*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.032 (2006)*

Natural oscillations in 3D plasma clusters

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The formation and investigation of 3D plasma clusters is a new challenge in complex plasma science. The particles in such structures show individual properties developing simultaneously collective effects. In this contribution we present the formation, the dynamical study and the analysis of characteristic oscillations of 3D plasma clusters an intermediate size, at which both, kinetic and fluid behavior, appear.

Experiments and three-dimensional diagnostics 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. Spherical clusters with number of particles below 100 have been obtained by using the segmented "adaptive" electrode divided by 57 small segments, which can be independently driven in dc and rf [1]. By applying rf voltage on one of these segments a bright glow appears in the above laying sheath. Injected melamine-formaldehyde particles of 3.4μm diameter are situated in this "secondary plasma ball" and not in a plasma sheath, as it normally happens in the laboratory experiments under gravity. A 3D optical system, together with programming analysis, allows us to get the information about the three coordinates of particle at the same time [2]. Particles' velocity vectors could be measured in 3D from the analysis of traces recorded during the shutter opening time of the CCD.

This system allowed us to form stable cluster structure giving the possibility to study some properties of cluster lattices. We could also follow particles in time and were able to estimate the force acting among them in small size cluster [3]. Vibrations are always present in the structures observed. They provide information about cluster behavior. One case has been studied in detail: a cluster of 63 particles loses 3 particles, one by one, during an 8 second sequence (Fig.1). In this time the particles of the cluster re-arrange, change their positions and oscillate.

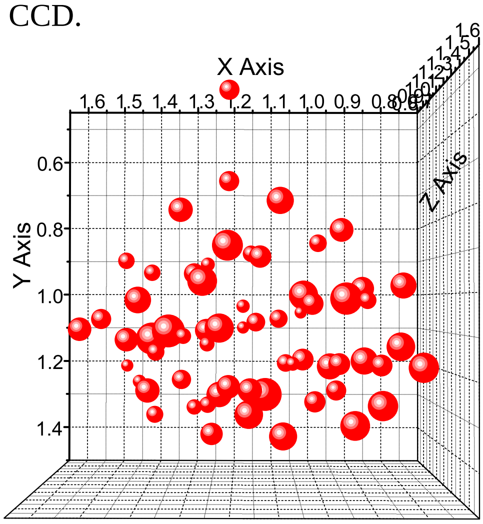

Figure 1: *Cluster of 63 particles with upper one, which leaves from the top.*

Energy calculation We have calculated of the whole assemble energy, which decreases while particles are leaving, i.e. the system approaches an equilibrium state. The elastic energy of the cluster has been calculated with respect to the number of bonds n:

$$\sum_n (E(n) + \frac{1}{2}K(d_{0_n} - d_0)^2), \tag{1}$$

where $E(n) = \frac{1}{2}K(d - d_{0_n})^2$ is the energy per bond, d is the distance between two particles in the chosen frame, d_{0_n} is the mean distance between particles in the frame, and d_0 is the equilibrium distance for this kind of interaction.

d_0 has been estimated with 2 methods: 1)The frame with a minimum of the energy has been identified, where the structure is stable enough (no dramatic re-organizations are observed). The mean distance between particles has been taken as $d_0 = 220$; 2)The second way is to analyze the shell structure of the cluster. From Fig. 2 we can distinguish two shells in 63 particles' cluster and get distance between them (around $200\mu m$).

