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Langmuir Probe Sheath Size and Comparison with Plasma Properties

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Abstract. The behavior of the plasma sheath has been well understood for steady-state and simple surface geometries, but it becomes more challenging to study in dynamic situations. One example is a change in the probe potential, which requires the plasma sheath to adjust itself to the new conditions. In order to accurately investigate the dynamics of the sheath and its transition time, it is crucial to correctly determine its size. To address this, we have developed a method that calculates the sheath size from the potential around the probe. The validity of such method was verified, and the calculated sheath was compared with the velocity properties of the plasma particles around the probe in hope to find faster way to calculate the sheath size.

Introduction

Understanding and measuring the properties of low-temperature plasma is crucial in various fields including astrophysics, gas discharge research or industrial applications such as semiconductor manufacturing and materials processing. The plasma parameters can be obtained by different diagnostic methods like optical absorption or emission, microwave diagnostics, probe diagnostic, and others that can be found, e.g., in *Hutchinson* [2002] or *Huddlestone and Leonard* [1965]. The Langmuir probe is one of the most effective and widely used diagnostic tool for various types of plasmas.

When the Langmuir probe is inserted into a plasma, the sheath layer forms around the probe due to the difference in flux of charged particles. Electrons, being much lighter and faster than ions, are initially collected by the probe, causing local disruption of plasma quasi-neutrality. The probe surrounding becomes more positively charged. This excess of positive charge attracts electrons while repelling the positive ions, leading to the establishment of the sheath region where the electric potential gradually changes from the probe surface to the bulk plasma. The sheath plays a crucial role in the interpretation of probe measurements, as it affects the current collected by the probe and thus influences the $I - V$ characteristics used to determine key plasma parameters. Understanding the dynamics and properties of the sheath is essential for accurate analysis and reliable plasma diagnostics using Langmuir probes [*Langmuir and Mott-Smith*, 1926].

As the probe potential changes during the measurements, the sheath can either expand or contract. When the probe potential decreased with respect to the plasma potential, it repels more electrons and attracts more ions, causing the sheath to expand. On the contrary, when the probe potential increased, it leads to a contraction of the sheath. This dynamic adjustment is essential for capturing the $I - V$ characteristics. In plasma with time-varying properties or when the probe potential is rapidly swept, the sheath does not instantaneously reach equilibrium. The time-dependent behavior of the sheath [*Lobbia and Gallimore*, 2010] can lead to transient effects, such as delayed current response and hysteresis in the $I - V$ characteristics. These effects are particularly important in pulsed plasma discharges and radio-frequency (RF) plasma, where the sheath dynamics must be carefully analyzed to avoid incorrect measurements.

To better understand and predict the dynamic behavior of the plasma sheath the particle models are used usually. The particle models give microscopic information about the studied system thus being extremely useful in studying plasma–probe interaction. On the other hand, they are computationally demanding and the information they provide might be overwhelming. The particle model was chosen for our study because it can provide us the size and shape of the sheath layer also with other plasma parameters like velocity profiles of the plasma particles inside the sheath.

Particle model

The particle model used for this study was developed in-house and used also in previous study [*Palacký and Roučka*, 2022]. It is 2D3V hybrid model using molecular dynamics for integration of particle motion namely particle-in-cell (PIC) and Monte Carlo method used for simulation of the collisions with neutral background. The model is able to simulate rectangular workspace with cylindrical probes, in this case the probe is places in the middle of square workspace. The boundary conditions on the sides of the workspace are open with particle sources present. The probe has also open boundary that only collects particles.

Model and plasma conditions

The model uses two different sets of parameters. One of them is the plasma parameters that describe the studied plasma while the second group is the simulation parameters. The second group needs to fulfil the the limitations of used algorithms for the chosen parameters in first group while trying to minimize computational resources.

The plasma parameters which can be chosen are the pressure p, external electric field E_{ext}, plasma concentration $n_{\text{e}} = n_{\text{Ar}^+}$ and neutral background temperature T. For this study they were chosen to reflect usual plasma conditions in positive column of the argon glow discharge with cylindrical probe of r_p radius.

The plasma parameters in Table 1 imply a certain electron temperature that was obtained using the Bolsig+ [*Hagelaar and Pitchford*, 2005] with the $\text{e}^- + \text{Ar}$ cross-section from LxCat database [*Pancheshnyi et al.*, 2012]. Same cross-section values were also used in the models Monte Carlo part. The result electron temperature was $T_{\text{e}^-} = 2.89$ eV and it was used as input temperature into the model to speed up the electron energy stabilization in particle source. The particle source uses Maxwellian EDDF for the initial state and the it is given time to stabilize the EDDF before the model uses it. Other calculated plasma parameters can be seen in Table 2.

The simulation parameters were obtained based on the plasma parameters in Tables 1,2. Then they were used in combination with the limits of used algorithms and the duration of the simulation. The result parameters can be seen in Table 3.

