Sheath Expansion around Langmuir Probes in Flowing Plasmas

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Sheaths form on probes, walls, and dust immersed in a bulk plasma. Understanding sheath properties is critical to applications like etching, and diagnostics like Langmuir probes. However, sheaths are not always immersed in static bulk plasmas, and may instead be immersed in a flowing plasma. For example, the sheath on a Langmuir probe positioned near a wall would be immersed in the ambipolar flow of the presheath attached to the wall. Here we use particle-in-cell simulations to characterize the structure of a sheath immersed in a flowing plasma.

Modeling sheath expansion around a Langmuir probe is necessary to analyze the probe signal since the sheath width determines the effective collection area. However, the current model of sheath expansion does not account for the effects of a flowing plasma. Furthermore, recent experiments have indicated that the current model of sheath expansion fails in the presheath, where there is significant plasma flow [1]. The experimental measurements were made in a multi-dipole plasma device, where the plasma is produced by a population of hot, dilute electrons from a thermionic cathode. A Langmuir probe was used to calculate the electron and ion densities at different distances from a grounded electrode. Specifically, the electron and ion densities determined from the probe agree well in the bulk plasma when the current model for sheath expansion is used. However, when the probe is moved into the presheath (or the sheath) region of a flat grounded electrode the electron and ion densities disagree such that the electron density is higher than that of the ions. This is exactly the wrong prediction, as the electron density should be smaller than that of the ions throughout the presheath and sheath regions.

Motivated by these shortcomings, we leverage simulations of a Langmuir probe near a biased electrode to correct the current model. We find that the sheath area expands significantly as the ambient plasma flow increases. The expansion is nonuniform and is greater on the downstream side of the probe, where the density is different compared to the upstream side. Accounting for the increase in

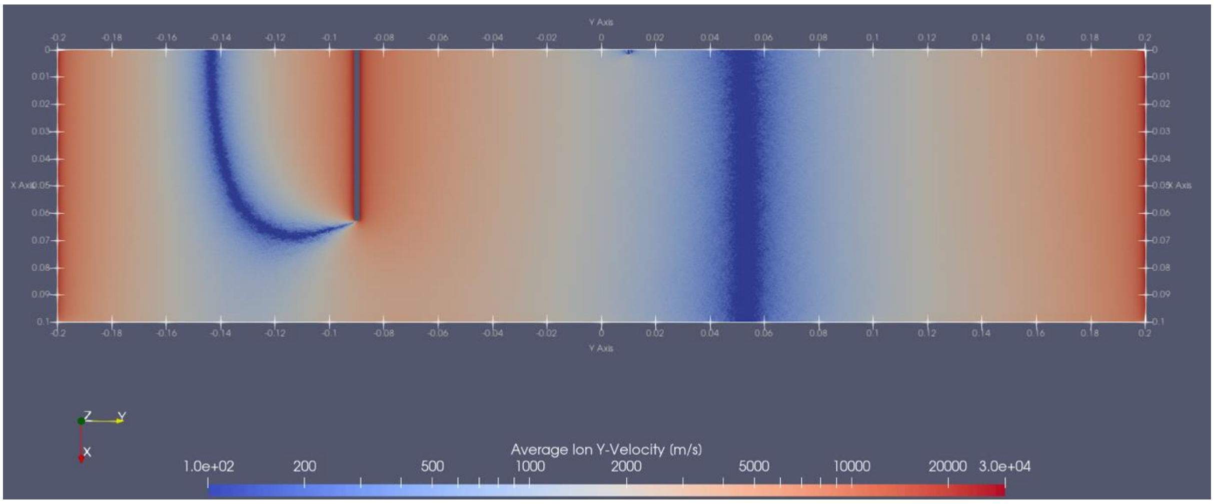

Fig. 1: Magnitude of the average y-velocity of ions in the simulation domain containing the grounded electrode. In this simulation the probe is located at $x = 0$ m and $y = 0.01$ m and represents a situation where the ion flow toward the probe is small.

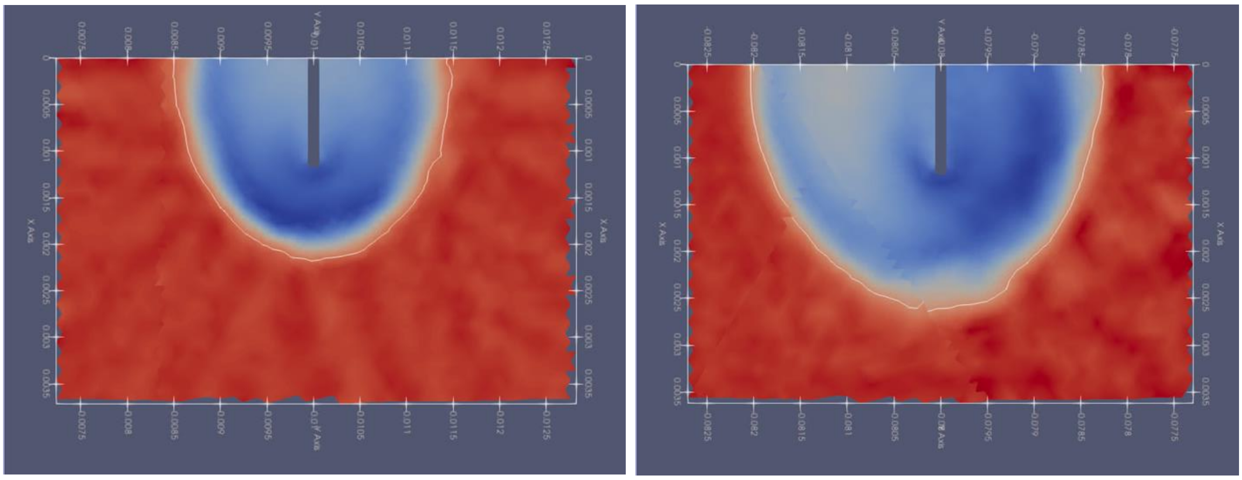

Fig. 2: Charge density around the probe for two cases: (left) where the probe is in a relatively stationary plasma and (right) where the probe is immersed in plasma flowing from right to left. The sheath edge is the white contour defined by $\rho = -5 \times 10^6\ C/m^3$.

the effective collecting area should act to correct the current sheath expansion model, allowing for accurate measurements of plasma density near other sheath regions using a Langmuir probe.

The simulations use a 2D domain, shown in Figure 1, where the boundary along x = 0 m is reflecting and represents a plane of symmetry, while all other boundaries are perfectly absorbing. The position of the probe is moved along the y = 0 m axis toward the electrode located at y = -0.09 m in a series of simulations designed to illustrate the effect a flowing plasma has on a probe. Figure 2 shows the charge density around a positively biased probe at two locations: (left) far from the grounded electrode and (right) near the grounded electrode. The structure of the charge density changes due to the relatively strong flow of plasma from right to left; namely, the sheath expands in all directions, but most notably on the downstream side of the probe. Similar behavior is observed for different probe biases and positive biases are shown here for convenience.

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