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Density and temperature profile of argon plasma in a plasma device

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Abstract

A single Langmuir probe measurements were performed in argon plasma of a plasma device. The plasma device is a cylindrical tube with a filament electrode at one end and plane electrode at the other end. Probe was designed to move longitudinally along the cylinder and to rotate around its axis for sweeping points at any radial position. A straight forward method based on the theory of Langmuir probe is generated for obtaining the plasma temperature and density from I-V characteristics of the probe in non-equilibrium cold plasma. Results show that for the argon plasma at 1.2×10^{-2} mbar working pressure and 2000 V voltage of discharge, the number density of electrons is much larger than that for ions, while the ion saturation current is negligible and the distance for plasma generation in this range of plasma pressure and discharge voltage is about 6 cm from the cathode toward the anode.

***PACs*:** 52.70.Nc; 29.25.Ni; 52.50.Dg; 52.80.Hc
Keywords: *Langmuir probe; Debye sheath; I-V characteristics; Bohm sheath criterion; floating potential*

1. Introduction

Langmuir probe (LP) is a device named after Nobel Prize winning physicist Irving Langmuir, to determine the electron temperature, electron density, and electric potential of plasma [1]. It works by inserting one or more electrodes into the plasma, with a constant or time-varying electric potential between the various electrodes or between them and the surrounding vessel. I-V characteristic is taken from a circuit consisting of a small metallic electrode (probe) of plane, cylindrical or spherical shape immersed in the plasma, a reference electrode, and variable external dc power supply. In single probe measurement the reference electrode is one of the discharge electrodes, and in double probe measurements a second immersed probe can be used as the reference probe. Generally, the immersed electric probe represents a disturbance of the plasma around the probe position due to space charge sheath in front of the probe surface and the extraction of charged particles. Despite the relative simple technique, specific conditions have to be fulfilled for accurate analysis of the plasma parameters derived from the I-V characteristic [2]. LPs are widely applied to determine experimentally the local electron energy distribution function or electron temperature in the case of plasma with Maxwellian distribution, local electron and ion density and potentials. Although in the hot plasma LPs can be used just in the plasma edge to avoid any extra perturbation in the plasma but in cold plasma LPs can be employed to measure plasma parameter everywhere in the plasma chamber.

In this paper, we present experimental determination of plasma parameters with single LP in a plasma device (PD). Following this brief introduction, the experimental set up is presented in section 2. A new technique based on Merlino et al. [3] model is generated to measure the plasma parameters which is explained in detail in Section 2. Experimental results and discussion are briefed in Section 3, while the conclusion is presented in Section 4.

2. Experimental details and method

The schematic of cold plasma device in which experiments were performed is presented in Fig. 1. The PD consists of a cylindrical vacuum vessel of 16.4 cm diameter and 60 cm length. The whole tube is evacuated down to 6.4×10^{-4} mbar by a turbo molecular pump backed by a rotary pump. Argon gas is introduced into the system under continuous pumping conditions at a working pressure of 1.2×10^{-2} mbar. Plasma in the tube is produced by DC discharge between a line filament near one end of the tube while the other end of the tube is grounded. The discharge currents and voltages are set to 100 mA and 2000 V, respectively, for the whole set of experiments. In this structure, the plasma can be assumed to be cylindrically symmetric. To determine the plasma parameters, a movable single LP is designed and constructed, which is also schematically presented in Fig. 2 with its control circuit. The Langmuir probe is made of a narrow quartz pipe with cylindrical tungsten tip. The length of the probe tip is vertically 10 mm and its radius is 0.3 mm. The probe can be moved longitudinally along the tube length (z axis) and by rotating the probe measurements can be carried out at different radial points (r direction). With these two motions all the points in

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the plasma tube can be swept by the probe tip. The probe was connected through a simple electrical circuit to a dc power supply ranging from 0 to 40 V with respect to the ground. The probe current as a function of the probe voltage was measured by a convenient ampere meter between the probe tip and the ground as is shown in Fig. 1.

