Simulation of the ground state of dust plasmas in an anisotropic confinement field

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The behavior of micro- and nanosized particles in complex plasmas is much addressed in research papers [1, 2, 3, 4]. Scientific and practical interest in dust plasma systems owes to their abundance both in outer space and in terrestrial environment and, in many respects, to their unique properties. With a finite number of charged dust particles (normally, no more than several thousands of particles) confined by an electrostatic field, the system under consideration is termed a dust plasma cluster and it is in the cluster form that dust plasma systems are studied in most of experimental and theoretical works [3, 4, 5, 6, 7]. Dust microparticles in complex plasmas can acquire a rather high negative charge (several thousands of electron charges), and thus their behavior is determined in many respects by the Coulomb interparticle interaction. Moreover, their behavior can be affected by gravitational, electrostatic, magnetic, thermophoretic and other external forces. For confinement of dust particles in an experimental facility, it is necessary to form a potential trap - a certain configuration of external fields precluding their scatter. The external confinement forces acting on the dust particles in the vertical and horizontal directions can differ in physical nature and in magnitude. This results in anisotropy of the potential trap in which the dust particles is confined. It should be noted that the anisotropy of the confinement field can greatly affect not only the state, but also the structure of dust plasma systems and, hence, their response to electric, magnetic, laser, and other external actions. In this context, of interest is to study the possibilities of purposefully changing the structural-phase state of a dust plasma cluster by varying the anisotropy of the trap in which the cluster is confined.

The posed problem was solved in the framework of the particle method for spherical dust particles of density the same as that of melamine formaldehyde. These particles are widely used in experimental studies on the properties and behavior of dust plasma clusters. For comparison of simulation results and available experimental data [5], the diameter of a dust particle was taken to be $7.10\mu m$, and its charge to be 2660e . Like in the previous works [6, 7], it was assumed that the interparticle interaction is determined the Debye-Hückel potential

$$\phi = \frac{Q}{4\pi\varepsilon_0 r} e^{\left(-\frac{r}{\lambda_d}\right)} \tag{1}$$

where λ_d- Debye screening radius, Q - particle charge.

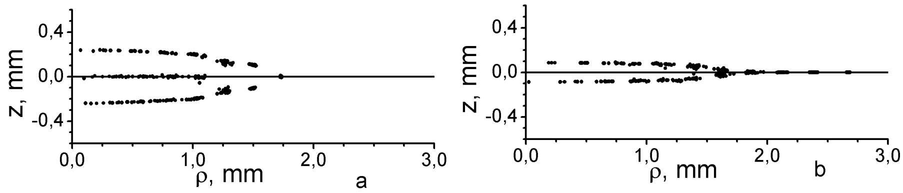

Figure 1: Structure of dusty plasma cluster consisting 360 particles at different magnitudes of anisotropy parameter ξ = 8 (a), ξ = 32 (b)

Confinement is defined as $F = \alpha_z Qz + \alpha_\rho Q\rho$, where $\rho = (x^2+y^2)^{1/2}$. α_z and α_ρ are the coefficients responsible for the confinement field force in the vertical and horizontal directions, respectively. For numerical determination of the degree of confinement field anisotropy, the dimensionless parameter $\xi = \alpha_z/\alpha_\rho$ was introduced. The number of dust particles in the model plasma clusters was varied from 14 to 2880.

The approach used in the work makes it possible to reproduce with a high accuracy the structure of both three-dimensional (bulk) clusters [6, 7, 8] and two-dimensional (plane) clusters [9]. In particular, it is possible to reproduce the population of shells of Coulomb balls, and the configuration and the interparticle spacing of two-dimensional structures.

The results of calculations show that the dust plasma cluster under the specified conditions has a shell structure. Figure 1 shows a projection of the structure of a dust plasma cluster of 360 particles on the axis of a cylindrical coordinate system for different values of the dimensionless parameter ξ. Note that in an isotropic confinement field, the model system has the form of a Coulomb ball with a characteristic shell structure. As the anisotropy parameter ξ is increased, the state and the structure of the model system changes, and the cluster size increases in the horizontal direction and decreases in the vertical direction Fig. 1. As the anisotropy parameter reaches a certain threshold, the structure of the model cluster becomes plane. The threshold value of the dimensionless parameter at which the structure becomes plane depends also on the number of dust particles in the system. Studies show that increasing the number of dust particles increases the threshold of ξ at which the model system transforms into a two-dimensional state.

