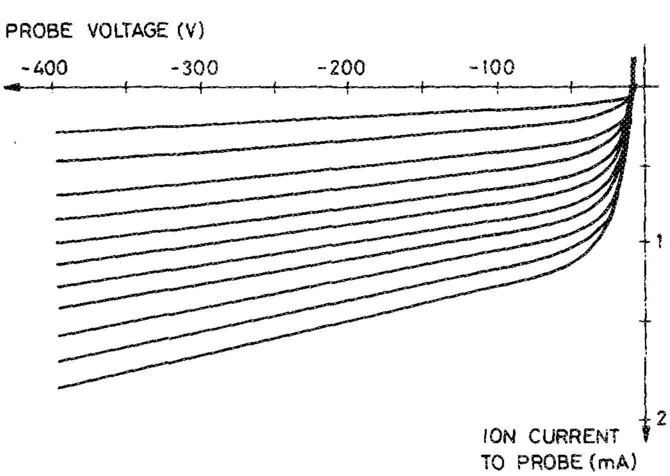

FIG. 4. Typical probe characteristics obtained from the expansion experiment (various arc currents 1–25 A, arc voltage = 60 V, pressure = 3 mT).

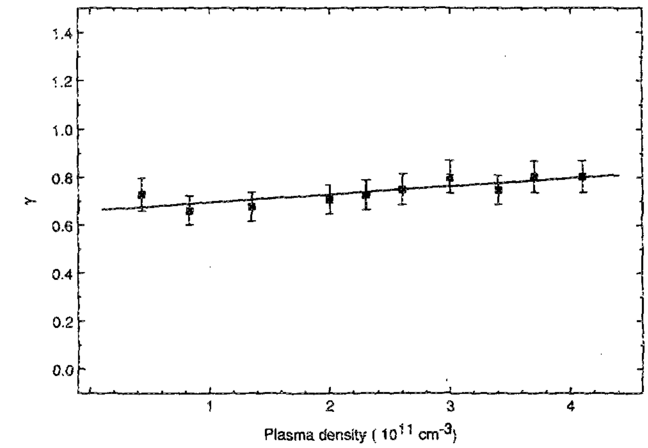

FIG. 5. Variation of index of expansion γ with plasma density (arc voltage = 60 V, pressure = 3 mT).

$$\frac{dI_m}{dV} = \beta\gamma I_+ V^{\gamma-1}.$$

Since I_+ is constant, taking the logarithm of both sides gives

$$\ln\left(\frac{dI_m}{dV}\right) = \ln(\beta\gamma I_+) + (\gamma - 1)\ln(V). \tag{8}$$

A plot of $\ln(dI_m/dV)$ vs $\ln(V)$ will therefore have a gradient of $(\gamma - 1)$. In analyzing the data, (dI_m/dV) was first calculated numerically for a set of points on each trace. A logarithmic plot of this against probe voltage yielded a line, from which a value of γ for the trace could be obtained. By this means, the variation of γ was studied with respect to the plasma parameters. The results (Figs. 5 and 6) show that over a wide range of conditions:

$$0.7 \leqslant \gamma \leqslant 0.8.$$

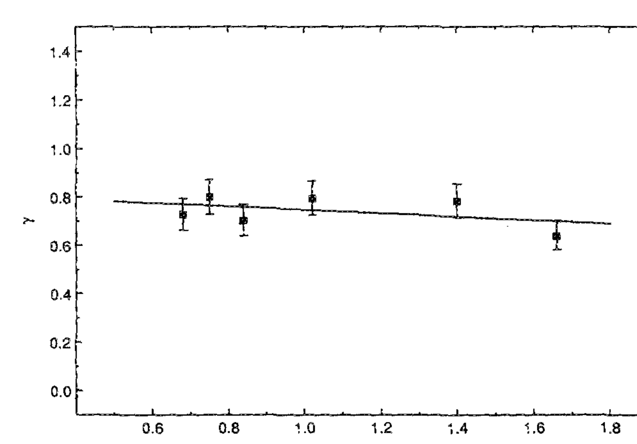

FIG. 6. Variation of index of expansion γ with electron temperature (arc current = 5 A, arc voltage = 60 V).