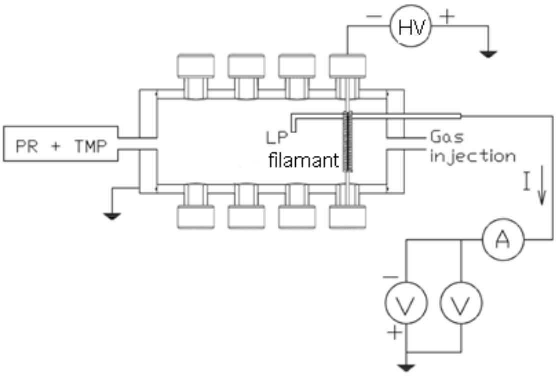

Fig. 1. Schematic of plasma device (PD) with Langmuir probe and its circuit.

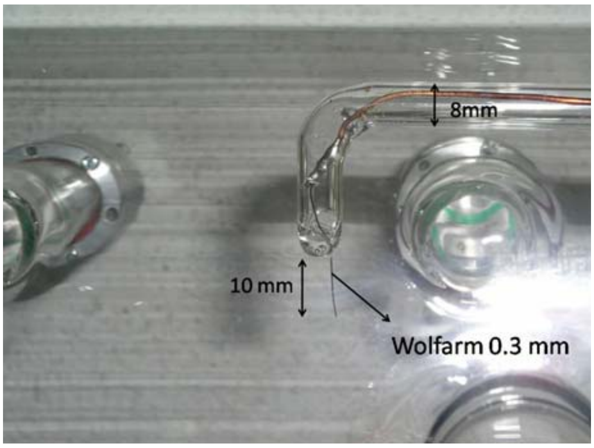

Fig. 2. Langmuir probe used for measurement of plasma parameters.

To measure the plasma parameters the probe was positioned at 5 axial points corresponding to r = 0, which are indicated in Fig. 3. One of them is $z = 0$ exactly at the center of the tube and others are at $z = \pm 3$ and $z = \pm 6$ cm distance from the center in both sides on the central axis of the tube. At each z, three radial positions were selected for measurement, namely r = 0, r = 2 cm and 3.4 cm corresponding to 0^o, 30^o and 60^o rotations, respectively.

In Fig. 4 the first look at the actual I-V characteristics is presented. There are several methods to deduce plasma parameters from this figure [4-6]. Here we have generated a straight forward method based on the theory proposed by Merlino [3] for obtaining the plasma temperature and density from I-V characteristics of Langmuir probe in non-equilibrium cold plasma.

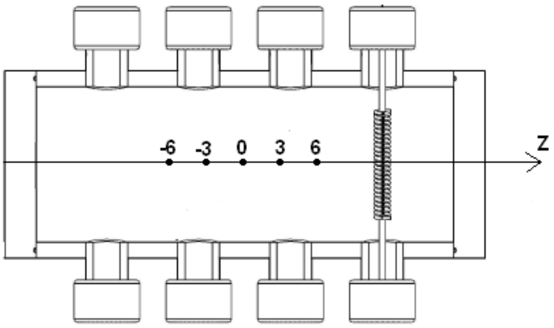

Fig. 3. Axial measurement points in the PD along its central axis. 0 is at the center of the tube and other points are at 3 and 6 cm from the center at both sides.

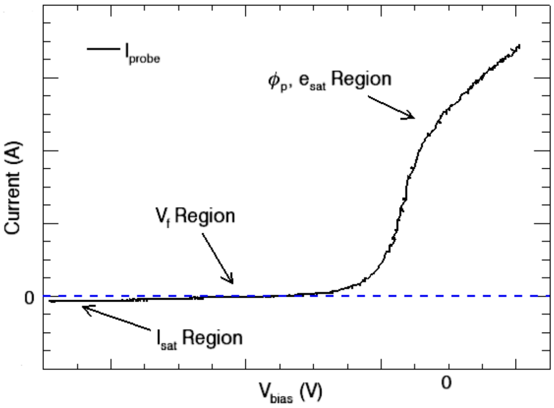

Fig. 4. Typical I-V characteristics of the Langmuir prob. Specific areas of interest are labeled.

In this figure the measured probe current is plotted as a function of applied probe bias voltage. Different plasma parameters can be deduced by analyzing this curve. The floating potential V_f, occurs where I_{probe}=0. Actually floating potential is the spatial plasma voltage with respect to the ground. If the negative voltage of the probe is large enough, essentially all electrons (and any negative ions) will be repelled. The ion velocity will satisfy the Bohm sheath criterion, which is, strictly speaking, an inequality, but is usually marginally fulfilled. The Bohm criterion in its marginal form says that the ion velocity at the sheath edge is simply the sound speed. In this condition, the ion saturation region occurs. The ion saturation current, I_{sat}, is seen at biases well below V_f. The ion saturation current density is given by:

$$j_{sat}^{ion} = en_eC_s, \qquad (1)$$

where the plasma parameters, in particular the density, are those at the sheath edge.

