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Formation of boundary-free dust clusters in a uniform low pressure gas discharge plasma in the experiment Plasmakristall-4.

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Micron sized dust particles injected into low temperature gas discharge plasma quickly acquire a large negative electric charge and form dusty plasma structures. The strong electrostatic repulsion between the charged dust particles tends to a dispersion of such structures. For the confinement of the structures usually external electrostatic traps are used. Such traps are naturally formed in the plasma sheath, in a diffuse plasma edge, as well as in dc strata, i.e., in rather disturbed regions of the discharge plasmas. The formation of so-called boundary-free dust structures, i.e., dust clouds in a uniform plasma without external electrostatic traps, is of great interest. Such structures would exist if attractive forces between negatively charged dust particles are present in the bulk plasma. The existence of such attractive forces in bulk plasmas was originally predicted by Tsytovich [1] and Ignatov [2], who considered a collective dust-dust attraction due to mutual shadowing of plasma flows on the particles. These forces are often called "shadowing forces". Due to the large cross-section of the dust-ion interaction the shadowing forces can achieve a sufficiently large value, if the ion number density is high enough. The conditions for the boundary-free structure formation can be estimated as ${r_p}^2 / r_{\mathrm{D}i}^2 >> T_i / T_e$ [3], where r_p is the dust particle radius, $r_{\mathrm{D}i}$ is the ion Debye radius, and T_i and T_e are the ion and electron temperatures, respectively. For typical dusty plasma experiments in low pressure gas discharge plasmas T_i / T_e ~ 0.01, and at n_i ~ 10^9 cm^{-3} the radius of the particles should be much larger than 4 μm. Hence, for the formation of boundary-free structures it is necessary to use either relatively big (r_p > 10 μm) particles or dense plasmas (n_i, n_e >> 10^9 cm^{-3}). It should be emphasized, that boundary-free structures could be created in bulk plasmas only under microgravity conditions, because the gravity always drags the particles to the inhomogeneous plasma sheath. Unfortunately, a high ion density leads also to a strong ion drag force, which quickly pushes out the dust particles from the bulk plasma to the chamber walls and leads to void formation. Due to this fundamental contradiction the boundary-free dust structures have not yet been experimentally observed. It should be noted that the "shadowing effect" is quite different from the "ion wake effect" arising due to the ion focusing or deflection of an external ion flow by a charged object. The "wake" clusters cannot be treated as boundary-free structures as they exist only in anisotropic plasmas.

In the present work, the above mentioned contradiction has been eliminated by using a combined gas discharge in the "Plasmakristall - 4" (PK-4) setup under microgravity conditions [4]. The experiments were performed in the PK-4 chamber during the 41st European Space Agency (ESA) parabolic flight campaign in October 2005 on the board of the A-300 ZERO-G plane. The experimental arrangement (Fig. 1) consists of the Π-shape glass discharge tube of 30 mm inner diameter with a total length of 85 cm filled by neon at a pressure of 60 Pa. The tube is equipped with two dc cylindrical electrodes installed at the ends of the tube as well as by an rf coil installed in the vicinity of the tube center. Under microgravity monodisperse melamine formaldehyde dust particles with a diameter of 1.28 μm were injected into the dc discharge plasma (I_{DC} = 1.0 mA, U_{DC} = 884 V) in the vicinity of the cathode. Being injected, the dust particles drifted to the tube center driven by the electric field of the discharge of about 2 V/cm. The injected particles were illuminated by a laser sheet of 100 μm width and recorded by a CCD camera with an image resolution of 680×240 pix and a frame rate of 120 frames per second. In addition to the injected small particles, heavy dust particle conglomerates were presented in the dc discharge. The conglomerates were formed on the tube surface in the vicinity of the dispenser and could easily be distinguished from the original particles by their different behaviour and their brightness on the recorded images (Fig. 2(a)). In particular, the conglomerates repelled the small particles. During the experiments the small particles formed an elongated uniform dust cloud with a diameter of 1.5 cm and a particle density of $n_d \sim 2 \cdot 10^5$ cm^{-3}, which was confined along the tube axis by the radial potential of the discharge. At the same time, the heavy conglomerates were subjected to a random movement within the tube due to a residual acceleration ($a < 0.02g$) of the A-300 plane during the parabolas. As soon as the heavy particle appeared in the FoV, an experimentalist initiated manually an rf Π-shape discharge

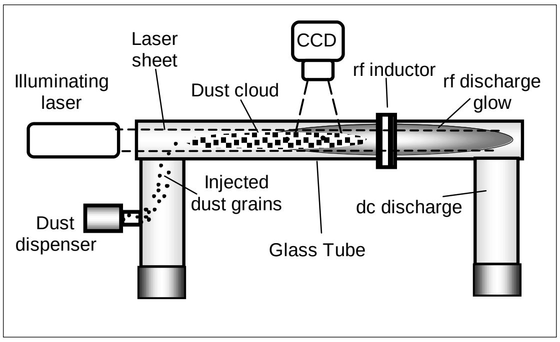

FIG. 1. Scheme of the PK-4 plasma chamber and experiment on cluster formation.

