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Hart, D.A.; Oleson, N.L.

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Use of Langmuir Probes in Low-Pressure Rare Gas Plasmas

D. A. HART AND N. L. OLESON*
Department of Physics, Naval Postgraduate School, Monterey, California
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Evidence is presented which indicates that the assumption of zero ion energy yields best agreement between the results of probes and other methods for charge densities in the range of 10^9 to 10^{11} cm^{-3} in a xenon discharge of several mTorr.

We are concerned with the use of cylindrical Langmuir probes for measurement of electron densities in the weakly ionized plasmas of the positive columns of xenon gas discharges at pressures of a few mTorr. Electron densities encountered in these columns are typically in a range of 10^9 to 10^{11} cm^{-3} and the electron temperatures are on the order of 3–5 eV. The usual technique of obtaining electron densities from the current-voltage characteristics of probes in these plasmas is to determine the electron saturation current which occurs when the probe is biased to the space potential of the plasma. In practice, however, this method has at least two disadvantages. Firstly, the magnitude of the electron saturation current may be large enough to seriously affect the plasma being measured. In some cases of low density, for example, the probe can extract electrons from the plasma volume faster than the electrons can rebuild their unperturbed energy distribution.[1,2] Secondly, noise and low amplitude moving striations in the kilohertz frequency range are often present in low-pressure rare gas discharges. These oscillations cause the electron saturation "break" point of the characteristic curve of the probe to become rounded and ill defined and can result in large errors in establishing the magnitudes of the space potential and the electron saturation current.[3] For these reasons it would be desirable to employ the saturation ion currents for establishing densities, but often the range of parameters is such that the classical Langmuir theory is not applicable.

In the past few years, several unified theories of the Langmuir probe have been published.[4-7] Numerical evaluations of current-voltage characteristics for some of these formulations have been presented by Chen.[8] Of particular interest here are the characteristics of a cylindrical probe for which Chen considers two cases depending on the ratio of ion energy to electron energy, $\beta = E_i/kT_e$, which is assumed to be either zero or finite. The theory for finite β does not converge to that for $\beta = 0$ in the limit $\beta \to 0$ due to slightly different formulations. A validity condition for the $\beta = 0$ case is

$$-\frac{E_i}{eV_p} \ll \frac{r_p^2}{\lambda^2}, \tag{1}$$

where r_p is the probe radius, λ is the ion mean free path for collisions with neutrals, V_p, is the probe potential with respect to space potential, and e is the magnitude of the electronic charge. For the plasmas considered here the left-hand side of the above inequality is smaller than the right but not negligibly so.

Messiaen and Vandenplas[9] have made comparison in a mercury plasma of densities obtained from the $\beta = 0$ calculations of Chen to densities measured from electron saturation currents and to densities obtained from a dipole resonance probe. The experiments were performed at milliTorr pressures and good agreement was found between the various methods. In mercury vapor the space potential is

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* Present address: Department of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

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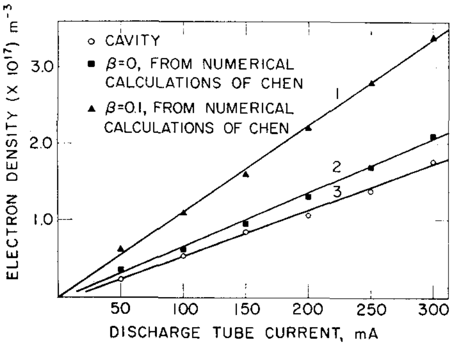

FIG. 1. Results of analysis of ion characteristics of a Langmuir probe in a xenon plasma column compared with cavity measurements of electron density. Pressure 4.8 mTorr, tube radius 0.4 cm, average electron temperature 3.3 eV (from probe measurments). Curve 1: Bernstein and Rabinowitz,[5] $\beta = 0.1$. Curve 2: Allen, Boyd and Reynolds,[4] $\beta = 0$. Curve 3: Cavity measurements.