As the potential drop in the Debye sheath is reduced, the more energetic electrons are able to overcome the potential barrier of the electrostatic sheath. So the electron contribution to the current of the probe can be written in terms of the ion saturation current as:

$$j_{elec} = j_{ion}^{sat}\sqrt{m_i/2\pi m_e}\ \ exp(-e\varphi_{sh}/k_B T_e). \tag{2}$$

The total current of course, is the sum of the ion and electron currents:

$$j = j_{ion}^{sat}\left(-1 + \sqrt{m_i/2\pi m_e}\ \ exp(-e\varphi_{sh}/k_B T_e)\right). \tag{3}$$

We are using the convention that current from the surface into the plasma is positive [3]. An interesting and practical question is the potential of a surface to which no net current flows. It is easily seen from Eq. 3 that:

$$\varphi_{fl} = (k_B T_e/e)(1/2)ln(m_i/2\pi m_e). \tag{4}$$

It is not enough to know the current density as a function of bias voltage, since it is the absolute current which is measured. In an unmagnetized plasma, the current-collecting area is usually taken to be the exposed surface area of the electrode.

If we refer to the probe area by including these effects as A_{eff} (which may be a function of the bias voltage) and make the assumptions T_i=T_e, γ_i=3, $n_{e,sh}$=0.5 n_e and ignore the effects of bulk resistivity, and electron saturation, then the I-V characteristic becomes:

$$I = en_e\sqrt{k_B T_e/m_i A_{eff}}exp\left[\frac{v_{pr}-v_{ft}}{\frac{k_B T_e}{e}}\right]. \tag{5}$$

The roll-off at large positive values of V_{bias} (technically, in this case the largest values of V_{bias} approaches zero and may not actually become positive) corresponds to the electron saturation current, e_{sat}. As with the floating potential, some estimate of this value may be made from the plot, but a more accurate method will be used to determine the final value [4,5]. For swept Langmuir traces such as those presented here, the most important relationship between the measurement and plasma parameters is given by:

$$ln\left|I_{probe} - I_{sat}\right| = \frac{q}{k_B T_e}\left(v_{bias} - v_f\right) + constant, \tag{6}$$

where q is the electron charge, k_B is Boltzmann's constant, and the constant term is not be important. Notice that this relationship is in the form of a line given by a function f such that f (V) = mx + b, where m is the slope of the line and b is the y-intercept. If our x is actually x = V_{bias}-V_f, then the slope of this line is related to the electron temperature. This method is based upon the plot of term ln|I_{probe} - I_{sat}| and then fitting a line to it. The slope of this best fit is inversely proportional to the electron temperature. In order to continue with the analysis, it is necessary to subtract the value of the ion saturation current I_{sat},from I_{probe}. It is important to obtain an accurate value for I_{sat}, therefore we must be sure of careful reading of its value. Since the I_{sat} value is negative, subtracting it from I_{probe} will result in positive values for almost all I_{probe}– I_{sat}. This is our intention because we will be working with the natural logarithm of the current in the next few steps and the natural log is not defined for negative numbers. Those values will not play a role in the temperature calculation that follows.

Knowing both the electron temperature and the ion saturation current allows us to calculate the electron density using:

$$I_{sat} = A_s exp\left(-\frac{1}{2}\right)qn_e\sqrt{k_B T_e/M}, \tag{7}$$

$$n_e = \frac{T_e}{qA_s exp\left(-\frac{1}{2}\right)}\sqrt{M/k_B T_e}, \tag{8}$$

where the new terms are M for the ion mass and A_s which represents the area of the probe sheath. For cases in which the applied probe bias does not greatly exceed the value needed to obtain one of the saturation currents we may approximate the sheath area as the area of the probe tip. For significant over biasing this is not a good approximation. In most cases this criteria is met and the approximation is one of the smaller sources of error for probe measurements. The concepts of sheath expansion and Debye length with respect to probe size are worthy of discussion in another effort [3].

