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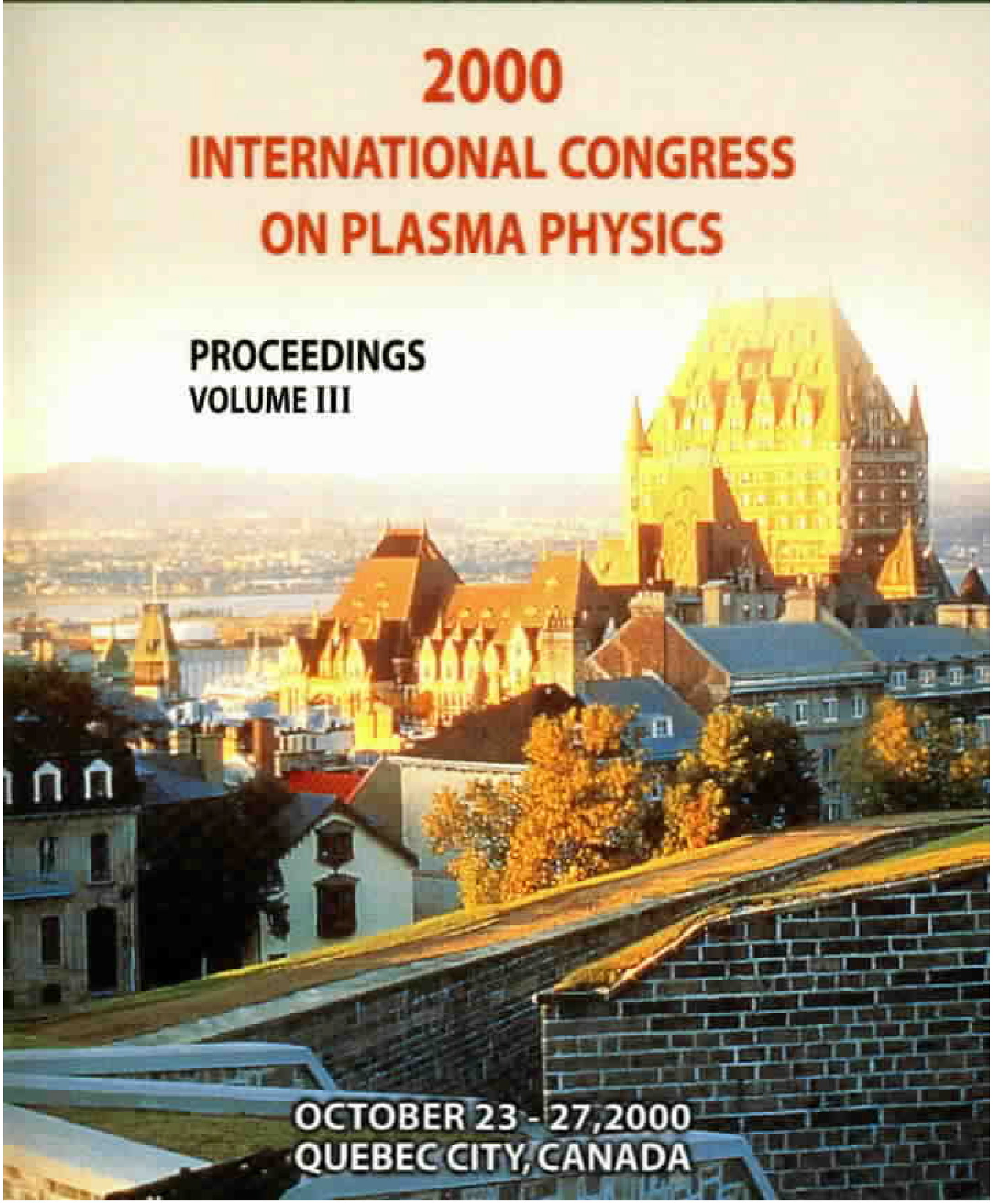

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Use of Langmuir probes in high density plasmas

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In this paper, existing calculations of saturation ion currents I_i to Langmuir probes at potential V_p are digitized and parametrized so that I_i — V_p curves for given plasma density n, electron temperature T_e, and space potential V_s can be reproduced in dimensional units rapidly on personal computers. Secondly, an iteration technique is used to separate the ion and electron currents in their overlap region near the floating potential. Probe measurements in an inductively coupled plasma (ICP) of the type used in semiconductor etching, were made in argon at various densities, pressures, RF powers, and probe radii R_p; and in one series n was measured also by microwave interferometry. Results show that the collisionless theories do not agree at large values of the parameter $x \equiv R_p/\lambda_D$ (λ_D = Debye length) and given values of n bracketing the real value. The discrepancy is thought to be due to charge-exchange collisions in the presheath.

