The structure of a plasma cluster as seen by an injected particle

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The dust particles in the plasma sheath form structured systems, which in most of cases have latices similar to solids [1]. The nature of forces responsible for these structures is still not theoretically explained. In this contribution we present the analysis of the re-organization of a spherical plasma cluster of 16 particles in weak external confinement after that one additional particle has arrived.

Experiments and three-dimensional diagnostic The plasma was generated by radiofrequency excitation, 13.56MHz, of the upper of two parallel plate electrodes in the so-called PKE-Nefedov chamber, which has glass walls. The lower electrode was grounded apart from a small central "pixel", 3.8×3.8 mm^2, which could be independently driven in dc and rf [2]. Melamine-formaldehyde particles of 3.4μm diameter were injected into an Argon plasma and levitated in the plasma sheath near the lower electrode. By balancing dc and rf on the central pixel a secondary plasma was created in the above laying sheath, much brighter than the bulk plasma. Particles leave their levitation positions in the 2D cloud, which usually forms at the plasma-sheath edge, where the electric field is compensated by gravity, and assemble in this secondary plasma in 3D structures. The number of particles can be controlled by varying the rf on the pixel. The cluster size is 10 times smaller than the dimensions of the pixel and the mean free path is 6 times smaller than the interparticle distance. Particles can freely move in vertical direction. These points allow us to make the assumption of weak external confinement. Clusters from 4 up to 73 particles were obtained at the pressure of 57, 65 and 76Pa. The structure of big clusters shows sub-parts in icosahedral geometry, the cluster of smaller size (17 particles) has hexagonal structure. This geometry can be reconstructed due to a unique 3D optical diagnostic [3]. Particles are illuminated by three lasers: one beam is formed by two lasers (686 and 656 nm) of complementary intensity, the scattered light is recorded at an optimal angle of 68° by two selective CCD-cameras; the second beam is infrared (785 nm), with the light collected by a third camera

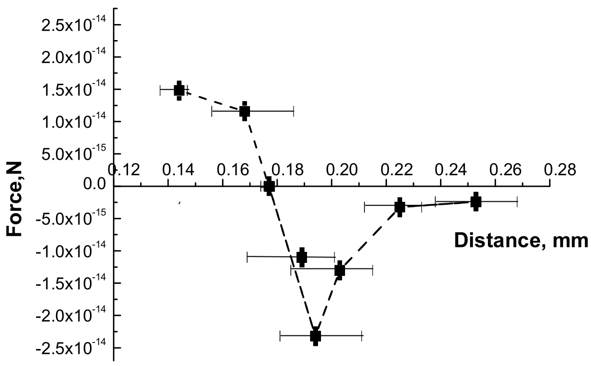

Figure 1: *Measured interparticle's force in 4 particle cluster with respect to distance.*

at 90^0 with respect to the other two cameras. This system provides the simultaneous images of particles in the xy and the zy planes. By correlation in y direction all particles coordinates can be obtained. From the equilibrium positions of particles above the pixel we can infer, that the levitation is uniform inside the glow of the secondary plasma. The charge on the particles can be estimated from different theories, see Table 1.

Theory	O.M.L.	A.B.R.	A.B.R.(collis.)
$V_f(kT_e)/e$	2.1	0.33	0.533
charge (e)	24814	3899	6298
$\vec{E}_{levitation}(V/m)$	76.5	486.9	301.5
$Energy_{ions,1m.f.p.}(eV)$	$2.3{\cdot}10^{-3}$	$1.5{\cdot}10^{-2}$	$9.1{\cdot}10^{-3}$

Table I. *Estimated values for the floating potential on isolated particles according to different theories. The charge on the particles, the electric field needed for levitation and the energy acquired by the ions in a m.f.p. are also shown.*

The O.M.L. (orbital motion limited theory) [4] theory cannot be used in our range of pressure, being the mean free path, $30\mu m$ at 60 Pa, much shorter than the Debye length, 160μ in this bright glow. The A.B.R. theory (Allen - Boyd - Reynolds theory for radial motion) [5] and the moderate collisional regime [6] are based on the hypothesis of "cold" ions ($T_i = 0$). We estimated, that the charge of our particles in a dense plasma lies between 3000 to 5000e.

Attractive force The motion of particles inside the clusters of 17 particles at pressure 76Pa and 4 particles at 57Pa has been studied in detail. It was not externally stimulated; we just recorded the spontaneous/thermally excited behavior. In the smallest 4 particles cluster the attraction between one of the cluster particle and another orbiting particle, rotating below the structure was recorded [3].

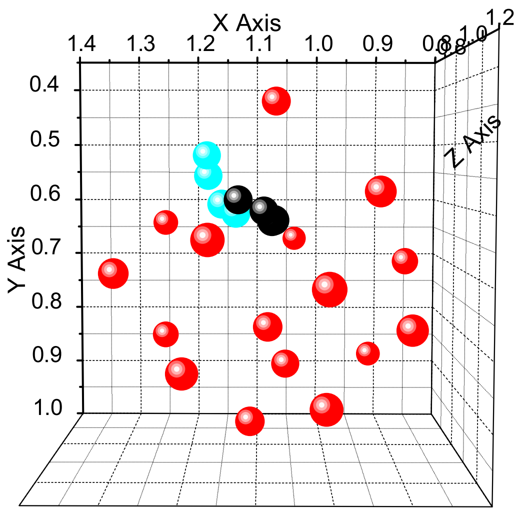

Figure 2: *Cluster of 17 particles. The black spheres show the positions of the moving particle during going to the inner shell, the light spheres show the motion outside. Units on the axis are in millimeters.*

