Cylindrical Langmuir probe measurements in magnetized Helium plasma

J. Ledig[1], E. Faudot[1], N. Lemoine[1], S. Heuraux[1], J. Moritz[1] and M. Usoltceva[2,3]

[1] *Institut Jean Lamour UMR 7198 CNRS – Université de Lorraine , Nancy, France*

[2] *Max–Planck–Institut für Plasmaphysik, Garching, Germany*

[3] *Department Of Applied Physics, Ghent University, Belgium*

Abstract – Understanding and exploiting cylindrical Langmuir probe measurements in magnetized plasma is a real challenge, although this technique is the most common one used to access plasma parameters such as density, temperature, potential, etc. Since the magnetic field confines the electrons in the plasma, the measurement is actually done on the flux tube connected to the cylindrical probe. In some conditions, the $I(V)$ characteristics displays a bump between the exponential growth and the saturation of the electronic current. We propose a new interpretation of such distorted characteristics as a function of the angle between the probe and the magnetic field lines, the RF–power and the magnetic field magnitude.

Introduction

Cylindrical probe measurements give access to several plasma parameters such as temperature T_e, density n_e, potential ϕ_p, etc. In the absence of a magnetic field, the understanding of the $I(V)$ characteristics is straightforward [1]. But in numerous plasma devices there is a magnetic field to confine the plasma and to enhance the discharge. The presence of magnetic field can lead to misunderstanding and miscalculation of the plasma parameters as already pointed out elsewhere [2, 3]. Indeed the electrons are strongly "magnetized" since $m_e \ll m_i \Leftrightarrow \rho_{ce} \ll \rho_{ci}$, thus the way there are collected by the probe is affected. Several papers [4, 5, 6] have shown that under specific conditions (magnetic field amplitude, angle of the probe with respect to **B**, plasma density) a bump appears on the characteristics between the exponential part and the electron saturation current.

The lower saturation of the electron current compared to the unmagnetized case is usually explained with an asymmetric double probe theory [7] or by the mean of an OML (Orbital Motion Limited) model [8]. But none of these models predict the raise of a bump in the $I(V)$ characteristics in an Helium plasma. In this paper we will study the dependence of the bump raise with $||\mathbf{B}||$, $\vartheta = (\mathbf{B}, \text{probe})$ and the input RF–power. We will also provide a simple fluid model to explain such characteristics.

Experimental setup

In the context of this study the discharges were performed in ALINE, A LINEar plasma device of length 1 m and 30 cm in diameter. The magnetic field is generated by 6 coils supplied by DC-current in a range $I_{\text{coil}} \in [0,220]$ A $\Leftrightarrow ||\mathbf{B}|| \in [0,100]$ mT. The cylindrical probe of length $L_p = 1$ cm and radius $r_p =$ 75 μm is RF-compensated to prevent RF-currents from disturbing the characteristics [9]. The Helium pressure is 1.2 Pa for all the measurements. There is a direct coupling between the amplifier and the

the RF–cathode (no blocking capacitor). The probe was tilted at different angles ϑ form 0 to 90° with respect to the magnetic field lines while the RF–power supply was driven from 20 to 200 W–RF and RF–frequency at 25 MHz.

Effects of the magnetic field magnitude

Without magnetic field, the flux arriving on the probe is isotropic and the $I(V)$ curve is typically strongly asymmetric due to electron over ion saturation currents ratio (fig. 1–**(a)**). By applying a magnetic field, the electron saturation current decreases and tends to a symmetric double probe characteristic in a perfectly magnetized plasma ($I \propto \tanh$).

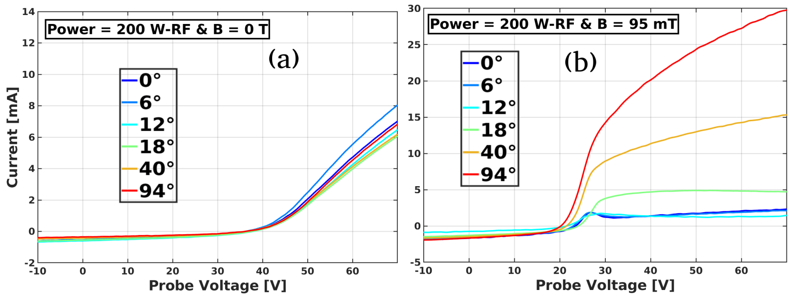

Figure 1: Plots of $I = f(V)$ characteristics without **(a)** and with **(b)** magnetic field at 98 mT for different probe angles with **B** and Power at 200 W–RF.

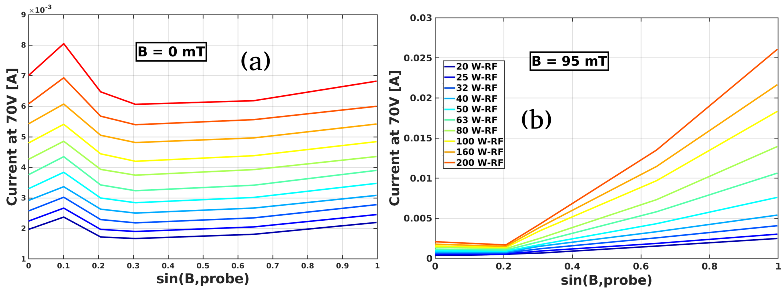

Figure 2: Plots of $I(V_{\max}) = f(\sin\vartheta)$ without **(a)** and with **(b)** magnetic field at 95 mT for several levels of RF power.

