Influence of the positive ion thermal motion in the radial motion to orbital motion to cylindrical Langmuir probes in low pressure plasmas Part II: He^+

J. M. Díaz-Cabrera[1], A. Tejero-del-Caz[2], J. I. Fernández Palop[2], and J. Ballesteros[2]

[1]*Department of Electrical Engineering, University of Cordoba, Campus of Rabanales, Building Leonardo Da Vinci, 14071 Cordoba, SPAIN* (jmdiaz@uco.es).

[2]*Department of Physics, University of Cordoba, Campus of Rabanales, Building Albert Einstein, 14071 Cordoba, SPAIN* (f52tecaa@uco.es, fa1fepai@uco.es, and fa1bapaj@uco.es).

In this contribution, we have verified that for low pressure, low temperature Helium plasmas, the behavior of the positive ion current collected by a cylindrical Langmuir probe considering the influence of the positive ion thermal motion, shows a transition from the orbital-motion limited model (OML) to the radial one (ABR). This has been carried out by using the same criteria than the one used for Argon plasma in another contribution to this conference. The transition can be justified because for the higher positive ion temperature to the electron one ratio, β, values, since the atomic mass of Helium is small, the initial azimuthal component of the thermal velocity, far from the probe, is high enough, and the Helium ions fall to the probe following an orbital motion trajectory. On the other hand, as β diminishes, that initial azimuthal component of velocity also diminishes and the positive ions falls to the probe following a trajectory which tends to be radial.

1. Introduction

As it was commented in a previous contribution to this conference for the case Argon plasmas, the knowledge of the trajectory of the ions falling toward a Langmuir probe is extremely important not only in plasma diagnosis, but also in material technological processes involving plasma wall/substrate interactions, since the probe plays a role similar to the wall/substrate.

This work study the results obtained in the application of several criteria to discriminate the trajectory described by the He^+ ions when fall toward the probe in a low pressure, low temperature Helium plasma as a function of the parameter $\beta=T_i/T_e$, T_i being the positive ion temperature, and T_e the electron one. All the criteria are based on the study of the ion saturation zone of the experimental current-voltage characteristic curve of a cylindrical Langmuir probe immersed in the plasma, $V_p << V_{plasma}$ (V_p being the biasing probe potential and V_{plasma} the plasma space potential). There are two well known limiting theories describing the ion current collected by the probe: on the one hand, the Orbital Motion Limited (OML) [1-3] and the other hand, the radial motion theory, which is usually referred to as the ABR theory [4, and 5]. The classical ABR theory is valid for cold ions, β=0, and has been extended by the authors to include the influence of the positive ion thermal motion, $\beta\neq0$ [6]. So, the existence of both theories implies a paradox in the analysis of positive ion saturation zone of a Langmuir probe current-voltage characteristic, since it is unknown a priori which of both theories is applicable before it is applied [7].

Therefore, ion current collected by cylindrical Langmuir probes has been experimentally studied by several authors, concluding that usually is the radial theory who describes adequately their experimental results [8-12]. This result can be justified for plasma conditions corresponding to β values close to zero, considering that, on their way to the probe, the positive ions lose their translation kinetic energy when colliding with other particles present in the plasma, mainly neutrals [8, 10-13]. So, after the last collision, they fall towards the probe following a radial trajectory, as described by the ABR theory. Nevertheless, when the influence of the positive ion thermal motion is considered, $\beta\neq0$, after the last collision, the thermal velocity of the ions must be taken into account, since for large β values, its azimuthal component could be large enough, to allow them to orbit in their falling towards the probe. This fact justifies this work.

2. Results and conclusions

This section is devoted to the presentation and discussion of the several criteria to discriminate whether the positive ions fall towards the probe following a radial or orbital trajectory, and the results obtained.

The experimental device used by the authors to obtain measurements is widely developed in Refs. 10, and 11.

In this way, since 433 current-voltage probe characteristic curves corresponding to the different He plasma conditions have been measured, we have selected three current-voltage probe characteristic, each of the conditions with a different behaviour. The experimental conditions for the case A are P=20.3 Pa, I_d=0.8 mA, and β=0.09, for the case B are P=28.4 Pa, I_d=4 mA, and β=0.2, and the last, for the case C are P=26.4 Pa, I_d=8 mA, and β=0.26.