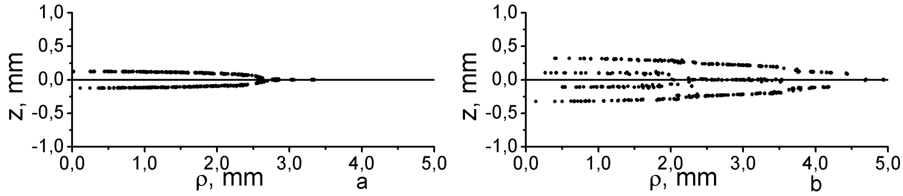

Figure 2: Structure of dusty plasma cluster in anisotropy confinement (ξ = 32) for different particle number 720 (a), 2880 (b)

The calculations show that the number of dust particles in the model system greatly affects the structure of the dust plasma cluster in both isotropic and anisotropic confinement fields. With a rather small number of dust particles, the model cluster forms a two-dimensional structure in the anisotropic confinement field. As the number of dust particles is increased, the structure of the model cluster is complicated and becomes three-dimensional; inner shells are formed. The threshold number of dust particles required for the cluster to transform from the two- to three dimensional state depends on the dimensionless parameter ξ. Fig. 2 shows simulation results for the structures of dust plasma clusters with different numbers of dust particles in a confinement field at ξ = 32. It can be seen from the figure that increasing the number of dust particles in a dust plasma cluster gives rise to additional shells. The behavior of the model system can be due to the particle density that increases at the center of the cluster as the number of particles is increased [7]; the increase in particle density amplifies the Coulomb interparticle interaction which can be the chief cause for "splitting "structural transition of the model dust plasma cluster from the two- to three-dimensional state.

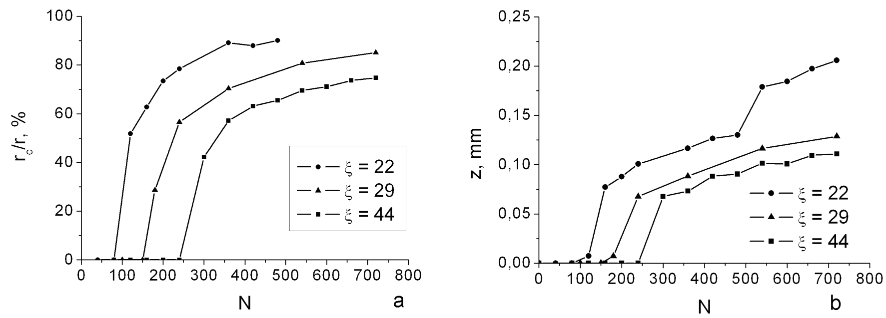

Figure 3: Sizes of the dust plasma cluster in the vertical direction versus the number of dust particles (N) for varying anisotropy of the confining field (a) and the position of the "splitting" point of the cluster structure versus the number of dust particles (b); r_c is the distance from the z axis to the split point, r is the distance from the z axis to the cluster edge.

Increasing the number of dust particles results not only in an increase in the size of the dust plasma cluster, but also in its splitting in the vertical direction. It should be noted that the splitting effect depends on both the number of dust particles and the degree of confinement field anisotropy (Fig. 3, a). The "step" on the curve corresponding to ξ = 22 is due to a structural change, namely, to the formation of a new shell in the dust plasma cluster. The calculations show that the splitting of the plane dust plasma cluster with decreasing the anisotropy parameter or increasing the number of dust particles begins in the central part of the cluster. Further increasing the number of dust particles expands the split region moving its boundaries away from the cluster centre (Fig. 3, b).

Thus, the obtained results demonstrate the possibility of purposefully changing the state and the structure of a dust plasma cluster by varying the number of dust particles and the configuration of the confinement field in a potential trap. In an isotropic confinement field, the model system is a ball with a shell structure in the “crystalline” state. Increasing the number of dust particles involves an increase in the size of the dust plasma system and abrupt formation of additional shells. As the anisotropy parameter is increased and the number of dust particles is decreased, the model system of dust particles tends to transform from the three- to two-dimensional state. The plane cluster, in turn, can be transformed into a bulk one by decreasing the degree of anisotropy of the system and/or increasing the number of particles in the system. In the latter case, the formation of the three-dimensional structure begins in the central region in which the density of dust particles is higher. It should be noted that the above “direct” and “reverse” transitions can proceed along different paths in the phase space due to abundant metastable states of the system under study.

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