Dust interactions in a flowing plasma

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Key factors affecting formation of plasma crystals include the particle interacting potentials, plasma fields, external forces, as well as plasma collective processes. Since dust crystal structures levitate in the sheath region, the ions flowing to the electrode provide a distinctive direction, with the plasma properties different in the parallel and perpendicular directions. The nature of dust interactions in flowing plasma can be understood by considering a simpler test system allowing elucidating their character. The simplest experiment and model consider a system of two particles arranged vertically or horizontally and maintained by an electrostatic confining potential in the horizontal direction and plasma sheath/gravity potentials in the vertical direction.

Here, we present investigation of interactions of two particles coupled in the ion flow that includes experiments and modeling. On the basis of the model simulations, the wake parameters are determined, including the influence of the particles on each other and on the wake parameters. Comparison of the experimental data is made with the theoretically obtained combined interparticle potential including the molecular dynamics wake simulation data, the plasma Debye interaction, the external sheath potential, and taking into account the change of the charge of the downstream particle.

The experiments were carried out in argon plasma with micron-sized dust particles. The plasma was generated at pressures in the range18–60 mTorr and a 15 MHz signal was applied to the powered electrode. The electron density is 2–9_10^8 cm^{-3}, the electron temperature is about of 2 eV, and the plasma potential is 10–80 V. The experimental setup is shown in Fig. 1.

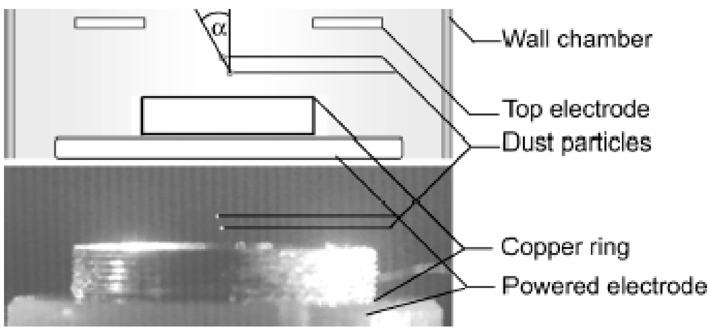

FIG 1. Experimental set-up

Disruptions of particle arrangements were triggered by changing the discharge controlling parameters (pressure and peak-to-peak voltage) as well as by applying an additional bias to the confining electrode. Where the transition was triggered by changes of the discharge parameters, the transition from the horizontal to the vertical alignment has been found to be more pronounced than the reverse one. The clear hysteretic phenomena were observed for the transition triggered by changes of the confining voltage. The phenomenon observed can be understood if we take into account that when changing the controlling parameters of the discharge, almost all values characterizing the dust particle interactions such as the particle charge, the plasma screening length, the parameters of the ion wake are changed. To elucidate the influence of γ_z/γ_x on the particle arrangement, it would be advantageous to change the confinement strength ratio without affecting other system parameters. The best way to realize that is to change the horizontal confinement by applying an additional dc bias to the confining electrode which does not affect the discharge.

The experiment was started by applying a dc bias to the confining electrode to investigate the stability of particle arrangements as a function of the ratio of the vertical to horizontal confinements. Starting from the zero bias, α slowly increases with increasing V_b from 48° to 62° until V_b=8.8 V, and then jumps up to α=86° corresponding to the lower particle moving below the upper and to the formation of the vertically aligned arrangement. When V_b decreases, the angle practically does not change until V_b=5.9, and then jumps down to α =64° when disruption of the vertical alignment occurs. After that, the angle slowly decreases back to the original value at V_b=0. Similar behavior was observed for other values of V_p (with different values of the threshold V_b).

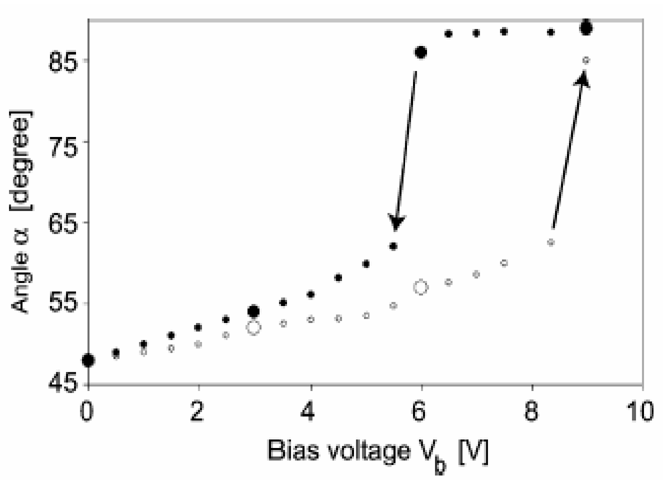

FIG 2. The hysteretic angle α as a function of the bias voltage V_b.

For the vertical arrangement, the lower particles is stabilized by the excessive positive ion charge of the wake. On the other hand, in the case of the horizontal alignment, the wake contributes to disruption of the arrangement [2]. The different role of the wake (stabilizing versus destabilizing) for different arrangements leads to the hysteretic behavior of the lower particle in the cyclic HVT-VHT transitions.