But in "real" magnetized plasmas it looks like an asymmetric double probe behaviour depending on effective collecting surfaces at each side of the flux tube and each species [7] (fig 1b). Moreover if the surface facing the magnetic field lines is of the same order of magnitude as $\pi\rho_{ce}^2$ (here for ϑ at 6° and 0°), then a bump appears as depicted in fig. 1. This effective collecting surface of the cylindrical probe (r_p the radius and L_p the length) is given by $S_{\text{coll.}} = \pi r_p^2 \cos\vartheta + \pi r_p L_p \sin\vartheta$.

The cosine term can be neglected ($r_p \ll L_p$) so that one should see a sine dependence by plotting the current at $V_{\max} = 70$ V (since the value of ϕ_p is unknown, we compare $I(V_{\max})$ rather than $I(\phi_p)$) : at $\mathbf{B} = \mathbf{0}$, fig.2–**(a)**, direction of the probe is unimportant because of random flux. At $\mathbf{B} \neq \mathbf{0}$, fig. 2–**(b)**, the collected current is proportional to $\sin\vartheta$ for $\vartheta \geq 10°$. This limit coincides with the apparition of the bump.

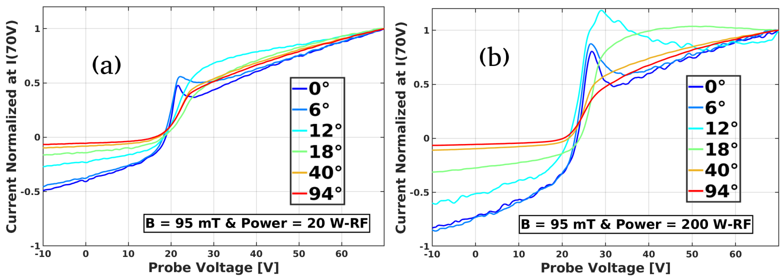

Figure 3: Plots of $I/I(V_{\max}) = f(V)$ with $||\mathbf{B}|| = 95$ mT, at 20 W **(a)** and 200 W **(b)** RF–power for different probe angles with **B**.

Effects of the input RF–power

As expected, increasing input RF power increases the overall density. Furthermore electron saturation currents of all characteristics nomalized to $I(V_{\max})$ (see fig. 3) tends to the same slope as soon as $\mathbf{B} \neq \mathbf{0}$. Since $I(V_{\max}) \propto \sin\vartheta$, normalization removes the sine dependence of the characteristics.

One can also note that RF–power heightens the bump, while at higher RF power levels, this bump appears for greater angles ($12°$ instead of $6°$).

Fluid model to explain the bump

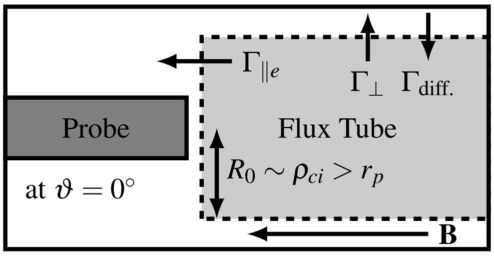

Figure 4: Schetch of the model

As seen in previous sections, the bump is more likely to appear when the surface facing the magnetic field lines is of the same order as ρ_{ce} and for strong enough magnetic field. We suppose the bump is induced by a density pumping in the flux tube connected to the probe, and this pumping is enhanced by perpendicular RF and DC currents [3]. The model is steady state, only perpendicular DC–currents are considered.

Since electrons have smaller gyroradius, they are trapped in the flux tube and can only leave it through ending (or front) surfaces. The typical flux tube radius R_0 scales as the ion Larmor radius ρ_{ci} [10] and the length L is the distance between the probe and the wall.

Perpendicular current are supposed high enough to saturate the parallel electron current (by current conservation through the flux tube) and thus to reverse the sheath polarity to accelerate electrons instead of ions. This assumption is fulfilled if $j_i S_\perp > j_e S_\parallel$ with j_i and j_e the ion and electron saturation current density ($S_\perp = \pi r_p^2$ and $S_\parallel = 2\pi r_p L_p$). Thus, one can neglect the parallel ion flux.

To prevent the flux tube density from falling down to zero, we assume a lateral ion diffusion flux (since $n_{\text{tube}} \leq n_{\text{bulk}}$ from bulk plasma) and an ion source term, S_0 :

$$\iiint_{\text{tube}} S_0 \,\mathrm{d}\tau = \pi R_0^2 \times 2 \times \frac{1}{2} n_{\text{bulk}} \langle v_{\text{TH}e} \rangle \tag{1}$$

This term replenishes the tube at the same rate the electrons quit the tube from both ends (which is an overestimation of the real S_0).