The main theories of ion collection are (a) the original orbital motion limited (OML) theory of Langmuir, the Allen-Boyd-Reynolds (ABR) theory [1], and the Bernstein-Rabinowitz theory [2] as extended to Maxwellian ions by Laframboise [3] (BRL). OML accounts for ion angular momentum but neglects the formation of thin sheaths. ABR includes sheaths but neglects orbiting. BRL accounts for both, but computed I_i— V_p curves exist only for a few values of x and are hard to reproduce. Furthermore, the curves are in dimensionless units which depend on the values of n, T_e, and V_s that one wants to determine. These curves can be generated from the function

$$\frac{1}{i^4} = \frac{1}{\left(Ah^B\right)^4} + \frac{1}{\left(Ch^D\right)^4}, \quad \text{where } h \equiv -\frac{e(V_p - V_s)}{KT_e}, \; i = \frac{I_i}{enA_p}\left(\frac{KT_e}{2p M}\right)^{-1/2}, \tag{1}$$

and the parameters $ABCD$ are functions of x. These functions are then further parametrized by fitting them to the following forms:

$$A = a + \frac{1}{\dfrac{1}{bx^c} - \dfrac{1}{d\ln(x/f)}}; \quad B,D = a + bx^c \exp(-dx^f); \quad C = a + bx^{-c}, \tag{2}$$

where different coefficients $abcdef$ apply to each parameter $ABCD$, as given in Table 1. These coefficients can reproduce the Laframboise curves to within 5%.

To separate the ion and electron currents, first guess the values of n, T_e, and V_s and compute the theoretical ion curve using Eqs. (1) and (2). Then make a least-squares fit with the data by varying n and T_e. Fig. 1 is an example of such an I_i^2 — V plot. In general, the data

Table 1

	a	b	c	d	f
A	1.12	.00034	6.87	0.145	110
B	0.50	0.008	1.50	0.180	0.80
C	1.07	0.95	1.01	—	—
D	0.05	1.54	0.30	1.135	0.370

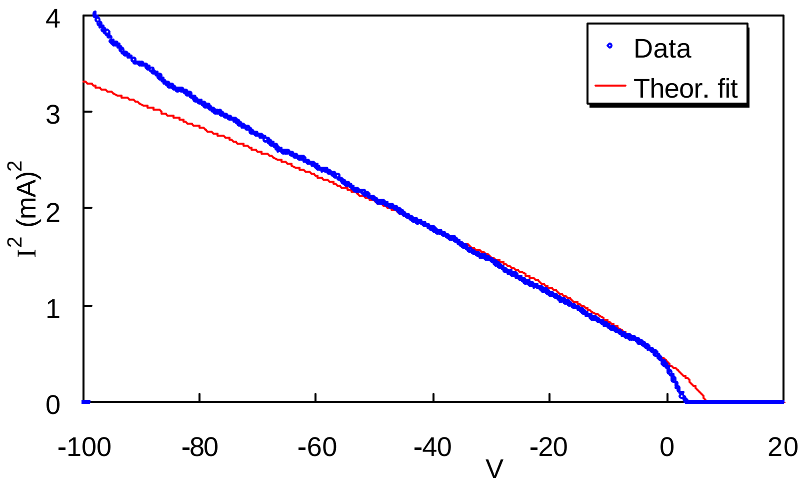


Fig. 1. Saturation ion current measured in a 2-MHz ICP at 200W in 20 mTorr of A, with a probe 0.15 mm in diam and 1 cm long. The lower curve is theoretical, computed from BRL for T_i = 0.

will follow a linear I_i^2 — V relation more closely than the BRL theory. Using this value of n, one can then plot the electron current semilogarithmically, assuming a Maxwellian:

$$I_e = neA_p(KT_e/2\pi m)^{1/2}\exp[e(V_p - V_s^e)/KT_e], \tag{3}$$

where V_s^e is, unfortunately, different from the value of V_s used to fit the ions. This straight line is shown in Fig. 2 together with the raw data and I_e with the *theoretical* ion current subtracted. It is seen that the modified data follow a straighter line. The values of T_e and V_s^e

