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Influence of the Ion Mass in the Radial to Orbital Transition in Weakly Collisional Low-Pressure Plasmas Using Cylindrical Langmuir Probes

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Abstract: This paper presents an experimentally observed transition from the validity of the radial theories to the validity of the orbital theories that model the ion current collected by a cylindrical Langmuir probe immersed in low-pressure, low-temperature helium plasma when it is negatively biased with respect to the plasma potential, as a function of the positive ion-neutral collision mean free path to the Debye length ratio $\Lambda = \lambda_+/\lambda_D$. The study has been also conducted on argon and neon plasmas, which allows a comparison based on the mass of the ions, although no transition has been observed for these gases. As the radial or orbital behavior of the ions is essential to establish the validity of the different sheath theories, a theoretical analysis of such a transition not only as a function of the parameters Λ and $\beta = T_+/T_e$, T_+ and T_e being the positive ion and electron temperature, respectively, but also as a function of the ion mass is provided. This study allows us to recognize the importance of the mass of the ion as the parameter that explains the transition in helium plasmas. Motivated by these theoretical arguments, a novel set of measurements has been performed to study the relationship between the Λ and β parameters in the transition that demonstrate that the effect of the ion mean free path cannot be completely ignored and also that its influence on the ion current collected by the probe is less important than the effect of the ion temperature.

Keywords: plasma surface technology; cold plasma; ion temperature; ion-neutral charge-exchange collisions; ion mean free path; plasma diagnosis; Langmuir probe; sheath theories

1. Introduction

In low-pressure, low-temperature plasmas, the study of the positive ion current collected by the Langmuir probe is very important, as the smallness of the positive ion current collected by the Langmuir probe when it is polarized negatively with respect to the plasma potential allows local diagnosis of the plasma parameters with very low disturbance to the plasma. In other words, the positive ion sheath that is formed around the probe shields out the influence of the probe, which in plasmas with low plasma density is crucial [1–7]. On the other hand, many surface technological processes that use plasmas depend on the ion current that reaches the surface, and thus the control of the ion current is essential in this kind of technology. Among these processes, we have plasma-assisted chemical vapor deposition (PACVD), ion implantation, etching, surface coating, thin films, nanotechnology, etc. [8–13]. In the semiconductor industry, which is a major application of PACVD, the properties of the plasma must be closely examined in order to control the energy and the frequency of the ion impacts against the surface, so that the optimal conditions for ion implantation are obtained [8,10]. Therefore, both theoretical analysis and experimental studies of the ion sheath surrounding the surface to be treated are important.

The ion current collected by a Langmuir probe has been extensively studied from a theoretical point of view. There are two main groups of theories to explain the fall of the ions towards the probe. The orbital theories, of which orbital motion limited (OML) is the most frequently used, study the movement of the ions in orbits around the probe that are calculated using the applicable laws of conservation. Some ions have a trajectory that does not intersect with the probe surface and orbit back to the plasma, so that not all of the ions are collected by the probe [14–16]. The radial theories, the first being the Allen–Boyd–Reynolds (ABR) theory for a spherical Langmuir probe, study the plasma as a fluid, so that all the ions fall radially towards the probe and therefore all the ions that enter the sheath are collected by the probe [17]. The Allen–Boyd–Reynolds theory, which was soon adapted to cylindrical Langmuir probes by Chen [18], is valid for ions that have an ion temperature that is negligible when compared to the electron temperature, so that the parameter $\beta = T_+/T_e$, with T_+ and T_e as the positive ion and electron temperature, respectively, can be given a value of $\beta = 0$. The cylindrical radial model has been extended by the authors to $\beta \neq 0$ [1,2,19–24].