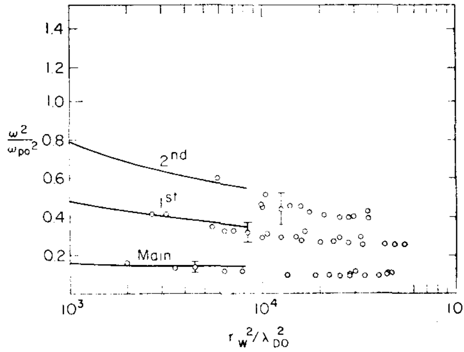

FIG. 2. Dipole resonance spectrum xenon, 1.2 mTorr, $K_{eff} = 3.74$, $T_e = 3.6$ eV, $r_w = 1.56$ cm. Comparison of charge densities using ion saturation portion of Langmuir probe measurements with theory of Parker, Nickel and Gould.[12] Open circles, experiment. Solid curves, theory. Average electron temperature from probe measurements. ω represents the resonance frequency, ω_{p0} and λ_{D0} are the electron plasma frequency and the Debye length at the center of the column, respectively.

somewhat easier to locate due to the relative absence of noise and oscillations compared with the rare gases and the magnitude of the electron saturation current is small enough not to affect the plasma. Although the validity condition [inequality (1) above] was not satisfied, the $\beta = 0$ calculations give best agreement with other methods of measuring densities, i.e., electron saturation currents and the dipole resonance probe.

In a recent experiment we have compared densities obtained from ion saturation currents of a Langmuir probe in a xenon plasma (containing moving striations of very small amplitude) to average densities obtained by measuring the resonant frequency shift of a cylindrical microwave cavity operating in the TM_{010} mode. The discharge column was inserted through the cavity and the densities were calculated from the frequency shift using a perturbation theory.[10] The discharge tube was 1 cm outside diameter 0.8 cm inside diameter operated at a pressure of 4.8 mTorr and the probe (length 6.3 mm, radius 0.19 mm) was located at the center of the column a few centimeters from the location of the microwave cavity. Probe current-voltage characteristics were taken with the help of an x-y recorder. The results obtained, as the discharge current was increased from 50–300 mA are shown in Fig. 1. From a theory for the radial profile of electron density in the positive column by Parker[11] it is expected that the average electron density in the positive column is about 0.7 times the density at the center of the column for the range of parameters encountered in this experiment. The cavity measurements give densities that are averages over the tube cross section and from Fig. 1 it is seen that the results obtained for average densities are about 0.8 times the densities obtained from the probe using the $\beta = 0$ calculations of Chen. The $\beta = 0.1$ case for analysis of the probe characteristics, on the other hand, gives densities that are about two times the average densities measured by the cavity. From these measurements it appears that the $\beta = 0$ theory yields better agreement with cavity measurements for the range of parameters covered dispite the fact that dependence on β is slight for the finite β theory. (It is estimated that β is on the order of 0.01 in the present case.)

Some additional evidence supporting the use of $\beta = 0$ numerical computations has been obtained in xenon in a larger 3.5-cm o.d., 3.1-cm-i.d. column at 1.2 mTorr. Densities covering a range from 3×10^9 to 4×10^{10} cm^{-3} were obtained from the ion saturation region of Langmuir plots making use of the $\beta = 0$ calculations of Chen. Resonant frequencies for Tonks–Dattner resonances were obtained in the uhf range using split cylinder electrodes. The circles of Fig. 2 shows the results of resonant frequency ω versus density n plotted in terms of the dimensionless parameters ω^2/ω_{p0}^2 and r_w^2/λ_{D0}^2. The variables $\omega_{p0} = (me^2/m\epsilon_0)^{\frac{1}{2}}$ and $\lambda_{D0} = (\epsilon_0 kT_e/me^2)^{\frac{1}{2}}$ are the electron-plasma frequency and the Debye length, respectively, at the center of the column. K_{eff} is a constant dependent on the electrode configuration, tube radius r_w, and the tube wall thickness. Both the main and the first and second Tonks–Dattner resonances are plotted. The solid curve in each case is the corresponding resonance predictions

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of Parker, Nickel, and Gould.[12] From Figure 2 it is seen that densities obtained from the $\beta = 0$ calculations are within about 15% of the theory for a given resonance frequency. Densities obtained from finite β calculations of Chen give densities about 50% higher than predicted by the theory.

In conclusion, the $\beta = 0$ numerical calculations of Chen seem to be most appropriate for measuring densities in the region 10^9 to 10^{11} cm^{-3} in low pressure xenon discharges in that good agreement is found with other methods of measuring charge densities. Furthermore, the use of ion saturation currents has advantages over the use of electron saturation currents as previously discussed.

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Work was begun at the Naval Postgraduate School (and supported by the Office of Naval Research) and completed at the Massachusetts Institute of Technology [work supported by the United States Atomic Energy Commission under Contract AT (30-1)-3285].

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