# Technical Information

## Introduction to High Pressure Langmuir Probe Analysis Techniques


## Summary

This report provides a brief introduction to the analysis of Langmuir probe data obtained in high pressure discharges. A simple method for probe analysis is presented in relation to collisional and transitional operating regimes for the case of both thin and thick sheaths.


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## Introduction

Beyond the difficulties associated with main-taining clean probe conditions and the usual problem of obtaining representative Langmuir probe data, the I-V characteristics obtained in high pressure plasmas are considerably more complicated to analyse than collisionless plasmas. The impact of collisions is most dramatically seen in reduced current to the probe. In addition, the energy distribution of electrons reaching the probe is depleted of low energy electrons.

To illustrate, the measured ion saturation current collected by a <1>=0.25mm probe in an 4eV Argon plasma with a neutral pressure of 10 Torr and an electron density of $10^{16}$ $m^{-3}$ is reduced by a factor of several hundred below that of a collisionless plasma. In general, collisions are usually ignored below operating pressures of 100 mTorr, even though collisional effects are present well below this pressure.

The discussion below presents methods of extracting the ion density, electron density and determining the electron temperature and EEDF. Operating regimes of the probe/plasma are also presented.

## Classification of Collisional Plasmas

Properly, the analysis of I-V characteristics of collisional plasmas requires classification of the plasma in conjunction with the probe dimensions and geometry. For a plasma to be considered collisional the electrons and ions must experience many collisions in the sheath. However, there exists a grey area between a collisional and collisionless plasmas in which current to the probe tip is heavily influenced by collisions, but not sufficiently that the behaviour can be described using collisional theory alone. These are known as transitional plasmas. Formally, the division between collisional, transition and collisionless is described by the relation between the mean free path for collisions between electron and neutrals, $\lambda$e-n, and the Debye length, $\lambda$D, as shown in Table 1.

*Table 1: Collisional Classification*

| | |
|---|---|
| Collisional | $\lambda_{e\text{-}n} < 4\lambda_D$ |
| Transitional | $\lambda_{e\text{-}n} \sim 4\lambda_D$ |
| Collisionless | $\lambda_{e\text{-}n} > 4\lambda_D$ |

The coillision mean free path e-n, is related to the operating pressure by;

$$\lambda_{e-n} = \frac{0.061}{P(mTorr)}[m],$$

where P is pressure in mTorr and an electron-neutral cross section of $5 \times 10^{-19}$ $m^2$ has been assumed.

Probe response is further dependant upon the thickness of the sheath in relation to the probe dimensions. For probes surrounded by a thick sheath ion current is modified by the fact that the effective probe area is significantly greater than the actual area of the probe surface as well as the fact that ions undergoes significant orbital motion. The boundary between thin and thick sheath is somewhat arbitrary and is shown in Table 2, below.

*Table 2: Thickness Classification*

| | |
|---|---|
| Thin Sheath | $4\lambda_d < R_p$ |
| Thick Sheath | $4\lambda_d > R_p$ |

## Electron Temperature and EEDF

For the case of a collisional plasma having a Maxwellian electron energy distribution function (EEDF) the electron temperature may be estimated using the same technique as with collisionless plasmas. However, matters are complicated by the fact that the energy distribution of electrons outside the sheath may not be representative of those reaching the probe surface since low energy electrons are depleted as they diffuse inward through the sheath. This effect becomes more significant as the pressure increases such that at pressures of 10mT only the high-energy tail of the distribution is reliable. This assumes careful subtraction of the ion from the total current in determining the electron current characteristic.

This depletion of low energy electrons in the EEDF can be corrected for by the modified Druyvesteyn formula developed by Swift [4] as follows:

$$\frac{d^2 I_e}{dV_p^2} = \tfrac{1}{4} e A_p n_o \left( \frac{2e}{m_e V_p} \right) F(V)\Big|_{V=V_p} \times (1 - GH)$$

where:

$$G = \int_{V_p}^{\infty} \frac{V^{-\frac{3}{2}} F(V)\, dV}{(1 + \frac{1}{2} H (1 - V_p / V))^3} \Big/ \left( V_p^{-\frac{1}{2}} F(V) \Big| V = V_p \right.$$

$$H = \frac{3 (R_p / \lambda_D)^2}{2 (1 + R_p / \lambda_D)}.$$

and:

- $I_e$ = electron current collected by probe
- $A_p$ = probe area
- e = electron charge
- $n_o$ = electron density
- me = electron mass
- Vp = probe potential
- F(V) = electron energy distribution function
- $\lambda D$ = the Debye length
- Rp = the probe tip radius

The aforementioned formula is accurate to within 25% for electrons with energies greater than $^1/_2$ <$V_e$> provided $R_p < {}^1/_2\, \lambda_{e\text{-}n}$ and the product of pressure and probe radius is below a constant dependant upon the gas as shown in Table 3.