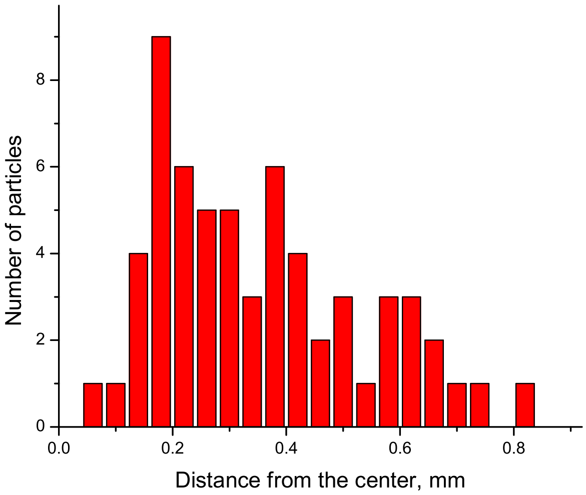

Figure 2: *The structure of shells in the cluster of 63 particles.*

The distance between particles in clusters with different number of particles increases for larger clusters (0.175mm for 4 particle cluster, 0.200mm for 63 particles cluster). If particles are far away each other, it can be assumed, that they do not interact any more. This cut off for interaction has been estimated from Fig.2 as an intermediate point between first and second shell (0.250mm). n is the number of the bonds of the pairs with distance less than the cut off.

Fig.3 shows the averaged energy of the cluster during 150 frames (6 sec), when the particles leave from the top of cluster. One can see that after the last particle jumped out (87 frame), the energy start to decrease and, eventually, it is lower than at the beginning of the sequence. Note, that during the particle leaving the system has minimum energy (frames 28, 63, 87), but after this and before next jump the energy rapidly increases (peaks at 22, 47 and 76 frames) demonstrating not preferable state. The small peaks after the 87th frame correspond to vibrations of the upper particle in cluster that nevertheless never leaves.

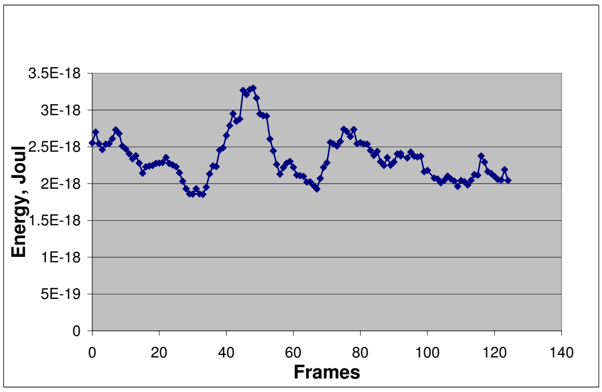

Figure 3: *Measured energy of the system in time.*

The results of numerical simulations of Coulomb clusters [4] show that 57 and 60 are the so-called 'magic' numbers in 3D configurations. This means that the system in these states is sufficiently stable and has less energy per bond than it would have with smaller or larger number of particles. Even if the interaction between particles in the cluster is not purely Coulomb we may conclude that our cluster loses particles in order to achieve 'magic' number, i.e. more stable state with minimum energy. Furthermore, the leaving of the particles can show the configuration of electric field, which is weak in the region of cluster and comes out much stronger at the position where particles jump up.

Analysis of vibrations. Dust acoustic waves We have analyzed the vibrations of upper particle in the cluster, which has demonstrated that particles leave due to self-oscillations of the cluster. By Fourier transforming the sequence we have obtained the natural frequency of system. Fig.4 present several modes of cluster frequency f , as more important peaks at 1.2, 2,6 and 3.57 Hz are indicated.

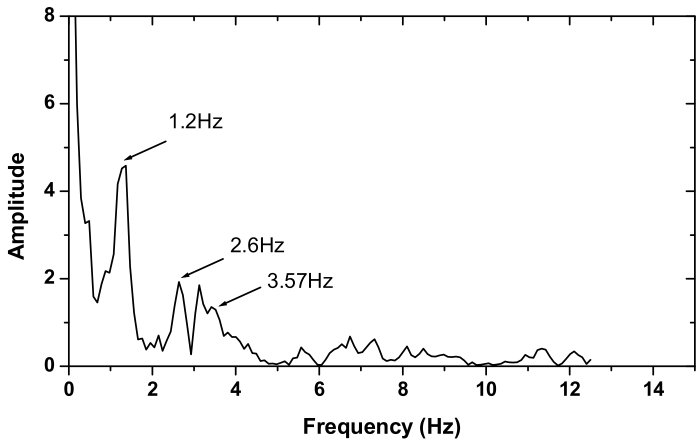

Figure 4: *Fourier transform of the vibrations of upper particle in the cluster.*