The attractive (and repelling) forces in this case were measured using the balance with other mechanical forces, such as inertia, neutral friction and centripetal force without any hypothesis regarding the nature of the electrostatic interaction. Fig.1 shows the profile of the interaction force. A change in cluster structure was observed in the 17 particles cluster. One particle is pushed by another just arrived at the top of structure from the above 2D cloud. The hit particle has an unstable position and moves in order to find equilibrium. During this motion it also pushes and re-arranges neighboring particles, without going inside the structure. Finally, after 1.12sec, this particle comes back to the external shell (Fig.2). Also in this cluster the interaction force has been measured ($1.1{\cdot}10^{-14}N$ maximum attraction and $1.9{\cdot}10^{-14}N$ maximum repulsion with $220\mu m$ interparticle distance).

Energy calculation The re-arrangement inside the structure can be explained by the motion of one particle to find more energetically preferable position, this provides a minimum energy for the whole system. The energy of one bond was calculated using the following approximation:

$$E(n) = \frac{1}{2}K(d - d_{0_n})^2, \quad (1)$$

where $K = 1.5 \cdot 10^{-9} N/m$ is the force gradient taken from the slope of the interaction force (Fig.1) at the equilibrium position. d is the distance from one particle to another, and d_{0_n} is the mean distance between particles for one frame.

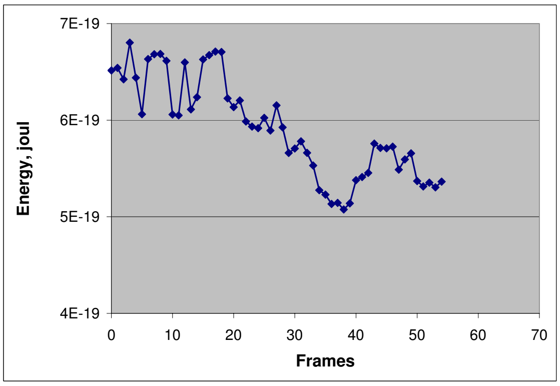

Figure 3: *Measured energy of the system in time.*

If particles are far away each other, it can be assumed, that they do not interact any more. From the behavior of interaction force [3] we choose the value of 0.27 mm as a cut off distance for interaction. n is the number of the bonds of the pairs with distance less than the cut off. Finally, after that the moving particle had found its place in the external shell, no motion inside structure was observed besides thermal vibration. This state of the cluster can be considered stable, and the distances between particles are near the equilibrium distances. The whole energy of the system should be calculated with respect to the number of bonds n:

$$\sum_n (E(n) + (d_{0_n} - d_{0_{30}})^2), \quad (2)$$

where *E(n)* is the energy, calculated from eq.1, $d_{0_{30}}$ is the mean distance between particles in frame 30, which can be taken as equilibrium distance in stable state structure. Fig.3 shows the averaged energy per bond during 60 frames (2.16 sec), which contain the re-arrangement and transition to the equilibrium. The energy after the re-arrangement (30th frame) is lower. The peaks correspond the frames, in which the changing of particle position has been observed.

We can conclude, that after the arrive of one new particle, the system goes to a state with minimum energy by inside re-organization. The peaks of energy are about 1 *eV*, that corresponds to the thermal energy of the particles. Fig.4 indicates the shells in the 17 and 73 particle clusters. Here the number of particles are plotted with respect to the distances from the center of the cluster . One can clearly see one shell in smaller cluster and two shells in larger one.

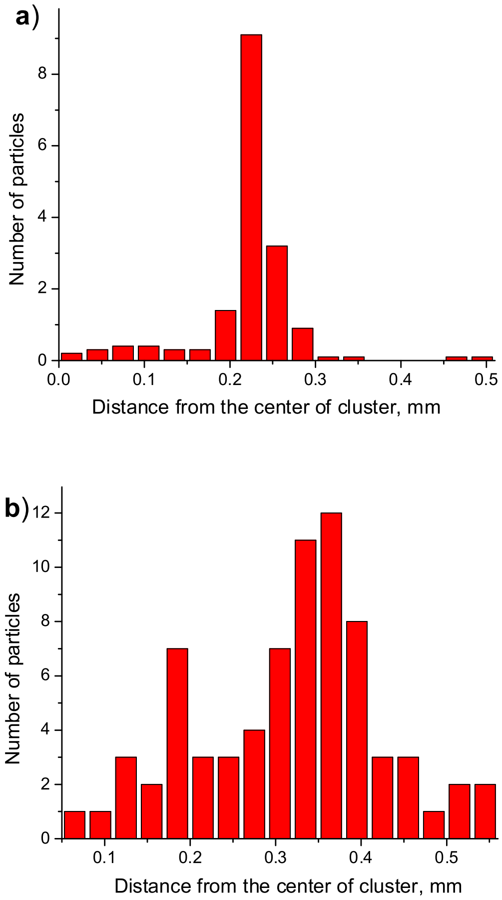

Figure 4: *Structure of shells in the clusters of 17 (a) and 73(b) particles.*

Conclusion In this contribution we have demonstrated that the observed re-organization of a plasma cluster is governed by the principle of the minimum energy. During this process the new particle is pushed from the inner shell to the outside shell. This feature has been detected in all the analysed clusters. In disagreement with the pair short-range interaction the inner shell is always empty. Our structures are situated in a secondary plasma, in which ionization takes place. The ions may provide an 'ion drag force', which pushes the particle out from the central position (mini void).

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