*Table 3: EEDF Accuracy Constants*
*(Swift, J.D, Proc. Physical Soc. 79 (162) 697)*

| Gas | P (Torr) x $R_p$ (cm) |
|---|---|
| $H_2$ | $1.8 \times 10^{-2}$ |
| $N_2$ | $1.5 \times 10^{-2}$ |
| $O_2$ | $1.5 \times 10^{-2}$ |
| Ne | $8 \times 10^{-2}$ |
| He | $3 \times 10^{-2}$ |

## Electron Density

For collisional plasmas the electron density can be inferred using the following equation for a spherical probe [ ]:

$$I_e = -\tfrac{1}{4} n_e e \langle v_e \rangle \alpha A_p \left( \frac{R_p + \lambda_{e-n}}{R_p} \right)^2 \left( 1 + \frac{3\alpha (R_p + \lambda_{e-n})}{4 \lambda_{e-n}} \right)^{-1}$$

This equation is valid $R_p \leq \lambda_{e-n}$, where the term $\alpha$ is the sticking co-efficient and assumed unity for a perfectly absorbing probe, and $A_p$ represents the probe surface area. For very high pressure, $R_p >> \lambda_{e-n}$, the above reduces to

$$I_e = -\tfrac{1}{4} e n_e \langle v_e \rangle A_p \left[\tfrac{4}{3} \lambda_{e-n} / R_p\right].$$

## Ion Density

Table 4 provides a summary of various equations to determine the ion density for the various operating regimes. [ ] Formulae are provided for both spherical and cylindrical probe geometry, except for the case of the collisional thick-sheath operating regime in where an analytic solutions exists for spherical geometry only.

In collisionless plasmas it is often possible to determine ion density without prior knowledge of the ion or electron temperature. This is not possible in collisional plasmas since both the ion and electron current to the probe are dependent on the diffusion process as well as the variation of the sheath potential. Extracting ion density from the ion current requires knowledge Ti which is necessary to calculate the ion mobility (diffusion). The ion mobility, $\mu$i is calculated as:

$$\mu_i = \frac{eD}{kT_i}$$

and where D is the diffusion constant given by:

$$D = \tfrac{1}{3} \langle v_i \rangle \lambda_{e-n}.$$

The ion mobility is thus a function of the collisional mean free path between ions and neutrals as well as the thermal energy and average velocities of the ions.

The ion temperature is usually assumed equal to that of the neutral gas temperature and in most instances this is a valid approximation.

In the collisional thick sheath-operating regime, the sheath expands significantly for very negative biases and the saturation current increases with probe bias.

In the transitional case, analysis based solely on collisionless or collisional theory is inadequate to determine the ion density. In this instance, the ion saturation current can be determined by the impedance model [ ] which assumes that the ion saturation probe current can be determined by assuming the total current is the sum of the collisional and collisionless currents added in parallel as shown in the table. In this technique, a reasonable ion density is first guessed at and the resulting collisional and collisionless ion currents are determined. This value is then compared to the measured current and a new value of ni is estimated until the calculated and measured results are self-consistent-- which may require several iterations.

No equations are indicated for ion current in the transitional thick sheath operating regime. This is an unlikely operating regime and in any case, can be avoided by the choosing a different probe radius.

*Table 4: Summary of Ion Current Collection Formulae*

| | Thin Sheath | Thick Sheath |
|---|---|---|
| **Transitional** | $\lambda_{e\text{-}n} \sim R_p \sim 4\lambda_D$<br><br>Impedance Method: Addition of current from thin sheath collisional and collisionless case. Cylindrical and Spherical Probes. Knowledge of Te, Ti required<br><br>$1/I_{total} = 1/I_{collisional} + 1/I_{collisionless}$ | $\lambda_{e\text{-}n} \sim R_p < 4\lambda_D$<br><br>Retake data using bigger probe radius and analyse as thin transitional sheath case |
| **Collisional** | $\lambda_{e\text{-}n} < 4\lambda_D < R_p$<br><br>Knowledge of Te, Ti required | $\lambda_{e\text{-}n} < R_p < 4\lambda_D$<br><br>Knowledge of Te, Ti required |
| Spherical | $I_1 = 4\pi e \mu_I n_o (kT_e + kT_i) R_p$ | $Ii = 4\pi\varepsilon_{o)}{}^{1/4}(R_p)^{1/2}(n_o kT_e)^{3/4}(V_p \sim V_b)^{1/2}\mu_I(1+Ti/Te)$ |
| Cylindrical | $I_1 = 2\pi L e \mu_I n_o (kT_e + kT_i)/1n(\pi L/4R_p)$ | N/A |

Where

$Ii$ = the ion saturation current

$kTe$, $kT_i$ = the electron, ion temperatures

$n_o$ = ion density

$R_p$ = probe radius

$L$ = probe length

$\mu_I$ = $eD/kT$ the ion mobility

$D$ = $^1/_3\, \lambda_{e\text{-}n} \langle V_i \rangle$ is the diffusion constant

$\lambda_D$ = Debye Length

$\langle V_i \rangle$ = average electron velocity

## Conclusion

The analysis of Langmuir probe traces in high pressures requires modifications of the techniques used for low pressure collisionless plasmas. In this report a method to determine the electron density for collisional plasmas measured

with spherical probes was presented along with a discussion of the effect of collisions on the determination of the electron temperature and EEDF. Further, equations were presented to allow the calculation of ion density on the basis of the operating regime for both spherical and cylindrical probes.

The above discussion is intended only as a brief introduction to the methods of analysing high pressure collisional plasmas and is thus far from complete. For more complete information and discussion, the reader is advised to consult the following references.

## References:

**[1]** Chen, F.F., Electric Probes, in Plasma Diagnostic Techniques, (Ed. R.H. Huddlestone and S.L. Leonard), Academic Press, NY, 1965.

**[2]** Ruzic, D.N., Electric Probes for Low- Temperature Plasmas, American Vacuum Society, 1994.

**[3]** Shott, L., Electrical Probes, in Plasmas Diagnostics, (Ed. W. Lochte-Holtgreven), AIP Press, Woodbury NY, 1968.

**[4]** Swift, J.D., Proc. Phys. Soc. 79 (1962) 697.

**[5]** Thorton, J. A., AIAA Journal 9 (1971) 342.