Both orbital and radial theories are used to diagnose plasmas to obtain plasma parameters such as plasma density. However, the values obtained using the two theories can be very different, the one predicted by the radial theory being up to an order of magnitude higher than the one predicted by the orbital theory. When the values of the plasma parameters deduced from these theories are compared to the values of the plasma parameters obtained using the much higher electron current in the electron saturation zone, depending on the plasma conditions, it is found that either the radial or the orbital theories are consistent with the well-established electron saturation zone theory. This implies a paradox when the ion current is used in plasma diagnosis, given that the appropriate theory that should be used is not known a priori before it is used in plasma diagnosis [1,4,25]. Actually, in many situations which depend on the plasma discharge power and the pressure, values for the ion current collected by the probe between the two theories are measured in experiments [5,26–28]. In two previous papers [26,28], the authors showed an experimentally observed transition in the positive ion current values that are derived from the radial theories and the orbital ones, as a function of the β parameter. The transition takes place only for helium plasmas. Similar experiments on argon and neon plasmas [1,2,19–24] show that the radial theory developed by the authors that takes into account the temperature of the ions, but does not take into account the mass of the ions or the ion mean free path, is successful in predicting the positive ion current.

Neither radial nor orbital models consider collisions in the calculation of the positive ion current of a negatively biased cylindrical Langmuir probe relative to the plasma. The most frequent collision of the ions in their fall towards the probe in low-pressure, low-temperature plasmas is the ion-neutral charge-exchange collision (INCEC) with the neutral atoms of the background gas [29,30]. In INCEC, an electron transitions from the neutral atom to the ion, effectively interchanging the moment between them. In radial models, this loss of moment is similar to a friction force in the fluid, so that the positive ion current is reduced. In the orbital models, the ions may lose their orbital velocity, so that, after the last collision, the ions will lose their angular momentum and fall radially towards the probe [1,2,5,7,17,18,26,28], increasing the positive ion current collected by the probe. The effect of collisions is opposed in both models and will affect not only surface technology but plasma diagnosis methods, both depending on the positive ion current.

Electropositive plasmas can be studied by means of three parameters—that is, the ion to electron temperature ratio, the ion mean free path to Debye length ratio and the ion mass [22,31]. The effect of the ion to electron temperature ratio was studied in previous works [4,22,24,26,28]. The INCEC mean free path is recognized as an important parameter to discriminate between the ABR and the OML behavior in recent theoretical works [29–32]. This article shows an experimentally observed transition from the ABR to the OML behavior as a function of the INCEC mean free path, λ_+, to the Debye length,

λ_D, ratio $\Lambda = \lambda_+/\lambda_D$ [26,28]. This study allowed us to recognize the mass of the ion, m_+, as the critical parameter in the presence of the observed transition in helium plasmas. A theoretical justification of the transition as a function of the β, Λ and ion mass parameters is proposed.

In the Section 2, after this introduction, the experimental setup and measurement method are briefly cited. The Section 3 states the experimental measurement conditions and the methodology. The Section 4 presents the results. In the Section 5, supported by a set of novel measurements, a theoretical discussion about why the transition takes place only for the helium plasmas is proposed. Finally, the Section 6 is an exposition of the conclusions.

2. Experimental Setup and Measurement Method

A high-voltage DC discharge has been chosen for these experiments. The gas is introduced in a large Pyrex cylinder, 40 cm high and with an inner diameter of 31 cm, where two stainless steel electrodes are held 15 cm from each other, each electrode having a diameter of 8 cm. The anode is connected to the ground. The electrodes are supplied a high DC voltage by means of the low ripple/low noise-to-signal ratio KEPCO BHK 2000-0.1MG high-voltage DC power supply. The DC power supply is configured as a current supply, given that the discharge current is related to the electron density and it better serves to characterize the discharge compared to the DC voltage or the discharge power. The entering gas flow is controlled by a mass gas flow controller, MKS 247. A tungsten cylindrical, 6 mm long, 0.1 mm diameter Langmuir probe is placed in the diffuse afterglow of the plasma discharge. In this zone, the plasma is spatially homogeneous and the electron temperature is found to be the lowest, so that the effect of the ion temperature cannot be neglected and the ion to electron temperature ratio, β, is not negligible [1,2,4,7,26,28]. The neutral and positive ions are supposed to be thermalized. As the electrodes are very hot during the measurements, the ion and neutral atom common temperature is estimated to be 350 K [1,2,5,7,24,26,28,33,34].