These above cited criteria are:

a) The proximity in the Sonin plot of the point, obtained from the electron density and temperature determined by using classical experimental diagnostic methods [10, 11 and 14], to the curves corresponding to the ABR or OML motion theories.

Figure 1 illustrated a Sonin plot including the theoretical OML and ABR curves for three interval of the β parameter. Moreover, 433 points, obtained from current-voltage characteristics corresponding to the same number of different plasma conditions, has been plotted. As can be seen, according to this criterion, the ions fall towards the probe following the ABR theory, the OML theory or an undefined behavior depending on the case study.

Furthermore, in figure 1 are plotted the three selected cases to verify the evolution between the two theoretical models. Being x_{Sonin} and y_{Sonin} the Sonin plot coordinates of the point obtained from the measured reference n_e(EEDF) value, for the specific cases illustrated in figure 1. First, for case A, corresponding to low β values, the Sonin plot coordinates values are ((x_{Sonin}, y_{Sonin})=(10.88, 17.58)) can be seen as the behavior of ions is radial. Secondly, for the case B corresponding to intermediate β values, ((x_{Sonin}, y_{Sonin})=(33.5, 8.18)) ions show mixed behavior, because a part of the ions fall toward the probe following a radial trajectory, while the other part orbit around the probe. Finally, in case C, for the higher β values, ((x_{Sonin}, y_{Sonin})=(46.75, 5.46)) the ions have an orbital behavior.

Therefore, the results are different than those observed in Ar^+ plasmas for which the ions fall toward the probe following a radial trajectory for all the β values studied, as can be seen in another contribution to this conference. This is due to the atomic mass of Helium is ten times lower than that of Argon, so, for the higher β values, the azimuthal component of the thermal velocity is higher enough for He^+ ions orbit while falling to the probe.

The favourable aspect of this criterion is that it let us a plasma diagnosis technique by using the ion saturation zone of the current-voltage characteristic curve. Nevertheless, the inconvenience is that it uses only one experimental point of the current to voltage characteristic.

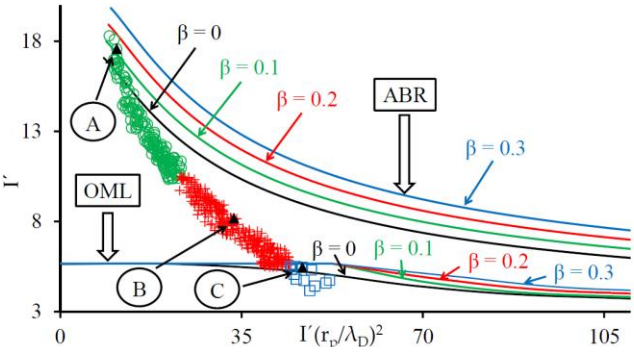

Figure 1. Sonin plot including the experimental data (symbols) and theoretical curves (solid lines) for Helium plasmas, y_p=25, and different β values. Circles mean 0.09≤β≤0.15, crosses mean 0.16≤β≤0.25, and squares mean 0.26≤β≤0.3.

b) The second criterion is the comparison between the experimental current-voltage characteristic curve of the reference case, for $V_p<V_{plasma}$ values, and the theoretical one obtained from the ABR theory considering the influence of the positive ion thermal motion [6].

Figure 2 illustrates such a comparison. As can be seen in figure 2, there is not a very good agreement in the B and C cases where the behavior is not radial. While in the case A only match for probe potential close y_p=25. So we can conclude that, this criterion is confined to probe potential values close to the one used in the Sonin plot criterion, y_p=25.