The value of M for argon is 6.62×10^{-26} kg. The cylindrical probe used to collect this data has an area of A_{probe} = 0.2826 cm^2 [6].

To calculate the electron density it is possible to directly insert the electron temperature in units of electron-Volts by noting the following relationship:

$$\frac{k_B T_e}{q} = T_e\ [eV], \tag{9}$$

where on the left side the temperature is in units of Kelvin.

3. Results and discussion

Result of the measurement for LP's I-V characteristic at the center of PD is shown in Fig. 5. This profile consists of two parts in the positive and the negative regimes of bias voltage of the probe. As is clear the floating potential V_f at the center of the discharge tube (occurs where I_{probe} = 0) is appeared to be -31.41 V and I_{sat} = -0.05 mA. According to the above mentioned notes there are two curves which are fitted to the two parts of the probe I-V plot. For the negative regime of the probe voltage the fitted exponential curve is:

$$\mathrm{I} = 2.2336\ \mathrm{exp}(0.105\mathrm{v}), \tag{9}$$

or:

$$\mathrm{Ln(I)} = 0.105\mathrm{v} + \mathrm{ln}(2.2336), \tag{10}$$

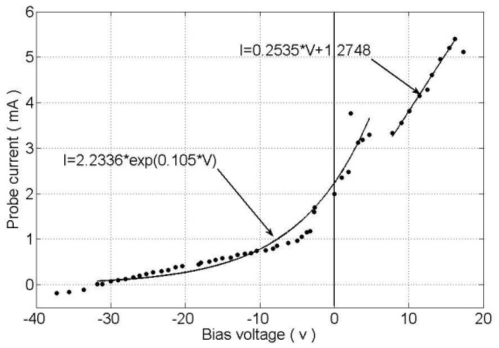

Fig. 5. Probe current plotted versus applied probe bias voltage at *z*=0 and on the axis.

and for the positive regime of the probe voltage the linear fitted line is given by:

$$I = 0.2535 \times v + 1.2748. \quad (11)$$

The least square method is used for obtaining the best fit to the experimental data.

Table 1. Values of T_e, n_e, I_{sat} and V_f for different positions of LP

		R = 0	R = 30	R = 60
Z = -6	T_e(eV)	2.1017	1.6071	1.2321
	$n_e \times 10^{15}$ (cm^{-3})	5.1014	4.1851	3.9114
	I_{sat} (mA)	-0.04	-0.03	-0.03
	$V_{floating}$ (V)	-17.75	-16.95	-14.88
Z = -3	T_e(eV)	3.8210	2.6117	1.8962
	$n_e \times 10^{15}$ (cm^{-3})	6.8308	5.1130	4.9114
	I_{sat} (mA)	-0.05	-0.04	-0.04
	$V_{floating}$ (V)	-22.35	-18.41	-18.2
Z = 0	T_e(eV)	9.5065	5.6887	3.8200
	$n_e \times 10^{15}$ (cm^{-3})	7.1431	5.2511	4.1838
	I_{sat} (mA)	-0.05	-0.05	-0.04
	$V_{floating}$ (V)	-25.41	-22.11	-19.18
Z = +3	T_e(eV)	9.6114	5.7113	3.7100
	$n_e \times 10^{15}$ (cm^{-3})	7.2411	5.4512	4.3114
	I_{sat} (mA)	-0.06	-0.05	-0.04
	$V_{floating}$ (V)	-25.81	-23.11	-20.10
Z = +6	T_e(eV)	9.8511	5.9510	3.8200
	$n_e \times 10^{15}$ (cm^{-3})	7.8152	6.1911	4.0110
	I_{sat} (mA)	-0.06	-0.05	-0.05
	$V_{floating}$ (V)	-26.11	-24.53	-21.14

Using Eqs. 9-11 and with the help of Eqs. 6-8 after substituting the quantities for our plasma device the electron temperature is found to be T_e = 9.5065 eV at the central point of the plasma tube. And the electron density is calculated to be $n_e = 7.1431 \times 10^{15}$ cm^{-3}. The results for measured plasma electron temperature and density at other points measured with the same procedure are presented in Table 1. In the plasma regime the ion saturation current in the I-V characteristics of the probe cannot be observed. This confirms that the total number of electrons (emitted from cathode and realized in ionization process) is much larger than ion density and the ion thermal velocity can be assumed to be zero.