Smirnov in [5] interprets the vibrations of particles as acoustic waves with a sound speed, which propagate inside clusters. In order to model theoretically our experimental results these oscillations have been compared to dust acoustic waves. For this kind of waves inertia of dust is very important and electrons and ions obey to Boltzmann distribution. The Poisson equation has been combined with the dust continuity equation and dust momentum equation [6]. In the case for the long-wavelength limit, ($k^2\lambda_D^2 \ll 1$, where k=1/D, D being the dimension of the cluster, λ_D is combined Debye length), the wave frequency can be found as:

$$\omega = kZ_{d0}\left(\frac{n_{d0}}{n_{i0}}\right)^{1/2}\left(\frac{k_B T_i}{m_d}\right)^{1/2}\left[1+\frac{T_i}{T_e}\left(1-\frac{Z_{d0}n_{d0}}{n_{i0}}\right)\right]^{-1/2} \qquad (2)$$

where Zd_0 is the charge of particles, which was calculated using the vacuum approximation with $r_p = 1.7\times10^{-6}m$ - particle radius and $V_{fl} = 1.3eV$ - the particle floating potential from the radial theory for electric probes [7].

In our collisionality regime (200 μm the distance between particles and the mean free path is 30 μm) the radial motion theory will give underestimated charge. However, considering that the presence of other particles nearby decreases the charge of chosen particle we use here the floating potential given by radial motion theory. Hence, the charge of particle is determined to be $7600e$. $n_{d0} = 2.35 \times 10^{11} m^{-3}$ is the dust density in our cluster of 63 particles. The plasma density n_{i0}, n_{e0} in "secondary plasma ball" volume has been estimated from the spectroscopic analysis to be in the order of $10^{16} m^{-3}$, higher than main plasma density. Ions are considered to have room temperature ($T_i = 0.025eV$), the temperature of electrons are supposed to be about 5eV (some how higher than in main plasma). At these parameters the estimated frequency of dust acoustic waves ω is 7.8Hz, which agrees well with the first peak of experimental frequency f =1,2Hz.

Conclusion The possibility to get 3D plasma clusters under gravity conditions and obtain the 3 coordinates of the particles simultaneously allowed us to perform the analysis of the cluster structure as well as the study of wave propagation inside the cluster. In this contribution we have demonstrated that the observed re-organization of a 3D plasma cluster is governed by the principle of the minimum energy. During this process the particles are pushed from the inner shell to the outside shell and viceversa. A cluster formed by 60 particles appears to be stable in accordance with the 'magic number' found in the simulation of [4] for Coulomb interaction. The analysis of 63 particles' cluster vibrations shows the collective effects of the particles inside structure. Using Fast-Fourier transform we have obtained the cluster frequencies, which are described well by the theory of dust-acoustic waves.

References

[1] B.M. Annaratone, M.Glier, T.Stuffler, H.Thomas, M.Raif and G.E. Morfill, New. J. Phys., 5, 92 (2003) **11**, 11 (2004)

[2] B.M. Annaratone, T. Antonova, D.D.Goldbeck, H.M. Thomas and G.E.Morfill, Plasma Physics and Controlled Fusion, 46 B495-B509 (2004)

[3] T. Antonova, B.M. Annaratone, D.D.Goldbeck, V. Yaroshenko, H.M. Thomas and G.E.Morfill, Phys. Rev. Lett. V 96, issue 11, 115001 (2006)

[4] P. Ludwig, S. Kosse and M. Bonitz, Phys. Rev. E 71, 046403 (2005)

[5] B.M. Smirnov, Springer, Berlin, Heidelberg (1999)

[6] P. K. Shukla and A. A. Mamun, Introduction to Dusty Plasma Physics (Institute of Physics Publishing Ltd., Bristol) (2002)

[7] Paul Bryant, J. Phys. D:Appl. Phys. 36, 2859-2868 (2003)