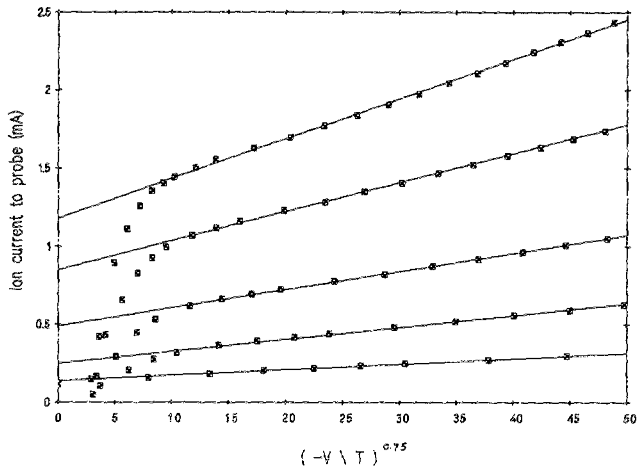

FIG. 7. Ion saturation characteristics corrected for sheath expansion (various arc currents 1–15 A, arc voltage = 60 V, pressure = 3 mT).

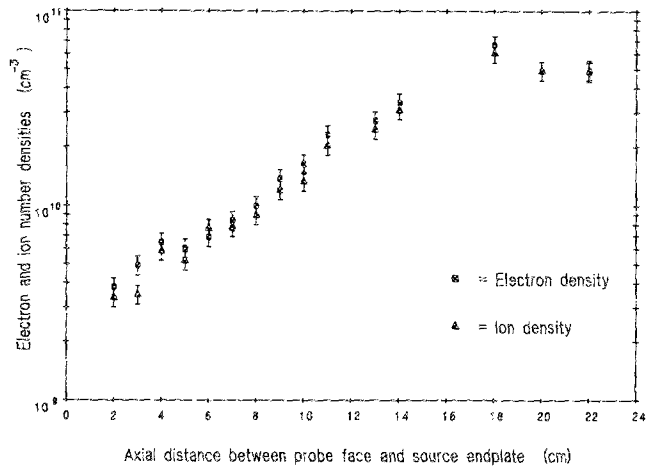

FIG. 8. Equivalence of electron and ion densities obtained from corrected probe measurements in a helium discharge (arc current = 5 A, arc voltage = 60 V, pressure = 3 mT).

IV. DISCUSSION

The theoretical relationship predicts that the additional current due to sheath expansion will grow proportionally less as the plasma density and probe radius increase. This is reasonable, the first being a consequence of the Debye screening mechanism and the second reflecting the simple geometrical relationship of the area of a circle to it's circumference. As already noted,[5] experimental evidence suggests that larger probes in denser plasmas suffer less from sheath expansion. A better test of the theory may be obtained by replotting the *I-V* characteristics of Fig. 4, replacing the voltage ordinate with the function $(V/T)^{0.75}$. As may be seen in Fig. 7, if the region between -60 and 0 V distorted by the presence of high energy "primary" electrons is ignored, an extremely good correlation is obtained.

The variation with plasma density requires that rigorous application of Eq. (7) to find J_+ at any particular potential be an iterative process. However, all that is actually required is the voltage-independent ion current I_+. To obtain J_+, a line is fitted as described above to ion saturation region data obtained at probe potentials greater than the arc voltage. The gradient of this line may be used to subtract the voltage-dependent contribution to I_m from the data. A line of zero gradient should result. I_+ is therefore given by the "*Y*" intercept of the original line, and a measure of its accuracy by the inverse of the gradient of a line fitted to the corrected data.

The effectiveness of the technique in removing spurious contributions to the ion density may be assessed from Fig. 8, which shows simultaneous ion and electron densities calculated from probe data obtained in a helium discharge. It may be seen that these are equal to within the limits of error, as required by plasma neutrality. Previously,[9] experimenters have reported large discrepancies in this ratio when operating small planar probes in noble gas discharges. Since the electron saturation current is generally an order of magnitude greater than I_+, under typical field-free conditions electron densities may be measured more accurately with probes than ion densities.

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