Mapping the field around a Langmuir probe with charged dust particles

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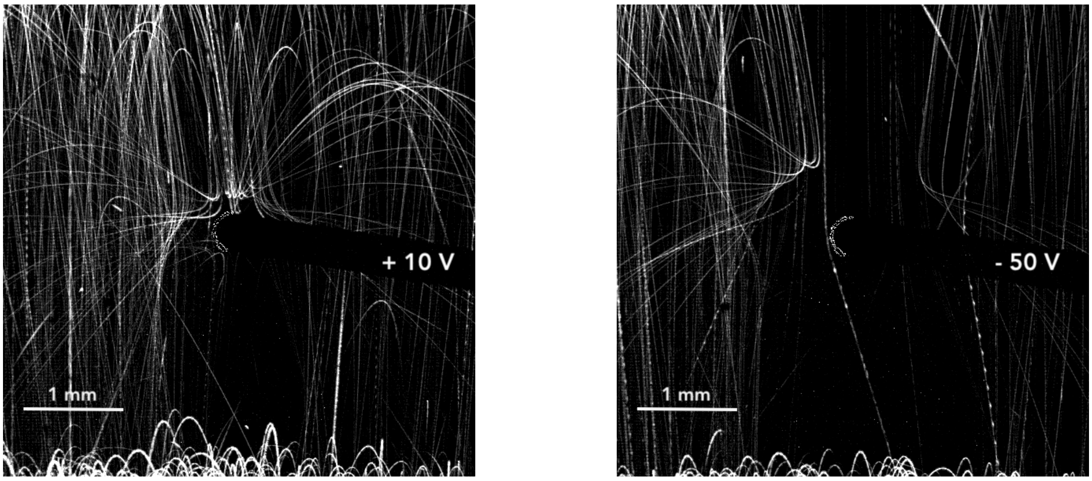
Langmuir and other probe diagnostics are routinely used to determine plasma properties such as electron density and electron energy distribution [1]. Although these experimental techniques are generally considered reliable, the main drawback is that, as an invasive method, the presence of the probe itself alters the properties of the discharge plasmas in its vicinity. Theoretical models, such as the orbital motion limited (OML) approximation of ion transport, can be used to estimate the magnitude and extent of the perturbation [2].

Here we use electrically charged solid dust particles dropped onto a DC biased tungsten probe tip inserted horizontally into the bulk region of an argon capacitively coupled RF discharge operated in a GEC reference cell to visualize and quantify the effect of the probe on the discharge. Fig. 1 shows stacks of 8000 individual sequential snapshots (each with 1/500 sec exposure time), representing two cases differing only in the DC voltage applied to the probe.



(a) Probe voltage = $+10$ V ($\approx$ floating potential). (b) Probe voltage = -50 V.

Fig. 1: Dust particles (8.89 μm diameter melamine-formaldehyde) raining down on the probe tip (in the center, 380 μm diameter) illuminated by a 1 mm thin vertical laser sheet. The 13.56 MHz RF discharge is driven in 10 Pa argon gas with $\sim$ 10 W RF power.

When a large negative DC voltage (-50 V) is applied to the probe tip, the negatively charged dust particles are strongly repelled at about 1 ± 0.2 mm from the probe. When the probe bias is near the floating potential ($+10$ V), the particles can get as close as approximately 0.1 mm. This suggests that electrostatic repulsion between the probe and the particles dominates. However, at even larger negative probe voltages, the interaction becomes more complex, as shown in Figure 2.

Here we can see three different regions concentric around the probe tip. In the case of -150 V applied to the probe, at a large distance ($r > 1.9$ mm) the trajectories of the dust particles are not influenced by the presence of the probe: they fall from above, bounce in the repelling electric field of the RF sheath, reach an upper turning point, fall back into the RF sheath, undergo a second reflection and reach a lower turning point, and finally disappear completely from the field of view. This behavior indicates that the dust particles are charging fairly uniformly (reaching the same turning point heights), and the difference between the first and second turning point positions could be used to infer the friction coefficient between the dust particles and the background gas, which is not the subject of this work. At intermediate distances (1 mm $< r <$ 1.9 mm) the dust particles are repelled by the probe, but at small