The current-voltage characteristic of the cylindrical Langmuir probe can be used to obtain an indirect measurement of the parameters that characterize the plasma in the zone of the discharge where it is placed. The plasma potential, V_{plasma}, the floating potential, V_{float}, and the electron energy distribution function, EEDF, can be measured [1,2,4,6,26,34–41]. Regarding the measured EEDF, it is checked that, in every measurement, the EEDF can be considered as following the distribution of Maxwell–Boltzmann [1,4,6,26,28], which is essential since the assumption of a Maxwellian EEDF is made in both radial and orbital theories. The EEDF is used to perform the calculation of the electron temperature, T_e, and the electron density, n_e, which is equal to the ion density, n_+, by means of the quasi-neutrality condition, $n_e \approx n_+$. These values for n_e and T_e have been used as in all further calculations since they do not depend on the radial or orbital theory used to obtain the results. The discharge and the measurements are controlled, and the initial calculations are performed, using a LabView Virtual Instrument [1,4,6,7].

The experimental device has been designed with the objective of obtaining a low electron temperature plasma, so that the ion temperature, in the range of the ambient temperature, becomes non-negligible when compared to the electron one [1]. This property of the DC discharge allowed us to check the validity of the radial theory developed by the authors, which takes into account the temperature of the ions in argon and neon plasmas in the conditions of the discharge [1,2,19–24]. On the other hand, the size of the probe was chosen to be small enough so that the small-radius OML theory would be of applicability in the cases in which the orbital theories are applicable, as was found in the helium plasma in some conditions of the discharge. The LabView-controlled measuring system makes fast measurements, each taking only 4 ms, so that the temperature of the probe does not change during the measurement of the current-voltage characteristic. In order to make sure that the measurements are quick enough, the current-voltage characteristics were measured, starting both in the electron saturation zone and in the ion saturation zone, making no difference to the results of the measurements.

3. Experimental Measurement Conditions and Methodology

The high-voltage DC power supply has an upper limit of 2000 V and 100 mA. The discharge currents are typically much lower, so that the voltage limitation is the relevant one. For argon, neon and helium plasmas, the discharge DC current is always lower than 12.5 mA. The pressure range for the argon plasma is $p(\text{Pa}) \in [2, 10]$; for the neon plasma, it is $p(\text{Pa}) \in [10, 35]$, and for the helium plasma, it is $p(\text{Pa}) \in [13, 37]$. Given that the transition in the validity of the orbital and radial theories is found in the helium plasma, a total of 448 current-voltage characteristics were measured, while in argon and neon plasmas, for which no transition was found, a total of 171 and 111 current-voltage characteristics, respectively, were measured. This set of measurements includes the measurements already published [26,28] together with additional measurements in which we explored the higher electron temperature range in the three kinds of plasmas, although no new insight was gained, as the measurements followed the same trend as the rest of the measurements, albeit extending the range in which the trend was observed. The measured electron density, n_e, gives values in the range from 9×10^{14} to 7×10^{15} m^{-3}, while the electron temperature, T_e, ranges from 1000 to 4400 K, corresponding to β values which vary from 0.08 to 0.35. The $\Lambda = \lambda_+/\lambda_D$ parameter is obtained from the following expression.

$$\lambda_+ = \frac{1}{n_+ \sigma_{+-n}}, \tag{1}$$

with $\sigma_{+-\text{n}}$ being the cross-section for positive ion-neutral collision [10,42], and $\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}}$ [10]. For each of the plasmas, the following apply.