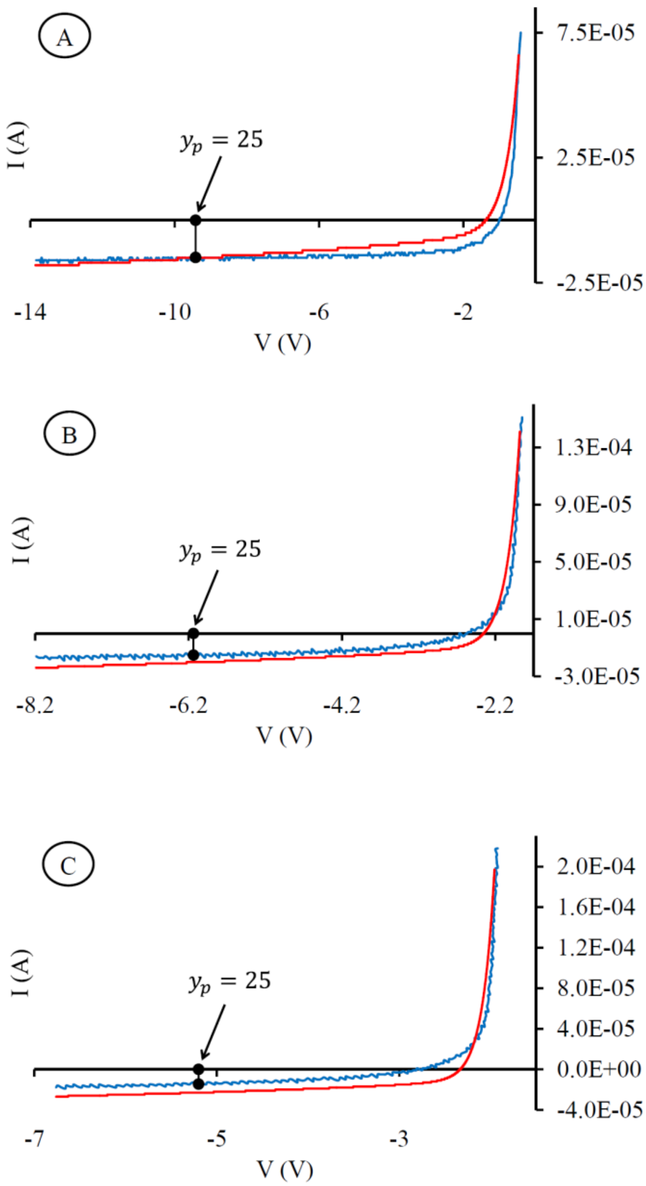

Figure 2. Theoretical (red line) and experimental (blue line) *I-V* characteristic. A, B and C correspond to the cases that are represented in the Sonin plot.

This is to say, for the case A the theoretical ABR curve and experimental *I-V* smoothed characteristics agrees in an interval close to y_p=25. On the other hand, there is no agreement in B and C cases between the theoretical and experimental *I-V* characteristic, since the behavior of ions does not fit the theoretical radial model.

The inconvenience of this criterion is that it not let to study its evolution as a function β parameter, moreover, it is a qualitative criterion.

c) The third criterion is the study of the linear approaching of the experimental plot I_+^2 versus V which must be accomplished if the OML motion theory is fulfilled. In this way, the I_+^2 versus V experimental data in the interval $y_p \pm 3k_B T_e$, of the current to voltage characteristic measured for all the studied plasma conditions, have been fitted to a straight line by using the least squared method obtaining a linear correlation coefficient of 0.5 and 0.8 for cases A and B, respectively. This is due to the ABR behavior of ions reaching the probe, for the corresponding β values, and did not correspond to that linear representation. In case C this value is 0.95 and this case fits a straight line as predicted by the OML theory. All the intervals used in the fits always contain approximately 100 data. So we can conclude that, under our discharge conditions, the ions fall toward the probe following an orbital trajectory only in the case C.

As in the a) criterion, the favourable aspect of this one is that it uses a wide interval of the current-voltage characteristic curve, while the inconvenience is that it not let to study its evolution as a function the β parameter.

d) The Allen-Annaratone criterion [8] is based on the following condition: the mean free path, λ, for ion-atom collisions, which is the more frequent kind of collision [8], is less than the effective radius of the probe for capture, the OML theory will not be fulfilled. This is due to the positive ions lose their kinetic energy when colliding with other particles present in the plasma. After the last collision suffered, they fall towards the probe by following a radial trajectory, as described by the ABR theory.

Figure 3 illustrates the evolution between radial and orbital behavior of He^+ ions reaching the probe as a function of β. For the higher β values, the behavior of ions falling to the probe is clearly orbital since the experimental measurements cross the, λ, value limit, 1 mm for our Helium discharge conditions, (red line) [15-17].

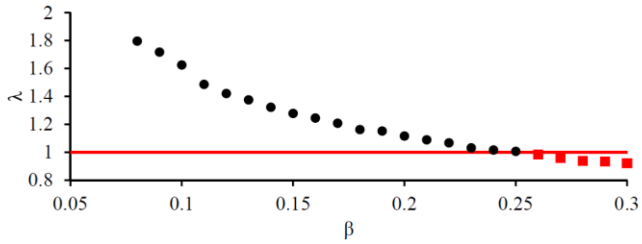

Figure 3. Allen-Annaratone criterion: Evolution of experimental measurements with the β parameter.