From the experimental data, we can clearly see that the arrangement of a pair of dust particles indeed depends on γ_z/γ_x. All transitions correspond to $\gamma_z/\gamma_x > 1$. We note that all VHT correspond to values of $7 > \gamma_z/\gamma_x > 3.8$ that are higher than those for VT. Most of HVT occur for nearly similar values of $\gamma_z/\gamma_x \sim 4$. While for VHT, the value of γ_z/γ_x where the transition occurs cannot be generally specified. If to assume that the interaction of vertically arranged dust particles is symmetric (i.e., the upper particle acts on the lower one in the same way as the lower one acts on the upper one), the transition frequencies differ only by the friction of dust particles with the neutral background: i.e., $\gamma_z/\gamma_x \neq 1$ when the transition from the horizontal to the vertical (or vice versa) arrangement takes place. However, the influence of the ion wake makes the interaction of the vertically arranged particles highly asymmetric. It has been pointed out [3] that this influence, modeled in the simplest case by assuming the region of an excessive positive charge below the upper particle, leads also to $\gamma_z/\gamma_x \neq 1$ when the transition occurs. We note that both (friction and wake) effects can contribute to the hysteretic behavior although for different discharge characteristics. Indeed, in the case of higher pressures when the ions are slowed down because of friction with the plasma neutrals, the wake effects are generally weaker. In this case, the friction (which is, on the opposite, higher) can define the hysteresis. In the opposite case of lower pressures when plasma ions are faster and the wake effects are more pronounced, the influence of friction can be negligible.

In the another set of experiments, a transition occurs in a system of two dust particles with the decrease of the particle separation. This phenomenon was triggered by the laser beam focused on one particle thus pushing it closer to another particle. The experiment was performed in the following steps. First, we have applied a small confining (in the horizontal) bias (up to 5 V) to force the initial vertical separation because of the strong Coulomb repulsion in the horizontal plane the particles cannot get closer to each other while being at the same height. Then, second, the lower placed particle was pushed in the horizontal direction by the diode laser towards the upper particle. The laser power was increased by increasing the current to shift the bottom particle

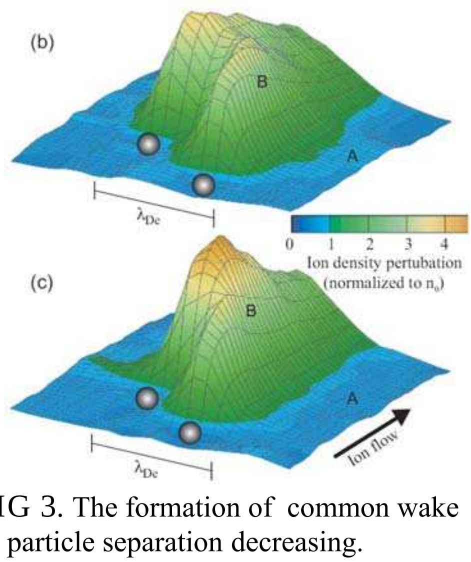

FIG 3. The formation of common wake as particle separation decreasing.

until it jumps directly under the upper one. Thus the change in the particle separation was accompanied by keeping all other system (plasma) parameters constant and disruption was induced by changing only the interparticle distance. This allowed us to relate the transition observed with the novel phenomenon in the wake formation when the *common* wake focus of two nearby particles appears. The formation of the common wake drastically change the interparticle interaction and therefore leads to the jump of the particle.

In the third set of the experiments it was demonstrated that in the case of the sufficiently strong ion flow, the vertical separation of dust particles can be significantly less than the plasma electron Debye length. At operating parameters between 30-100 mTorr and 10-40 V, dust was introduced into the plasma, one particle at a time. Once two particles were isolated in the plasma, the pressure would be increased until vertical alignment occurred. Once the alignment occurred, the heights and separations of the two particles would be measured under varying operating parameters. Fig.4 presents dependence of particle separations on discharge pressure. From this plot, its is evident that as the pressure increases so to does the separation between the particles. Such close pairing could be explain by the fact that bottom particle influence the wake and vice versa .

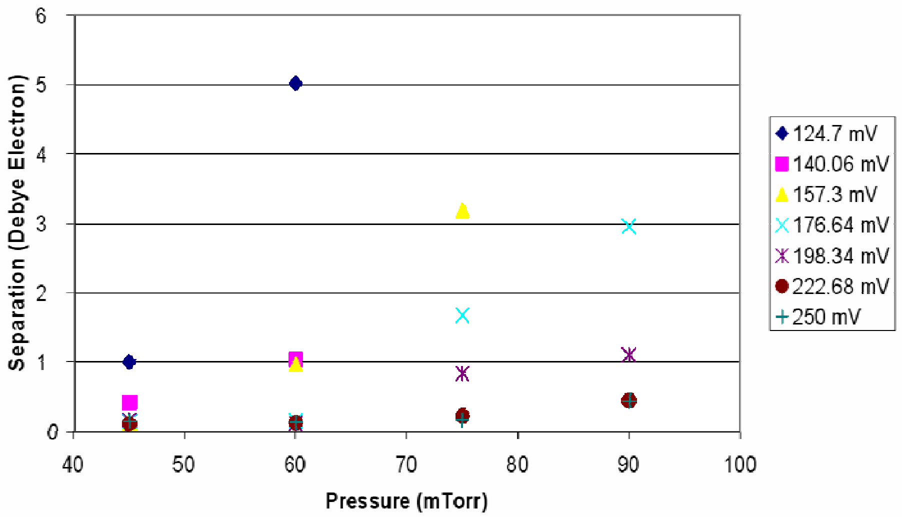

FIG 4. Particle separation vs. pressure.

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