- For argon plasmas, the cross-section for positive ion-neutral collision, under our experimental conditions, is $\sigma_{+-\text{n}} = 7.84 \times 10^{-15}$ cm^2 [10,42]. Therefore, the ion mean free path for argon is the following:

$$\lambda_+ = \frac{133}{218 \cdot p(\text{Pa})} (\text{cm}). \tag{2}$$

  Therefore, the Λ values vary from 3.98 to 29.71 for the argon discharges studied in this article.
- For neon plasmas, the cross-section for the ion-neutral collision is $\sigma_{+-\text{n}} = 4.25 \times 10^{-15}$ cm^2 [10,42]. Therefore, the ion mean free path for neon is the following:

$$\lambda_+ = \frac{133}{118 \cdot p(\text{Pa})} (\text{cm}). \tag{3}$$

  Therefore, the Λ values vary from 1.52 to 24.27 for the neon discharges studied in this article.
- For helium plasmas, the cross-section for the ion-neutral collision is $\sigma_{+-\text{n}} = 3.99 \times 10^{-15}$ cm^2 [10,42]. Therefore, the ion mean free path for helium is the following:

$$\lambda_+ = \frac{133}{111 \cdot p(\text{Pa})} (\text{cm}). \tag{4}$$

  Therefore, the Λ values vary from 2.27 to 14.29 for the helium discharges studied in this article.

Note that the upper limit for the ion mean free path to Debye length ratio Λ for the three gases decreases with decreasing ion mass, such that for argon, the upper limit is $\Lambda_{max,Ar} = 29.31$, close to the double the helium Λ upper limit, $\Lambda_{max,He} = 14.29$. It is also interesting to compare these Λ ranges with the sheath edge, which has values always lower than $k \cdot \lambda_D$. The k value depends on the sheath edge criteria used, usually considered to be $4 < k < 8$ [20,34,36], but regardless of the criteria used, there is a range in which the ion mean free path is comparable to the size of the sheath.

Two novel series of measurements were performed in the helium plasma, one for constant background pressure $P = 20.2$ Pa and one for constant discharge current $I_d = 5.0$ mA.

The methodology that is followed in this work is based on the use of the Sonin plot [1,2,4,26,28], which uses the positive ion current per unit length collected by the probe, I_+, when it is biased at a fixed electric potential, V_p in $k_B T_e/e$ units, e being the elementary charge and k_B the Boltzmann constant, referring to the plasma potential, V_{plasma} [43]. In the Sonin plot, the ordinate of the plot is the non-dimensional ion current,

$$y_{Sonin} = I'(y_{SP}) = \frac{I_+(y_{SP})}{e r_p n_+}\sqrt{\frac{m_+}{2\pi k_B T_e}}, \tag{5}$$

where r_p is the probe radius and y_{SP} is defined as the non-dimensional probe potential $y_{SP} = -eV_p/k_B T_e$. The abscissa of the plot has the following expression:

$$x_{Sonin} = {x_p}^2 I'(y_{SP}) = \frac{I_+(y_{SP}) e r_p}{\varepsilon_0}\sqrt{\frac{m_+}{2\pi {k_B}^3 {T_e}^3}}, \tag{6}$$

which does not depend on the ion density, with x_p being the non-dimensional probe radius $x_p = r_p/\lambda_D$. The V_p value must be chosen carefully, so that it is negative enough to ensure that the current collected by the probe is almost exclusively positive ion current, and the electron current can be neglected. Regarding the other extreme, if the difference between the plasma potential and the probe potential is too high, the emission of secondary electrons from the probe would be accounted for as an increase in the positive ion current collected by the Langmuir probe [1,2,4,5,26,28]. As in other articles, we have chosen $y_{SP} = -eV_p/k_B T_e = 25$ [1,2,4,26,28], which accounts for V_p values in the range $V_p(\mathrm{V}) \in [2.15, 9.48]$ for the given range of electron temperatures $T_e(\mathrm{K}) \in [1000, 4400]$. A single point in the Sonin plot is obtained for each set of plasma conditions—that is, for each set of experimental values for $I_+\big(V_p\big)$, n_e and T_e [1,4,5,26,28]. The experimental Sonin plot point is placed in the Sonin plot and its position relative to the theoretical orbital and radial curves is analyzed. The plasma conditions are studied in relation to the position of the experimental Sonin plot points.

