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Interaction forces between cluster particles in a dense plasma

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Up to now, cluster structures have been investigated only under sheath conditions. In this paper, we study the particle dynamics in a small cluster suspended in a different plasma regime - the specific secondary plasma produced by an adaptive electrode inside the sheath of the discharge [1]. The main features of our observations are: 1) the particles levitate inside a modified sheath region; 2) weak external confinement; 3) the clusters particle number can be externally controlled, 4) perturbations of the cluster introduced by a rotating grain trapped below the main cluster; 5) use of simultaneous 3D diagnostics for reconstruction of the particle dynamics. The highly resolved 3D measurements enable us to determine main plasma parameters and forces providing the particle equilibrium. These measurements indicate that the secondary plasma has properties peculiar to the presheath region of a discharge rather than to a typical sheath plasma.

To model the dust-dust interactions in the presence of subthermal ion flows, we introduce a "hybrid" type of interaction, containing the screened Coulomb repulsion of the particle charges and attraction due to the positive charge of the ion wake [2]. Accordingly the force describing binary dust-dust interactions can be represented as a combination of the electrostatic force due to the repulsion of the residual like particle charges and a dipole force due to the streaming ions

$$F = \frac{Q^2}{\lambda_D^2}\left[\frac{(1+\kappa)\exp(-\kappa)}{\kappa^2} + 3\varsigma\frac{\left(1-3\sin^2\chi\right)}{\kappa^4}\right], \tag{1}$$

where F denotes the force component along the radius-vector between two particles, $\kappa = \Delta/\lambda_D$, is the so called lattice parameter, Δ is the interparticle distance, and the dimensionless coefficient $\varsigma = q^2 l^2/(Q\lambda_D)^2$ specifies the value of the electric dipole moment. The quantity χ denotes the angle between the normal to the ion flow and the radius-vector connecting the two particles. It can be easily verified that the interparticle force (1) changes its sign (for a given κ) when

$$\varsigma = \frac{1}{3}(1+\kappa)e^{-\kappa}\frac{\kappa^2}{3\sin^2\chi - 1}. \tag{2}$$

In the following, we will use this expression to estimate the dipole contribution (the coefficient ς) in the total force for given particle positions. This simple "dipole" model of binary dust-dust interactions is then employed to explain the observed distortion of the cluster structure by a particle rotating beneath.

In the undisturbed phase, the cluster particles were suspended in the weak electric field ($E_y \simeq (4.8-6)$ V/cm) of the secondary plasma and form almost a tetrahedron with the average interparticle distances of the order of $160-200$ μm. Apart from thermal vibrations, the cluster particles are apparently periodically disturbed by the motion of the lower orbiting particle. We denote the cluster particles lying in almost horizontal plane as A, A1, A2, an upper grain as D, and the grain orbiting below the cluster as B. As the (perturbing) particle B approaches, the lower grains, A and A1, break the bond with the upper grain D and start to move towards the rotating particle B (almost along the vertical direction). When the particle distances A-B and A1-A become small enough, the particles return back to their places inside the tetrahedron structure to restore equilibrium (for more details see ([1]).

Assuming that positions of any cluster particle is mainly determined by the interactions with other particles (in our case the external confinement is found to be weak [1]), we consider dynamics of the two particles (subscript n refers to A and A1) governed by

$$\mathbf{F}_n = M\ddot{\mathbf{r}}_n + \gamma\dot{\mathbf{r}}_n, \tag{3}$$

where $\mathbf{F}_n$ is the force acting on the n-th particle. At the high gas pressures ($p \sim 57$ Pa) used in the experiment the inertia term is always much smaller than the neutral drag force, so that we may estimate the force acting on the individual particles during snapshots. From the 3-D trace of the particle one can determine the vector velocity and, using Eq. (3) reconstruct the instantaneous vector force acting during the attraction-repulsion phase, when the particle displacements are much larger than the uncertainties of the measurement. Since the motion in the vertical (y) direction is most pronounced we consider the vertical component of the total force, $\mathbf{F}_n$. Figure 1 shows the computed vertical projection of the measured force acting on cluster particles A and A1 due to interactions with all other grains during cluster distortion phase (frames 151-158). Using the results of the force measurements we are now able to investigate whether the dust-dust interactions described by (1) are compatible with these direct force estimates. From the measured particle coordinates one can easily calculate the instantaneous interparticle distance and angle χ corresponding to the closest approach of grains. For example, for the grains A-B we obtain $\kappa_{\min} \sim 8$, and the angle $\chi_{\min}$ lies between $0.65-0.7$. One can consider the values of $\kappa_{\min}$ as points where the transition from repulsion (due to like-charges) to the dipole attraction occurs (the left hand side of Eq. (1) goes to zero). Hence, substituting $\kappa = \kappa_{\min}$ and $\chi = \chi_{\min}$ in (2) gives the wake-coefficient in the binary interactions, ς. We get $\varsigma \sim 0.15-0.35$ (interactions between A and A1) and $\varsigma \sim 0.35-0.65$ (interactions between A and B). To calculate the corresponding force we take the average values $\varsigma \simeq 0.25$ for the binary interactions between the cluster particles and $\varsigma \sim 0.5$ for the pair A-B. The difference in the dipole coefficients ς can be attributed to specific properties of the rotating particle B: i) its nonshperical form and thus another value of the particle and wake charges; ii) its location in the vicinity of the lower electrode, and particle-electrode interactions probably affect interactions with the cluster particles.