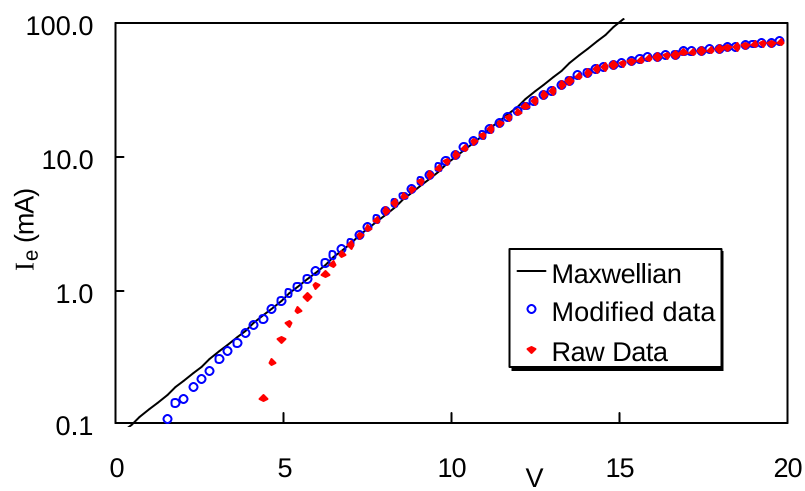


Fig. 2. Semilog plot of I_e vs V for the case of Fig. 1.

are then adjusted for the best fit. Using the new value of T_e, the ion curve can be recomputed and n readjusted. If the modified I_e is then subtracted from the ion data, the following I_i—V curve results (Fig. 3):

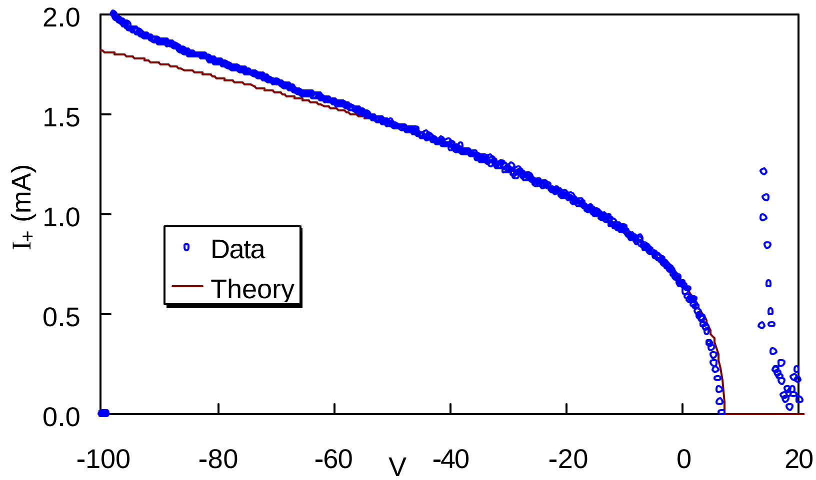


Fig. 3, Fit of I_i—V curve after iteration.

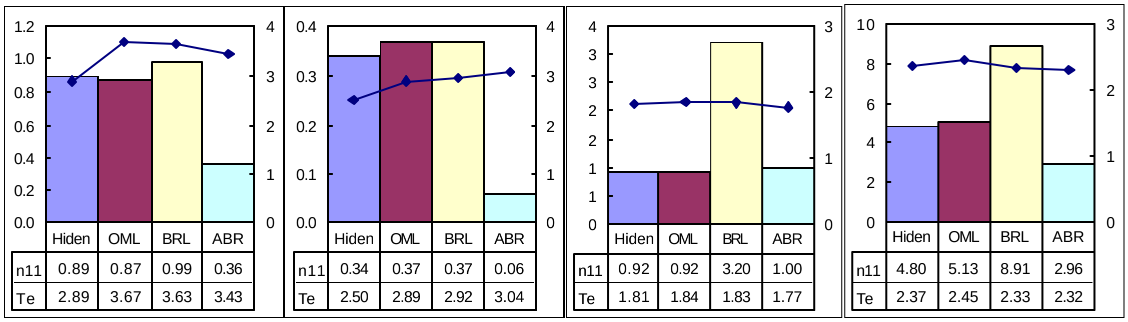
The points at the right beyond V_s appear because different values for V_s had to be used to fit I_i and I_e. This is an unresolved problem. The theory for I_i near V_s is subject to uncertainty, and the value of V_s is sensitive to the curvature there. This points out the danger in computing the electron energy distribution function from the $I - V$ curve near the floating potential.