4. Results

The experimental points are plotted for the different plasmas in Figures 1–3. The experimental Sonin plot points are grouped in terms of the INCEC mean free path to Debye length ratio Λ, which allows a comparison between the three plasmas in which the scale of the sheath varies with the Debye length. We show the Sonin plot that includes the theoretical curves that correspond to the orbital and the radial theories in Figures 1–3. The complete solution by Laframboise [16] for the orbital theory is used, calculated from the fitting curves obtained by Peterson and Talbot [44]. The radial model developed by the authors for several β values, which converge to the Allen–Boyd–Reynolds model adaptation to cylindrical Langmuir probes by Chen for negligible ion temperature with respect to the electron temperature [19,21,22]. In Figure 1, we also show the experimental Sonin plot points corresponding to different ranges in the Λ parameter for argon plasmas. The results of the measurements show that the radial theory describes appropriately the positive ion current collected by a cylindrical Langmuir probe immersed in an argon plasma, in the conditions of the DC discharge used in the measurements.

Figure 2 shows the experimental Sonin plot points obtained from the different neon plasma discharge conditions measured. Figure 2 also includes the experimental points colored and symbolized as a function for the Λ parameter. As can be seen in Figures 1 and 2, the Λ parameter shows an evolution in the Sonin plot points—that is, the points for which the ion mean free path is longer are grouped to the right, while the points for which the ion mean free path is short are grouped to the left. These points are located over the radial model theoretical curves for $\beta \neq 0$ and fit well with the experimental β values for each point. Therefore, the influence of Λ is not very important in terms of the ions' behavior in this range for argon and neon plasmas.

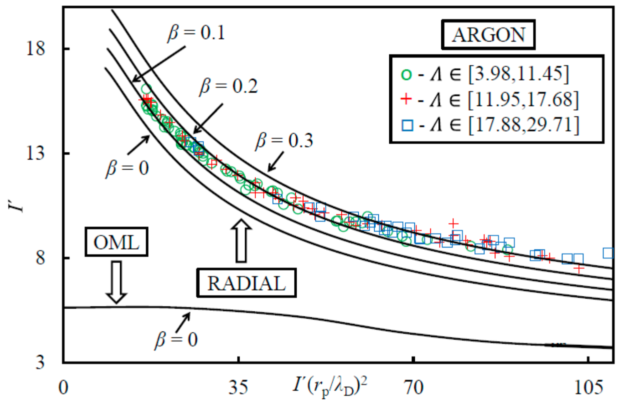

Figure 1. Argon plasma Sonin plot for the normalized probe potential $y_{SP} = 25$. Experimental data for the argon plasma: green circles for 3.98 ≤ Λ ≤ 11.45, red crosses for 11.95 ≤ Λ ≤ 17.68 and blue squares for 17.88 ≤ Λ ≤ 29.71. In solid lines, the orbital and radial theoretical curves are shown.

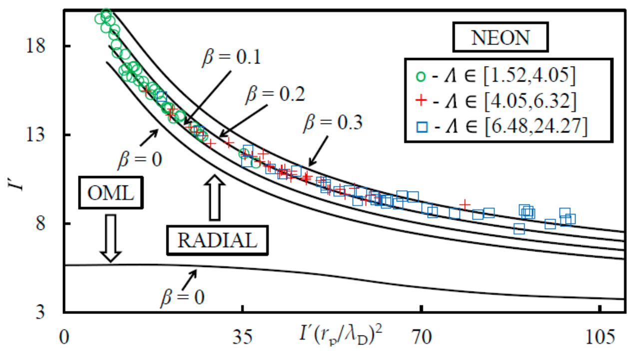

Figure 2. Neon plasma Sonin plot for the normalized probe potential $y_{SP} = 25$. Experimental data for the neon plasma: green circles for 1.52 ≤ Λ ≤ 4.05, red crosses for 4.05 ≤ Λ ≤ 6.32 and blue squares for 6.48 ≤ Λ ≤ 24.27. In solid lines, the orbital and radial theoretical curves are shown.