Table 1. Input model parameters–Macroscopic plasma parameters.

p	133 Pa
E_{ext}	100 V/m
$n_{\text{e}} = n_{\text{Ar}^+}$	1.59×10^{15} m^{-3}
T	300 K
r_p	1×10^{-4}m

Table 2. Plasma parameters: electron f_p^{e} and ion plasma frequency $f_p^{\text{Ar}^+}$, collision frequency f_{coll}, Debye length λ_{D} and Bohm velocity c_s.

f_p^{e}	360 Mhz
$f_p^{\text{Ar}^+}$	1.39 Mhz
f_{coll}	6.11×10^{13} s^{-1}
λ_{D}	2.98×10^{-5} m
c_s	2.56×10^{3} m s^{-1}

Table 3. Computational parameters: time step Δt, size of the PIC cell Δh, the size of the workspace $X_{\text{WS}} \times Y_{\text{WS}}$ and the number of electrons N_{e} and ions N_{Ar^+}.

$X_{\text{WS}} \times Y_{\text{WS}}$	1 cm $\times$ 1 cm
Δh	10^{-5} m
Δt	10^{-11} s
$N_{\text{e}} = N_{\text{Ar}^+}$	2×10^{6}

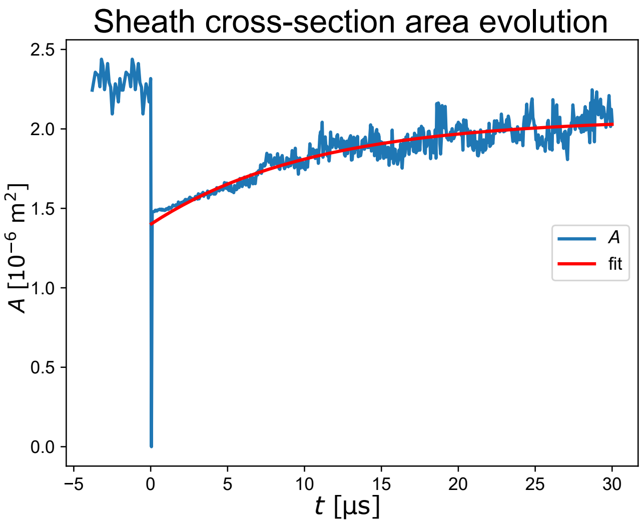

Figure 1. The sheath area time evolution during a probe potential change from $\phi_p^i = 6$ V to $\phi_p^f = 5$ V at time $t = 0$ s.

The first parameter is the size of the workspace and it must be large enough to allow the sheath to form. The plasma sheath requires at least 5 to 7 $\times\ \lambda_{\mathrm{D}}$ to all directions, but one must count with the presence of the presheath and the dynamic simulations requires even more space since the sheath might expand. Then the size of PIC cell Δh is picked limited by the λ_{D} to fulfill the PIC stability condition [*Birdsall*, 1991] $\Delta h \leq 3\lambda_{\mathrm{D}}$. The time step Δt is also limited by another PIC stability condition $\Delta t < 2\omega_{\mathrm{e}}^{-1}$ in combination with the $T_{\mathrm{Ar^+}}$ and T_{e}, Euler's precision and the ω_{coll}. Based on those Δt conditions the lowest one is picked. At the end, the N_{e} and $N_{\mathrm{Ar^+}}$ is based on the PIC requirements that every cell has to contain more than 10 particles and the plasma concentration $n_0 = n_{\mathrm{e}}$.

Results and Discussion

The particle model mentioned in previous chapter was used to calculate dynamic system with initial steady state having probe set to probe potential $\phi_p = 6$ V. The initial state was then used for another simulation with changed $\phi_p = 5$ V. The stabilization of such system was observed, to be specific the sheath around probe was the focus. The sheath calculation is not easy task if one does not want to use theoretical assumptions for the charged particle concentration profiles. The simulation allows us to calculate sheath shape and size directly from the potential around the probe. The sheath forms around a probe inserted into the plasma shielding its potential. Outside of the sheath the electric field $\vec{E} = \vec{E_{ext}}$, where $\vec{E_{ext}}$ is external electric field. This was taken to create a method where radial profile of electric field from the probe outwards is calculated and compared to the radial profile of external electric field. in other words when $E_{\mathrm{r}}^{calc} = E_{\mathrm{r}}^{ext}$, the algorithm found sheath boundary point and marks it. Repeating this process around the probe the whole sheath boundary is found.

The sheath area evolution in time is then shown in Figure 1. The fit of the data was made with decaying exponential function:

$$f(x) = A \cdot \exp(-x/\tau) + B \tag{1}$$

to find the characteristic transition time $\tau = (1.1 \pm 0.2) \times 10^{-5}$ s which corresponds to tens of the ion plasma cycles.

Radial velocity profiles for electrons and ions were also analysed to be used for a comparison and a possible sheath size calculation tool. To achieve that, the radially resolved velocity distribution function was calculated in rings of λ_{D} width with the probe in the centre. One of the electron profiles can be seen in Figure 2.

