Clusters of the charged dust particles in a magnetic trap at cryogenic temperatures

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Abstract. The formation of cryogenic colloid of charged particles in static magnetic traps was studied for the first time. We presented experimental results of formation of strongly correlated structures consisting of about \(10^3\) particles. Ordered structures were formed by particles with a diameter of 30–60 microns with a charge up to \(10^7\) e. Estimates of mean interparticle distance, dust particle charges, coupling parameter and Lindemann parameter, which turned out to be typical for strongly coupled crystalline or glass-like systems.

1. Introduction

The problem of particle confinement has been discussed in a large number of papers. Ordered dust structures of liquid and crystal type are often considered as an example of strongly coupled Coulomb systems in gas discharge plasma [1–5]. Dust particles in contrast to the real atoms of liquids and solids can be observed separately by naked eye. It allows studying various processes such as phase transitions, wave propagation, formation of instabilities of various types, in these non-ideal systems on the kinetic level. However, in a gas discharges, dust particles acquire a charge, which is not fixed, depends on local conditions, and is partially screened. Besides that, the charge on the particles affects on both the interparticle interaction and particle levitation in electrostatic traps formed in the striations of dc discharges or near-electrode sheath in rf discharges. Thus, changing the interparticle interaction, and therefore the conditions of formation of the structure itself, we change the conditions of its levitation and its spatial position.

Another alternative method of trapping dust particles for experimental study of strongly coupled Coulomb systems is based on well known capability of diamagnetic body to levitate in a non-uniform stationary magnetic field [6, 7]. In that work, graphite was used as a material of particles, as it has the largest magnitude of specific magnetic susceptibility. However, in laboratory experiments, even at the magnetic fields up to 2 Tesla per mm, we enabled to form a cluster consisting of only a few particles.

At the same time in the experiments on board the International Space Station the possibility of the formation of an extended cluster of charged diamagnetic macroparticles under microgravity conditions has been demonstrated [8].

2. Experiment and results

In this work, for the first time we propose a method of forming a classical Coulomb system in laboratory experiments, meaning an ensemble of a large number of charged particles that
can have a charge of both positive and negative signs. The technique is based on the well known Meissner effect, which is the expulsion of the magnetic field from the superconductor, so that superconductors may be considered as perfect diamagnets [9]. In our work we used high-temperature yttrium ceramic (figure 1).

In figure 2, there is a schematic view of the experimental setup, the main element of which is an optical helium cryostat with a range of operating temperatures from 1.8 to 273 K. The cryostat is a system of two coaxial positioned nitrogen and helium baths, thermostatic chamber with the heat exchanger, and shell with optical windows. Before the experiment in order to prevent condensation of water vapor in the refrigerant, which in turn may cause problems with optical diagnostics of dust subsystem, thermostatic chamber is evacuated and then it is filled with helium gas to atmospheric pressure.

To visualize the particles we used illuminating laser with a wavelength 523 nm and high-speed camera for particle detecting. The resulting video images were processed using specially designed computer software. In such a way, we obtained the coordinates of the particles, their trajectories and velocities, the average interparticle distances, and kinetic temperature of dust particles.

In our study, we used polydisperse particles of diameter up to 60 microns. Macro-particles were injected to the area of magnetic trap with a buffer gas temperature \(\sim 77\) K. After cooling the particles to a critical temperature below 91 K we observed the formation of a cluster of superconducting agglomerated particles levitating near axial area of the magnetic trap (figure 3). Charging was carried out by direct contact of the probe tip with the surface of the particles. Depending on the potential on the electric probe, the charge acquired by a particle could be both positive and negative. In the performed experiments, the potential at the tip of the probe was \(\sim 2 \times 10^3\) V.

After the mechanical contact with the probe, the particles acquired a charge which can be estimated as \(10^6\)–\(10^7\) of elementary charges for a particle diameter \(d = 30\) mm. After this we observed an expansion of cluster due to the Coulomb repulsion and the formation of an ordered structure (figure 4).

Due to formation of structure by particles of different sizes, interparticle distance in such a structure ranges from 160 to 1060 microns. At this, the mean interparticle distance is \(l_p \sim 475\) microns. The potential energy of the interaction of charged particles can be estimated as \(\sim 10^8\) eV.

To estimate the kinetic energy of the motion of charged particles we obtained the particle
velocity distribution in the horizontal and vertical directions. The average particle velocity was \( \sim 180 \text{ mm/s} \). For a particle of mass \( \sim 9 \times 10^{-8} \text{ g} \) the kinetic energy was \( \sim 10 \text{ eV} \). Thus, the coupling parameter which is equal to the ratio of the potential energy of the interaction of particles in the system to their kinetic temperature is about \( 10^7 \). According to the results of experimental measurements and obtained diffusion curve, mean square displacement of particles was \( \sim 13.2 \text{ mm} \). Thus, taking the mean interparticle distance as 475 microns, Lindemann parameter [10] for our experiments would be \( L \sim 0.03 \), typical for strongly coupled crystalline or glass-like systems.

3. Conclusions
To summarize, we have obtained formation of cryogenic colloid of charged particles in a static magnetic traps for the first time. The experimental results of formation of strongly correlated structures consisting of about \( 10^3 \) particles were presented. Ordered structures were formed by particles with a diameter of 30–60 microns with a charge up to \( 10^7 \text{e} \). Estimates of mean interparticle distance, dust particle charges, coupling parameter and Lindemann parameter, which turned out to be typical for strongly coupled crystalline or glass-like systems.

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