Ion flux continuity writes : $S_0 = \operatorname{div} \Gamma_i \approx \nabla \cdot \Gamma_{\perp i} = \nabla \cdot (\Gamma_\perp + \Gamma_{\text{diff.}})$. The perpendicular flux due to lateral conductivity can be expressed as $\Gamma_\perp = \sigma_\perp \mathbf{E}/e \approx -\alpha n \nabla\phi/e$ and the diffusion flux as $\Gamma_{\text{diff.}} = -D\nabla n$. Using Gauss integration rule over the whole flux tube, we obtain :

$$\pi R_0^2 n_{\text{bulk}} \langle v_{\text{TH}e} \rangle = \oiint_{\text{tube}} \Gamma_i \cdot \mathrm{d}\mathbf{S} \Leftrightarrow \frac{n_{\text{bulk}} \langle v_{\text{TH}e} \rangle}{2L} R_0 = -\left(D\frac{\partial n}{\partial r} + \frac{n\alpha}{e} \cdot \frac{\partial \phi}{\partial r} \right) \tag{2}$$

With strong magnetic field, $\rho_{ci} \approx v_\perp/\omega_{ci} = \sqrt{v_{\text{TH}i}^2 + v_{\text{drift}}^2}/\omega_{ci} \approx |v_{\text{drift}}|/\omega_{ci} = -\partial_r \phi / B\omega_{ci}$. Putting this into (2) we get a ODE of first order for n :

$$\frac{\partial n}{\partial \phi} = -\frac{\alpha}{De} n + \frac{n_{\text{bulk}} \langle v_{\text{TH}e} \rangle}{2\omega_{ci} BLD} \tag{3}$$

The value of α depends on the current nature (collision, inertia, viscosity, anomalous...) and is chosen here equal to Rozhansky's inertial current [10] : $\alpha = e/B$. Solution of (3) is then,

$$n_{\text{tube}}(\phi) = (n_{\text{bulk}} - n_\infty)e^{(\phi_p - \phi)/\delta\phi} + n_\infty, \text{ where } n_\infty = \frac{n_{\text{bulk}}\langle v_{\text{TH}e}\rangle}{2\omega_{ci}L} \text{ and } \delta\phi = BD \tag{4}$$

Now using OML formula (only valid for a spheric potential well [8]) for the collected current on a cylindrical probe under magnetic field , with a circular collecting area of radius $r_p + N\rho_{ce}$,

$$I(\phi) = \frac{1}{2} e n_{\text{tube}}(\phi)\langle v_{\text{TH}e}\rangle \times \frac{2}{\sqrt{\pi}}\left(\sqrt{\chi} + \frac{\sqrt{\pi}}{2}\text{erfc}\sqrt{\chi}e^{\chi}\right) S, \text{ where } \chi = -\frac{e\phi}{k_B T_e} \tag{5}$$

We have plot the result (5) in fig. 5 for $\phi \geq \phi_p$. Below plasma potential, the classical exponential formula is plot. And starting from the plasma potential the formula 5 is used to fit the experimental IV characteristics for N the number of electron gyroradii between 0.1 and 5 and the limit flux tube density $n_\infty \sim n_{\text{bulk}}/10$. This model suggests the plasma potential is at the top of the bump, where the pumping mechanism starts.

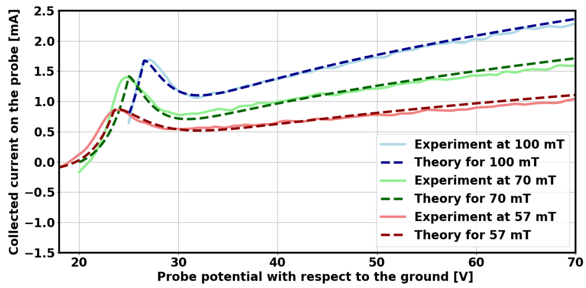

Figure 5: Result of the model vs. theory for $\vartheta = 0°$ at 200 W–RF

Conclusion

Interpreting probe measurements (cylindrical probe in the present case) in magnetized plasma can be very difficult as soon as the probe surface facing the magnetic field lines is of the same order of $\pi\rho_{ce}^2$. Above this limit the $I(V)$ tends to an asymmetric double probe behaviour depending on the effective collecting surface of the probe which also depends on the angle of the cylindrical probe with the magnetic field . The angle scan has shown the sine dependance of the collected current in the electron saturation part of the characteristic. The RF power scan has revealed that RF current have a strong influence on the bump width and height, proving they contribute to deplete the flux tube, in addition to DC currents.

Finally, our basic fluid model with DC perpendicular currents for strong magnetic field showed that density depletion of the flux tube can explain the bump in the characteristics . The pumping must be strong and is able to decrease the flux tube density to approximately a tenth of the bulk density before it makes appear the bump. Moreover OML theory seems a good candidate to fit the sheath expansion region above the plasma potential. This model suggests the plasma potential coincides with the top of the bump.

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