One can clearly see a change in the most probable velocity at a certain distance when the electrons start to be heavily attracted to the probe. This distance is marked in Figure 2 with red line. Similarly, the

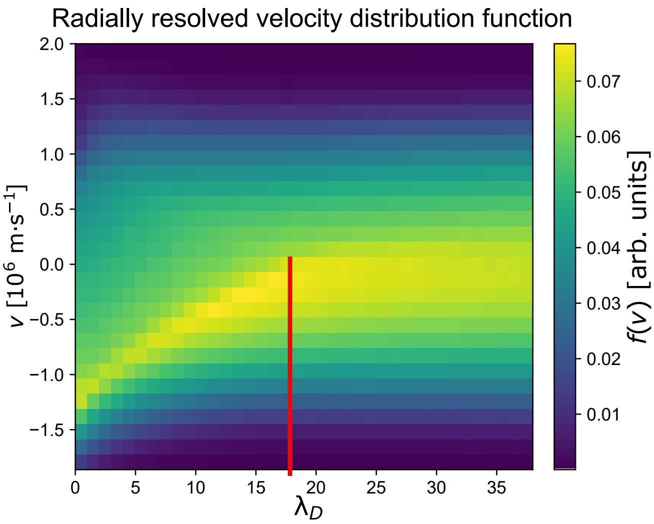

Figure 2. Radially resolved non-normalized electron velocity distribution function example with red line marking the distance at which change in most probable velocity occurs.

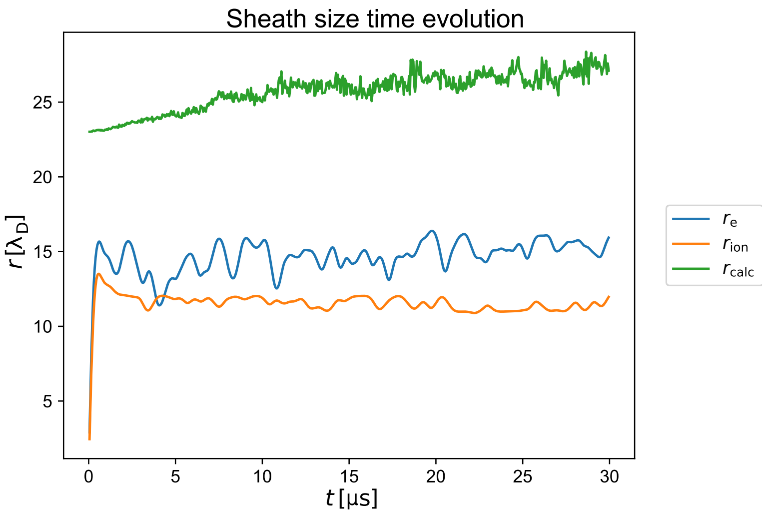

Figure 3. The time evolution of the calculated sheath radius r_{calc}, the sheath radius from electron velocities r_{e} and the sheath radius from ion velocities r_{ion}.

ion profiles contain in this part of the probe characteristics a cut off. This is due to the probe repulsion being stronger than their energy.

Those distance points can also be used to calculate the sheath size, since those are the points where electric field created by the probe is clearly not shielded. Both change points for electrons and ions were analysed in time and expressed in terms of λ_{D} from Table 22. The sheath area A from Figure 1 was also converted to an effective sheath radius as $r = \sqrt{A/\pi}$ and all of the time series are shown in Figure 3.

The sheath calculation done from potential being more precise shows the proper time dependency instead of the radial velocity ones. This may be due to the calculation of the radial velocity distributions had fixed λ_{D} parameter as the smallest recognition unit or due to the number of particles in the sheath. Unfortunately because of that the information obtained from the velocity distributions is not useful for the characteristic transition time calculation. Although, if more precise calculation would be used it might be possible but it would require to simulate with even more particles to reduce the noise. Even in this case the noise was significant enough that the Butterworth low-pass filter had to be used. Clearly there is a difference between the sheath radius that was found. The calculation from the potential includes the whole sheath, including the presheath, while the radial velocity analysis covers an approximation of the sheath without the presheath, which has roughly twice smaller radius. If the radial velocity analysis were more precise it might be interesting to combine both methods to really distinguish between sheath, presheath and bulk plasma in the models.

Conclusion

The characteristic transition time for the sheath was calculated $\tau = (1.1 \pm 0.2) \times 10^{-5}$ s for the potential change on the probe from $\phi_p^i = 6$ V to $\phi_p^f = 5$ V in Argon plasma under $p = 133$ Pa. It was found that the sheath size including the presheath must be calculated directly from the potential if the exact value is needed. It was expected since the calculation is done from the sheath definition. On the other side, the size obtained from the radial velocity distributions might be usable as a rough approximation of the probe sheath without the presheath, but it is not usable for evaluation of the sheath size time-evolution. This might be due to the fact that the potential is calculated with Δh while the radial velocities have precision in λ_D. Also the small changes in potential are directly affecting the calculation of the sheath size, while it takes few λ_D since the effect of changed potential profile is significant enough to be seen in the radial velocity profiles. Increasing the precision and reduction of the noise might help, but the computational effort would rise enormously. Increasing the precision and reducing the noise might help, although this would require significantly higher computational effort.

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