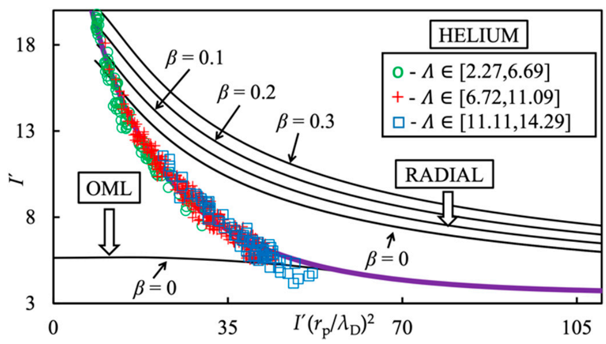

Figure 3. Helium plasma Sonin plot for the normalized probe potential $y_{SP} = 25$. Experimental data for the helium plasma: green circles for 2.27 ≤ Λ ≤ 6.69, red crosses for 6.72 ≤ Λ ≤ 11.09 and blue squares for 11.11 ≤ Λ ≤ 14.29. In solid lines, the orbital and radial theoretical curves are shown. In purple bold line, the fitting curve for the experimental helium plasma Sonin plot points is shown.

As in Figures 1 and 2, Figure 3 shows the Sonin plot for the experimental points colored and symbolized as a function of the Λ parameter. On one hand, those points corresponding to the lower Λ values (green circles for 2.27 ≤ Λ ≤ 6.69) are mainly placed in the radial zone or close to it, and none of them are placed in the orbital zone. On the other hand, those points corresponding to the higher Λ values (blue squares for 11.11 ≤ Λ ≤ 14.29) are mainly placed in the orbital zone or close to it, and none of them are placed in the radial zone. Finally, those points corresponding to intermediate Λ values (red crosses for 6.72 ≤ Λ ≤ 11.09) are mainly placed in the intermediate zone, where none of the theories are verified, and only a few of them are placed in the other zones. Nevertheless, Figures 1–3 show that the dependence on Λ does not seem to be so critical than that on β [26,28], since the Λ parameter depends not only on T_+ and T_e but also on $n_e \approx n_+$ and p through λ_+ and λ_D. Finally, Figure 3 also shows a fitting curve that may be used to diagnose this helium plasma in these conditions of pressure and discharge current, and that converges with OML in the range of abscissa of the Sonin plot, x_{Sonin}, of $[70, 100]$. However, although it is of great theoretical interest, the transition range of plasma conditions for the helium plasma should be avoided in plasma diagnosis by means of the Sonin plot, and the plasma conditions should be used in which one of the two theories, ABR or OML, is valid. The fitting curve, in purple bold line in Figure 3, follows the following formula:

$$y_{Sonin\ He,exp} = ae^{-b(x_{Sonin\ He,exp})^c} + d, \tag{7}$$

with $a = 32.11693$, $b = 0.13901$, $c = 0.77237$ and $d = 3.56418$.

5. Discussion

The finiteness of the ion mean free path and the experimental observation of its influence in the transition from radial to orbital behavior can be justified theoretically. After the last collision, the ions lose their orbital motion, so, for small β and Λ values, the OML theory cannot appropriately describe the ion current collected by the probe. For higher ion temperatures, after the last collision, the ions have a non-negligible velocity in a random direction. For the ions that have a direction that is predominantly in the azimuthal direction of cylindrical coordinates, the mean thermal velocity is important enough so that the trajectory of the ion will not intersect the probe and the ion will orbit around the probe back to the plasma. The mass of the ion thus becomes an essential parameter, since the mass of the ion is inversely proportional to the square of the thermal velocity.

$$\overline{v_{+,th}} = \sqrt{\frac{2k_B T_+}{m_+}}, \tag{8}$$

where m_+ is the mass of the ion. This fact explains why the transition is only found in the helium plasma but not in neon or argon plasmas.

