RF plasma parameter determination by a Langmuir multipoint double probe array

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Abstract: A multipoint double Langmuir (MDL) probe system, which is exempt from interference, has been designed and assembled to be applied to an RF plasma. The system provides the measurement of fundamental plasma parameters such as density, temperature, plasma potential, etc., on the basis of the Bohm Approximation Theory and the Orbital Movement Limit. Thus, one pair of the MDL system is selected so as to consider the right plasma parameters within the prevailing pressure-power intervals. Both the hardware and software of the system have been applied to the modification of material properties by means of the PIII process.

1. Introduction
Radio-frequency (RF) plasmas are widely applied to material processing, such as plasma immersion ion implantation (PIII or PSII). These plasmas are generally characterized by means of Langmuir probes in some of their kinds, simple (SP), double (DP) or triple (TP), whose $I-V$ curve contains information about the electron temperature ($T_e$), particle density ($n$), etc. In contrast to SP, DP is constituted by two electrodes whose voltages are mutually referenced (electrically floated electrodes) which is particularly convenient in the extremely noisy RF plasma environment with constant ample plasma potential ($V_p$) fluctuations [1]. Probes have been developed in different geometries (planar, spherical, cylindrical, etc.) [2,3]. Several studies have shown that $n$ can be overestimated by a SP [4] whereby a DP validation would apply. The present report describes the measurement of particle density at one single point by means of a multipoint double Langmuir (MDL) probe array in an environment similar to an RF plasma discharge reactor.

2. Setup
The probe radius to Debye length ratio $\xi_p = R_p/\lambda_D$ value is relevant, as shown by Laframboise [5]. This relation is important at the moment to choose the probe radius ($R_p$), when selecting the collision theory approximation to describe mathematically the attraction and recollection of species towards the probe, such as the Bohm approximation and the orbital movement limit (OML) [6]:

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The first one is useful when $\xi_p \leq 3$ [6], whereas, with $\xi_p \geq 10$, the OML is dependable [7]. It follows a considerable $3 < \xi_p < 10$ gap. Chen [8] has developed a plot relating $\xi_p$ and $n$ in this region for different $R_p$ values. According to this, $n < 1 \times 10^{17} \text{ m}^{-3}$ can be measured at $\xi_p \leq 3$ provided that $R_p < 0.1$ mm. Likewise, with $R_p > 0.4$ mm, one can measure $n \geq 1 \times 10^{17} \text{ m}^{-3}$ values provided that $\xi_p \geq 10$. Thus, the $\xi_p$ gap could be eluded at specific $R_p$ values.

The discharge reactor used in the present study is constituted by a 50 cm long glass cylinder, with a 10 cm radius and endowed with two flat lids, where plasma is produced a low pressure with argon working gas, by an RF generator operating at 13.56 MHz. The multipoint probe contains three sets of Tungsten (S1, S2, S3) of one same length ($L_1=L_2=L_3=5.56 \text{ mm}$) and three different radii ($r_1=0.090 \text{ mm}$, $r_2=0.435 \text{ mm}$ and $r_3=0.640 \text{ mm}$). Each point is insulated and supported by an alumina tube thanks to an especially designed coupling (figure 1).

**Figure 1.** Main parts of the multipoint probe with one same length and three different radii.

![Figure 1](image1)

**Figure 2.** Plasma characterization program. (a) Calculated $n$ during the voltage scanning (b) Response of the RF plasma density to a sudden pressure change.

![Figure 2](image2)
The characteristic $I-V$ curve is obtained due to a data acquisition system [9] in order to specify the $n$ value at one point and then to get the information in similar conditions. A PC program was developed so as to calculate the plasma parameters in situ, visualizing the $n$ results. Figure 2(a) shows the program main window with the input parameters (voltage limit, probe radius $R_p$, etc.). Some output parameters are also listed, such as the $T_e$ value resulting from both the saturation current slope technique [10] and the mathematical approximation to the $I-V$ curve [7], the correction to the $I$ signal shift created in practice by potential grads [10-12]. The program is capable to calculate three different values of the density: the first one was calculate from the Bohm approximation though a convergence iterative algorithm ($n_{\text{corrected}}$) [7], the second one by OML theory ($n_{\text{OML}}$) and finally the average between two mentioned above ($n_{\text{average}}$). Sudden pressure changes (up and down) were deliberately produced to test the PC program, the outcome is presented in figure 2(b).

3. Experimental results

The MDL was laterally introduced to the centre of the reactor varying the argon plasma pressure from 1 Pa to 30 Pa as well as the power (100-500 W). Figure 3 presents the ensuing plasma characterization results from the PC program, at constant 400 W, the pressure varying between 10 Pa and 30 Pa.

**Figure 3.** Density using multipoint Langmuir probe with constant 400 W power at different pressures.
At 1 Pa, $T_e \sim 3.5$ eV which decays to 2.5 eV as the pressure increases up to 10 Pa, in agreement with Herman et al [7]. The density, according to the Bohm approximation ($n_{\text{corrected}}$) using the probe radii $R_p = r_2, r_3$, are very alike whereas, with $R_p = r_1$, $n$ turns out to be overestimated given the gap ($3 < \xi_p < 10$) and the $R_p < 0.1$ mm region. However, the average of the $n_{\text{corrected}}$ and $n_{\text{OML}}$ values coincides with the results from $R_p = r_2, r_3$, as seen in figure 3.

Figure 4 displays the Bohm approximation results with $\xi_p \leq 3$, the OML theory for $\xi_p \geq 10$ and their average over $3 < \xi_p < 10$, with a minimal discrepancy between curves. The $R_p = r_2$ results have been selected to plot the pressure versus density plasma response (figure 5) indicating that the maximal density takes place within 17.5 Pa and 25 Pa, according to the power input.

Figure 4. Variation of density vs. power at different pressure using multipoint probe.
4. Conclusions
A multipoint double Langmuir (MDL) probe array has enabled to deduce the I-V characteristic curves at one single point using three probe points of diver dimensions operating in the same environment. The $R_p = r_2$ probe provides a good estimation of the density following the Bohm approximation ($n_{\text{corrected}}$). In the case of $R_p = r_1$ the OML theory has to be applied instead, according to the $\xi_p$ value in order to avoid the overestimation of the density. The specifically developed PC program not only calculated accurately the plasma parameters in situ but also to follow up the density behavior when the value of some of the remaining variables is modified. By plotting the pressure versus density plasma response when $R_p = r_2$, the maximal density is achieved between 17.5 Pa and 25 Pa.

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