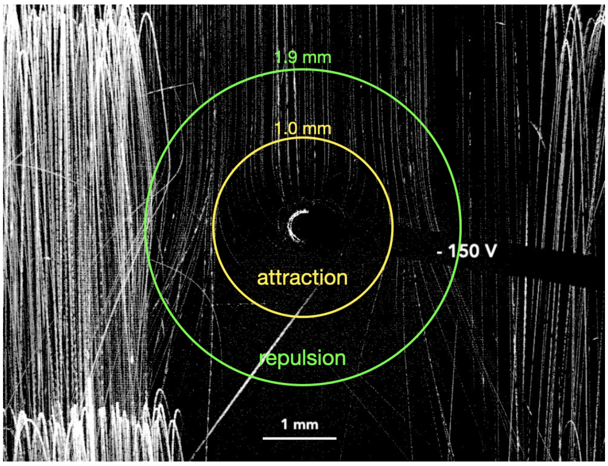


Fig. 2: Same as figure 1 with -150 V probe voltage. Circles indicate regions, centered around the probe tip, which show attractive and repulsive interaction between the probe and the dust particles.

distances ($r < 1$ mm) the dust trajectories are bent towards the probe tip, a clear indication of attractive interaction.

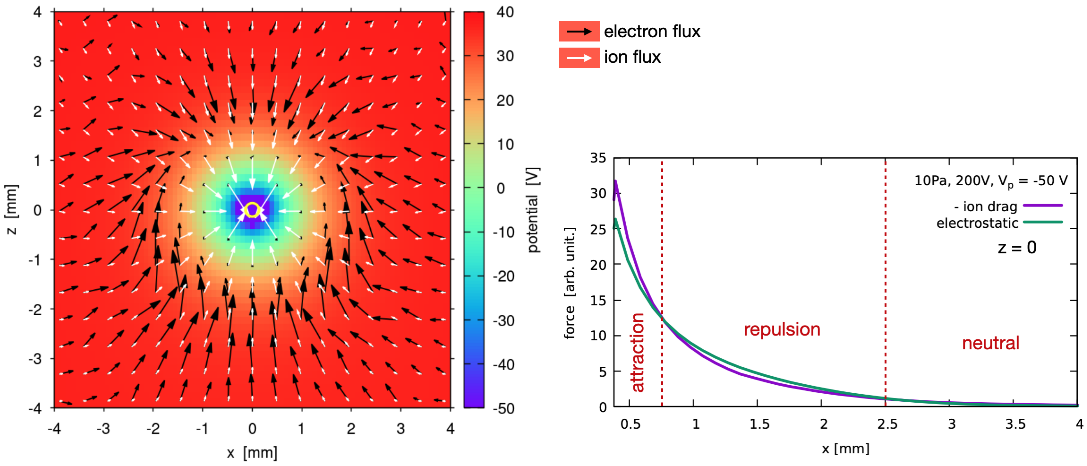


Fig. 3: PIC/MCC simulation results for 10 Pa, 200 V RF amplitude, -50 V probe voltage. Left: electron flux (black arrows) and Ar^{+} ion flux (white arrows) distributions superimposed on the colormap of the electrostatic potential around the probe tip. Right: electrostatic and ion drag force distributions acting on 8.89 μm diameter dust particles with 10 000 electron charges.

Figure 3 shows PIC/MCC simulation results for the distribution of electron and Ar^{+} ion fluxes around a negatively biased probe tip for discharge conditions 10 Pa pressure, 200 V RF amplitude, -50 V probe voltage. The formation of an electron-depleted sheath region, characterized by a significant ion flux towards the probe, is visible. Using the OML approximation to estimate the ion drag force experienced by the dust particles [3] we can compare the effects of electrostatic repulsion and attraction due to the drag force, which qualitatively reproduces the observed net force field structure with distinct attractive, repulsive, and neutral regions around the probe tip.

A detailed analysis of the experiments and PIC/MCC simulations will be presented, providing a deeper insight into the mutual interaction of the probe with the plasma and the dust particles. These findings suggest that using dust particles for the diagnosis of local plasma parameters can reveal information both on electrostatic and flow dynamic properties.

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