In Fig. 6 the measured plasma electron density at the above mentioned points in the tube is demonstrated.

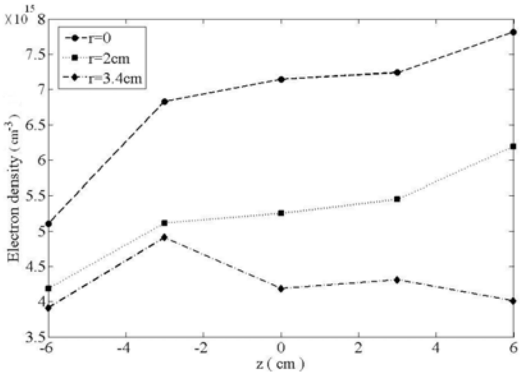

Fig. 6. Electron density measured at z = ±3 cm and ± 6 cm along the tube height at the central axis and 2 cm and 3.4 cm along the radial direction.

As can be seen the electron density decreases with increasing the distance from the filament electrode. In the experiment tube, plasma is generated by ionizing collisions. It shows that in this range of gas pressure and discharge voltage, the emitted electrons from cathode lose their energy in travelling along the tube to grounded anode. Uniform plasma with approximately constant density is formed in about 3.5 cm from the axis of the tube.

In Fig. 7 the electron temperature in different points of plasma device is presented. Up to 6 cm from the filament cathode electron temperature is constant but after this distance it suddenly falls down. In the applied voltage and pressure of this experiment the effective distance for plasma generation is about 6 cm from the cathode toward the anode and after that, electrons are so weak that no ionization will occur. There is no ionization due to secondary electrons. They are also very week. Of course ion flux toward the grounded anode expands the plasma in the whole tube.

Floating potential or plasma potential in different points of plasma device is shown in Fig. 8. Considering the plasma density and potential simultaneously confirms that decreasing the plasma electron density leads to increasing of plasma potential.

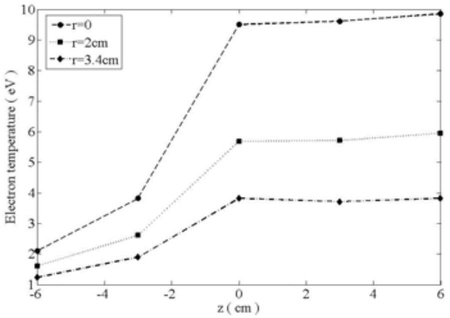

Fig. 7. Plasma electron temperature measured at z = ±3 cm and ± 6 cm along the tube height at the central axis and 2 cm and 3.4 cm along the radial direction.

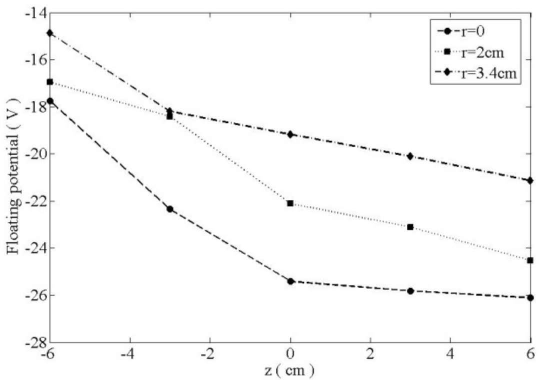

Fig. 8. Plasma potential measured at z = ±3cm and ± 6 cm along the tube height at the central axis and 2 cm and 3.4 cm along the radial direction.

In the pressure range which the present experiment is performed, decreasing the plasma electron density is analogous to the increasing of the number of negative electrons in Debye sphere (i. e., Gaussian surface). Therefore a more positive potential will appear in this region. This result is in good agreement with theoretical calculations and experimental reports [7,8].

4. Conclusion

The argon plasma characteristics in a cylindrical tube with a filament cathode and one end grounded anode discharge are investigated using the Langmuir probe technique. Results show that for the argon plasma at 1.2×10^{-2} mbar working pressure and 2000 V discharge voltage the number density of electrons is much larger than that for ions and the ion saturation current is negligible. The distance for plasma generation in this range of plasma pressure and discharge voltage is about 6 cm from the cathode toward the anode. Decreasing the plasma potential with increasing the plasma electron density is observed and electron energy is not enough for generating the secondary electrons.

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