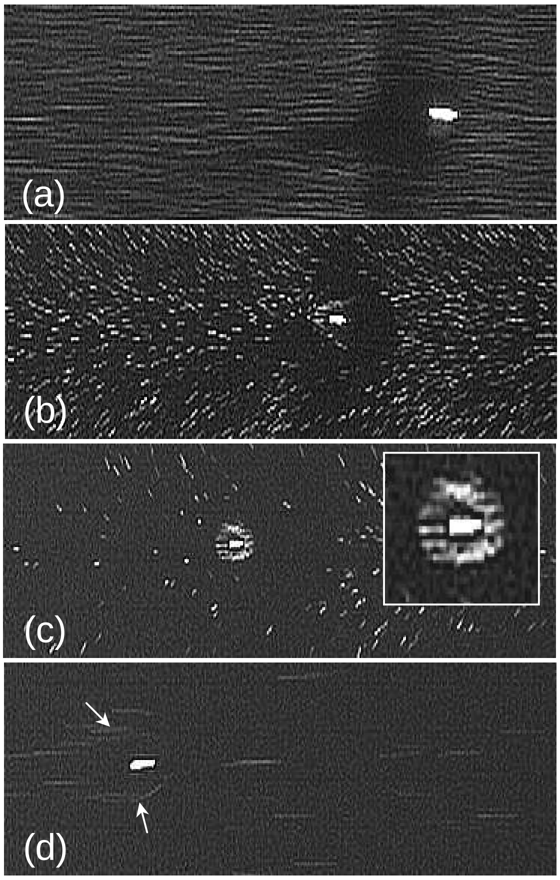

FIG. 2. Cluster formation and destruction in the central part of the discharge tube. (a) Dust cloud in uniform positive dc column before the rf pulse; (b) 60 ms after the rf pulse ignition: beginning of the cluster formation; (c) 120 ms after the rf pulse ignition: formation of cluster is complete; (d) 180 ms after the rf pulse ignition: rf pulse is finished, cluster is disrupted instantaneously. Area shown is about 7×3 mm^2.

pulse with a duration of 180 ms. This duration was chosen to achieve a stationary state of the cluster after the pulse ignition as well as to investigate a cluster disordering process after the pulse completion. The ion density n_i and electron temperature T_e for both discharge modes were diagnosed by a Langmuir probe in laboratory investigations. Just after the rf discharge ignition the electron and ion density rapidly increased from its value in the dc discharge of $2\cdot10^8$ cm^{-3} up to $4\cdot10^9$ cm^{-3}, and all dust particles drifted away from the tube axis to the tube walls due to the increased radial ion drag forces. Only the heavy conglomerates randomly approaching the tube axis kept their positions. During the rf pulse some of the injected small particles driven by the ion flow were attracted by the big particle (Fig. 2(b)), and a stable boundary-free dust cluster formed within about 120 ms in the bulk plasma at the axis of the tube. As the laser knife had a thickness of 100 µm, Fig. 2(c) displays the cross section of the cluster. Analyzing Fig. 2(c) one should remember that the cluster is moving and its image is spread. The total number of the small particles in the cluster has been estimated to be about 60-80, the distance between them is Δ=100 ±10 µm. After the pulse the cluster was rapidly disrupted during 1 frame (8 ms) via Coulomb explosion due to the strong Coulomb repulsion, while the other small dust particles began to return to the tube axis (Fig. 2(d)). The cluster formation after increasing the ion density and the disruption with decreasing ion density reveals the important role of the ion drag force for the particle linking in the cluster.

A scheme of the formed cluster is presented in Fig. 3. The cluster consists of the big central grain and a number of small monodisperse particles. The cluster is almost spherical indicating isotropic conditions in the bulk plasma. The cluster radius is given by R_{cl} =190±15 μm. The small particles form a single layer around the big grain. The most interesting question is how to estimate the observable stable cluster radius R_{cl}. The authors had calculated the charges of the big and small particles as 16500e and 1500e correspondingly using the MDS method [5] and the probe measured plasma parameters, and had estimated the attractive ion drag force as F_i=6·10^{-15} N [6]. The electrostatic repulsion F_{e1} between the small and big particle was found to be 5·10^{-15} N, that is about the same as F_i. Nevertheless, both F_i and F_{e1} are proportional to the electric field induced by the central particle, hence no stable position R_{cl} can be found only for the two interacting particles. We propose two possible explanations for the observable stable value of R_{cl}: mutual electrostatic repulsion F_{e2} of the small particles and a diminishing of the F_i due to an overlap of its momentum-transfer cross-sections, when the small particles are enough close each to other. A more detailed explanation is under developing now.

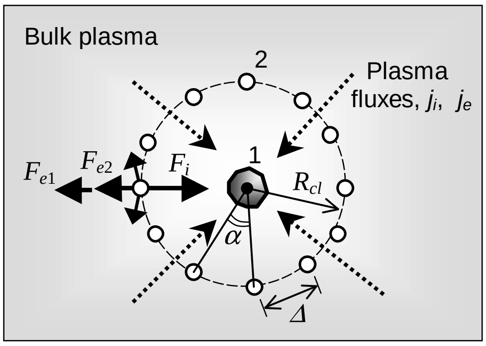

FIG. 3. Scheme of cluster: 1 – central big particle, 2 – small bound particles; dotted arrows – plasma fluxes. F_i – attractive ion drag force; F_{e1} and F_{e2} – electrostatic repulsion from the central and the neighbor particles, respectively.

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