The most frequent ion collision in this kind of plasma is INCEC, which removes an accelerated ion and results in a new ion with the temperature of the background gas [45,46]. It is interesting to note that the effect of INCEC in both radial and orbital models is the opposite: on one hand, in orbital models, usually the new ion created after an INCEC has a lower orbital kinetic energy, so the ion is more likely to be collected by the probe. If the orbital motion limited model is used, the exact potential profile of the sheath can be ignored, and the probability of the ion being collected can be calculated using the conservation laws. Therefore, the positive ion current collected by the probe is increased when INCEC is taken into account [47–49]. On the other hand, the effect of collisions in radial models is to reduce the mean velocity of the fluid particle, which is composed by many ions, in its fall towards the probe. That is, the positive ion current collected by the probe is reduced, having an effect similar to that of the transition from radial to orbital behavior. This effect can be estimated using the radial model that takes into account the ion temperature and the collisions of ions with neutral atoms developed by the authors [31] and proved to be opposite to the effect of the positive ion temperature in radial models, which increases the positive ion current [1,2,4,5,19,21,22,26,28]. It is interesting to note that, in neon and argon plasmas, the points in the Sonin plot shift up into regions of higher theoretical β values with increasing Λ, as can be seen in Figures 1 and 2, which is consistent with this development for radial theories—that is, less collisions in the ion sheath and a higher ion to electron temperature ratio have a similar effect in radial theories of increasing the current both in neon and argon plasmas, in the range of discharge parameters studied.

In the helium plasmas, the same increase in the ion mean free path to Debye length ratio Λ and in the ion to electron temperature ratio β has a very different influence on the movement of the ions in their fall towards the probe. The effect of collisions in the helium plasma can be studied with the available experimental data of the discharge. If the discharge current is decreased while maintaining the background pressure, the plasma and the electron density decrease [40,41]. Therefore, the Debye length increases, and the ion mean free path to Debye length ratio—that is, the Λ parameter—is decreased. We note in Equation (1) that the λ_+ parameter is constant if the background pressure is kept constant. Moreover, the measurements show that the electron temperature is higher when the discharge current is lower [40,41], so that the effect of a decrease in the discharge current is to cause a decrease in the β parameter value and a decrease in the Λ parameter (Figure 4). We have performed a series of novel measurements at constant background pressure, changing the discharge current, which show that the predicted trend is correct. This does not allow us to distinguish between the effect of the ion to electron temperature ratio β and the effect of the ion mean free path to Debye length ratio Λ in the experiments. However, if the discharge current is kept constant, the plasma density remains constant and so does the electron density [40]. Moreover, if the background pressure is decreased, the measurements show that the electron temperature, T_e, increases [40,41], causing a decrease in β. Accordingly, regarding the Λ parameter, we predict two opposite influences: (a) the Debye length increases with T_e, and thus the Λ parameter decreases; (b) the collisions are less frequent, increasing λ_+, and so the Λ parameter increases. Therefore, the trend that the Λ parameter will follow with changing background pressure alone cannot be predicted for a constant discharge current. We have also performed a series of novel measurements at constant discharge current to verify the influence of the background pressure on both the β and Λ parameters. Figure 5 shows that a decrease in the β parameter and an increase in the Λ parameter are experimentally found when the gas pressure decreases, according to argument (b) above. As the transition is found for decreasing background pressure, this proves that the most relevant parameter in the transition between radial and orbital behavior of the ions in the helium plasma is the positive ion to electron temperature ratio, β.