Nevertheless, for intermediate and low β values, the ions fall toward the probe following a radial trajectory. This match to the result observed in the previous criteria.

e) The Pilling and Carnegie criterion [7] examines the "gradients" of the current to voltage, and can resolve the differences between the radial-motion theory and the OML, for which the gradient takes the value of two.

Figure 4 shows the "gradient", $d(\log_{10} V)/d(\log_{10} I)$ versus V_p, plots for the ions saturation, $V_p << V_{plasma}$, for several plasma conditions. For each case plotted in figure 4 we have taken an interval $y_p \pm 2k_B T_e$. As can be seen, the curve tends the value 2 when the β value increases. So we can conclude that the ions fall toward the probe following an orbital trajectory when the β value increases.

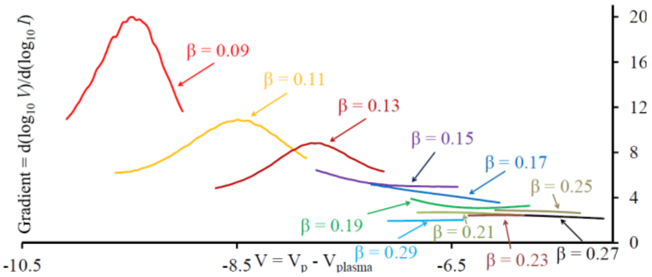

Figure 4. Pilling and Carnegie criterion: Evolution of experimental measurements with the β parameter.

Both d) and e) criterion discriminate whether the ions fall towards the probe following an orbital trajectory.

We can conclude that our measurements are accurate enough to discriminate and explain the experimental plasma conditions for each theory to be appropriately used in each case.

3. Acknowledgments

This work has been partially supported by the Spanish Ministerio de Ciencia e Innovación. Ref. No FIS2010-19951, which is partially finaced with FEDER funds.

4. References

[1] H. M. Mott-Smith and I. Langmuir, *Phys. Rev.* **28** (1926) 727.

[2] I. B. Bernstein and I. N. Rabinowitz, *Phys. Fluids.* **2** (1959) 112.

[3] J. G. Laframboise, *UTIAS Report No. **100**, University of Toronto* (1966).

[4] J. E. Allen, R. L. F. Boyd, and P. Reynolds, *Proc. Phys. Soc.* **70** (1957) 297.

[5] F. F. Chen, *J. Nucl. Energy* Part **C 7**, (1965) 47.

[6] R. Morales Crespo, J. I. Fernández Palop, M. A. Hernández and J. Ballesteros, *J. Appl. Phys.* **95** (2004) 2982.

[7] L. S. Pilling and D. A. Carnegie, *Plasma Sources Sci. Technol.* **16** (2007) 570.

[8] B. M. Annaratone, M. W. Allen and J. E. Allen, *J. Phys. D: Appl. Phys.* **25** (1992) 417.

[9] F. F. Chen, *Plasma Sources Sci. Technol.* **18** (2009) 035012.

[10] J. M. Díaz-Cabrera, M. V. Lucena-Polonio, J. I. Fernández Palop, R. Morales Crespo, M. A. Hernández, A. Tejero-del-Caz, and J. Ballesteros, *J. Appl. Phys.* **111** (2012) 063303.

[11] J. M. Díaz-Cabrera, J. I. Fernández Palop, R. Morales Crespo, M. A. Hernández, A. Tejero-del-Caz, and J. Ballesteros, *Measurement* **55** (2014) 66.

[12] J. M. Díaz-Cabrera, J. Ballesteros, J. I. Fernández Palop, and A. Tejero-del-Caz, *Plasma Sources Sci. Technol.* **24** (2015) 025026 (5pp).

[13] J. T. Gudmundsson, *Plasma Sources Sci. Technol.* **8** (1999) 58.

[14] J. I. Fernández Palop, J. Ballesteros, V. Colomer, and M. A. Hernández, *Rev. Sci. Instrum.* **66** (1995) 4625.

[15] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (*New York: Wiley*) (2005).

[16] S. A. Maiorov, O. F. Petrov, and V. E. Fortov, *34th EPS Conference on Plasma Phys. Warsaw* **31F** (2007) P-2.115.

[17] D. Curreli and F. F. Chen, **LTP-1107** (2011) 90095-1594.