Since the ABR theory yields I_i — V curve closer in shape to the data, this theory was also double-parametrized in a similar manner, using the computations of ABR theory by Chen [4] for cylindrical probes. The OML theory has the following simple form for $T_i = 0$:

$$I \xrightarrow[T_i \to 0]{} A_p ne \frac{\sqrt{2}}{p} \left(\frac{|eV_p|}{M} \right)^{1/2} . \tag{4}$$

The software for the ESPion® probe of Hiden Analytical, Ltd. uses OML theory. We have analyzed a large number of $I - V$ curves using these three theories. Examples for four values of x are shown in Fig. 4. The resulting values of T_e are insensitive to the theory used, but the n values differ widely. OML fits the shape of the curves best, but it should not be valid for $x > 3$ and requires an unreasonably high value of V_s. The ABR theory gives too low a value of n, and the BRL theory shows more saturation than is observed.

The disagreement in densities found from different theories increases with x, as shown in Fig. 5, and reaches factors of 3 or more. In Fig. 6, BRL and ABR densities are compared with microwave interferometry measurements for increasing RF power. It is seen that ABR yields too low a density, as expected since orbiting is neglected and therefore too high an I_i is predicted. BRL yields too high a density. We believe that this is because orbiting to over-emphasized. In partially ionized plasmas, incoming ions can lose their angular momentum and be drawn in radially in their final trajectory. Curiously, the geometric mean of the BRL and ABR densities seems to agree with the microwave results.



$\xi = 1.1$ $\xi = 3.1$ $\xi = 4.6$ $\xi = 9.1$

Fig. 4. Values of T_e (points) and n (bars) obtained from different theories.

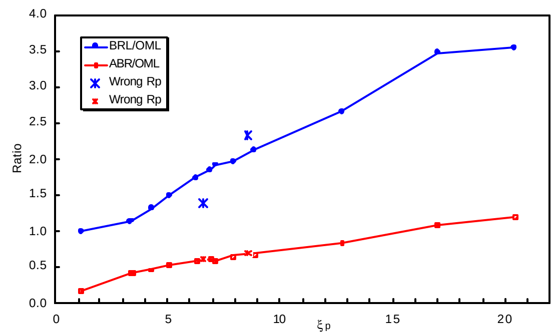


Fig. 5. Ratio of n obtained from BRL (upper curve) and ABR (lower curve) theories, normalized to that from OML theory. The points (*) lying off the BRL curve result if the wrong value of R_p is used.

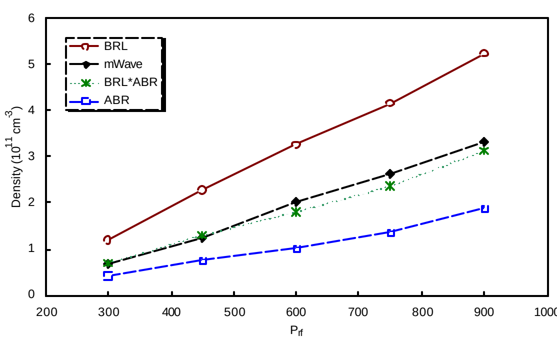


Fig. 6. Comparison of BRL (O) and ABR (ÿ) densities with microwave measurements (à). The (*) points are the geometric mean between the BRL and ABR densities.

Until a simple collisional theory is available for such plasmas, it is best to use small R_p at low n, so that OML can be used, and large R_p at high n, so that orbiting does not occur.

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[1] Allen, J.E., Boyd, R.L.F., and Reynolds, P. 1957 *Proc. Phys. Soc. (London)* **B70** 297
[2] Bernstein, I.B. and Rabinowitz, I.N. 1959 *Phys. Fluids* **2** 112
[3] Laframboise, J.G. 1966 Univ. Toronto Inst. Aerospace Studies Rept. 100 (June, 1966)
[4] Chen, F.F. 1965 *Plasma Physics* **7** 47