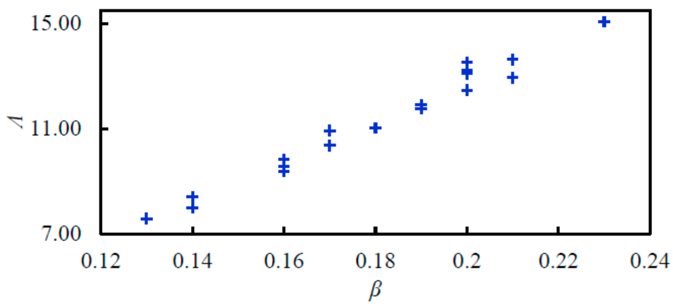

Figure 4. Increasing figure between β and Λ for constant background helium pressure $p = 20.2$ Pa.

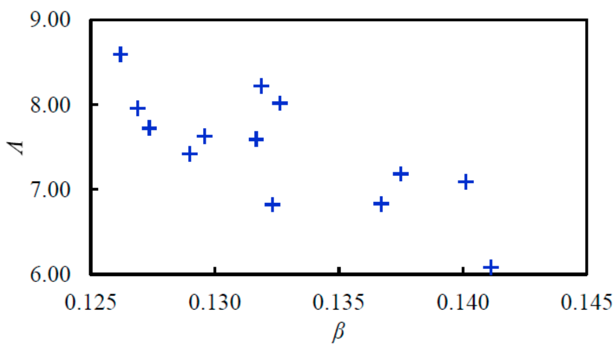

Figure 5. Decreasing figure between β and Λ for constant discharge current $I_d = 5.0$ mA in a helium discharge.

6. Conclusions

In plasma diagnosis experiments, when measuring the ion current collected by a cylindrical Langmuir probe, it is found that sometimes the orbital theories correctly predict the ion current and, at other times, the radial theories are found to be valid. Therefore, a transition from the validity of the orbital theories towards the validity of the radial theories is expected, depending on the experimental conditions of the plasma—that is, the ion temperature to electron temperature ratio, β, and the ion mean free path to Debye length ratio, Λ.

The transition has been theoretically justified in the context of INCEC, so that positive ions lose their translation kinetic energy in collisions with the neutral atoms of the background gas. Therefore, for small β and Λ values, after the last collision, the ions lose their orbital motion and the OML model is no longer valid to describe the ion current collected by the probe. This way, when collisions are included, the OML model provides higher positive ion current collected by the probe, i.e., approaching the values predicted by the ABR model. Alternatively, for higher Λ values, after the last collision, the ions are far away from the probe, and the orbital component of the ion thermal motion is high enough for those ions to fall towards the probe, following an orbital trajectory, diminishing the ion current collected by probe, i.e., approaching the OML model.

The aforementioned transition has been experimentally observed only for helium plasmas and not for argon and neon plasmas, and it has been justified due to the lower mass of the helium ions, which makes the helium thermal velocity higher for the same ion temperature. Therefore, only for higher Λ and β values in helium plasmas, the transition has been observed. Moreover, as an extreme case comparison, for electrons of even lower mass, the OML theory always predicts well the electron current collected when the probe is positively biased with respect to the plasma potential. Although it has been proven that the positive ion to electron temperature ratio, β, is a more relevant parameter than the INCEC mean free path to Debye length ratio Λ in the transition between radial and orbital behavior of the ions, the ion mass is crucial, since it determines the existence of the transition.

In view of these experimental results and theoretical arguments, the positive ion thermal motion and the collisions must be included in the sheath models, since they influence the radial or orbital behavior of the positive ion current to the substrate/probe, even though the collisions included in this article mainly take place outside of the sheath. This fact also explains that the β parameter has a more definite influence on the transition than the Λ one, as shown in Figures 4 and 5, but the influence of the ion mean free path to Debye length ratio Λ cannot be altogether ignored.

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