Substituting the values of ς, λ_D and particle charge Q (which have been estimated independently from the analysis of the particle dynamics) in Eq.(1), yields the binary interparticle force, $\mathbf{F}_{n_j}$, for a given particle's position. The total force acting on any grain, n, can be then obtained by computing the sum $\mathbf{F}_n = \sum_{(j)} \mathbf{F}_{n_j}$, where $\mathbf{F}_{n_j}$ is determined by the binary force (1) and j denotes the number of neighbor cluster grains including the orbiting particle, B. Limiting ourselves to the three nearest neighbor contributions ($j = 3$), we compare the calculated force $\mathbf{F}_n$, acting on the cluster particles, A and A1, with the direct force measurements in Fig. 1. As one can see both curves demonstrate the functional dependence close to the measured force (except for the frames 156-157 for A-particle). For $Z_d = 4.5 \times 10^3$, the calculated force is decisively below the experimental data for both particles. The best quantitative agreement between the measured force and the dipole model is found for the particle charge corresponding to the highest theoretical proposed value $Z_d = 5.5 \times 10^3$. An interpretation of the measurements using only screened Coulomb interactions ($\varsigma = 0$) does not yield any quantitative agreement, the qualitative trend is even opposite to the observations!

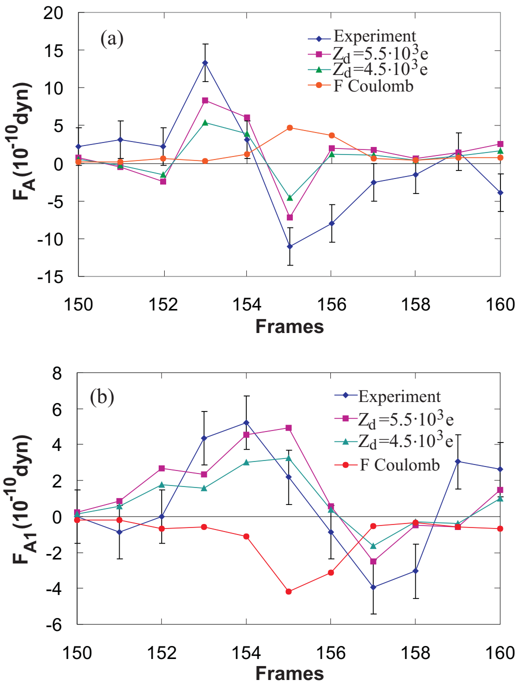

Figure 1: Vertical projections of the force acting on the cluster particles A and A1 during the distortion phase.

Considering the crudeness of the dipole model (assumption of the constant coefficient ς, constant screening length λ_D, the estimate of the ion flow velocity u, identical particle charge Z_d etc.) the agreement shown in Fig. 1 is surprisingly good. Note also, that the external confinement force, F_v, can also affect the interaction force (especially at small particle displacements, when F_n may be of the same order as $F_v \sim 10^{-10}$ dyn).

Considering separately the contributions of the neighboring grains in the total force acting on cluster particle A1, we found that its motion is mostly governed by the dipole attraction to the downstream grain A, while the dynamics of the particle A is more complicated and depends on the contributions of all close neighbors: A1, A2 and B, (however it is mostly determined by the dipole attraction to the grain B in frames 152-154, when their intergrain separation achieves its minimum). This observation independently supports the finding that at large intergrain separations ($\kappa \gg 1$), the particles indeed interact rather like dipoles than separated charges. The implication is that we observe a very different situation to that considered e.g. in Ref. [3] for the sheath plasma, where the particle-wake attraction was strongly asymmetric and was communicated only downstream along the ion flow (the upper grain experienced no attractive force from the lower one). The difference can be explained by the specific properties of the dense plasma, produced by the adaptive electrode: a) the small screening length provides the condition $\kappa \gg 1$ and the particle interaction resembles point dipoles rather than lengthy distributed charges, b) the flow of ions is subthermal, hence information can pass between the interacting particles in both directions and thus modify the dynamics. Determination of the vertical projection of the force acting on the orbiting particle B and comparison with the model prediction would shed more light on this, but unfortunately, the particle B rotates too close to the lower electrode, so that its influence probably dominates in this particle dynamics.

References

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