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Dusty plasma at cryogenic gas temperatures

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1. Introduction. The problem Cryogenic dusty plasma is a gas discharge dusty system formed at very low (cryogenic) temperatures of gas [1 - 3]. The experiments [2 - 3] conducted with liquid nitrogen and liquid helium cooled dc glow discharges showed that "cooling" of thermal motion of ions down to cryogenic temperatures leads to decreasing of ion Debye radius and formation of super dense dust structures where density of dust grains can be of the same order as plasma density and ion Debye radius can correspond to grain size. In this case, plasma dynamics and dust charging are sufficiently different from those at room gas temperature.

2. Experimental results. The experiments were conducted in a cylindrical dc glow discharge generated in vertically oriented glass tube placed inside cryostat (glass double Dewar system). The discharge was generated in *He* gas at pressures ~1 Torr (hereinafter neutral gas density n_a will be designated by gas pressure at room temperature) and discharge currents ~0.1 mA. Detailed scheme of experimental setup was given in [3] where results of the first experimental observations at 4.2 K and 77 K were described. In this work the modernization of the experimental setup was made for temperature regime control. Blowing trough inner Dewar with liquid helium vapours provides the possibility of varying the temperature of tube walls in the range from 77 K down to 4.2 K. In the experiments at room temperature we observed levitation of anisotropic crystalline dust structures with chain-like ordering of dust particles in preferred vertical direction along discharge axis. It should be noted that such dust crystals are typical for dc low pressure glow discharges. The interparticle distance l_p was measured to be 500–750 μm [3]. At the transition down to cryogenic temperatures the structures and dynamics of dust are being changed. At 77 K large-scale structures (~10^3 particles) consisted of long chains of approximately 15–20 dust particles and about 200–250 μm interparticle distance were observed [3]. Such structures were at least an order of magnitude denser at the same discharge current and neutral gas density in comparison with structures at room temperature. At further discharge cooling the interparticle distances continue decreasing. Temperature transition down to 30-50 K leads to decreasing of interparticle distances to about 120-160 μm and to formation of dust structure, which filled almost all the volume of the head of striation, where strong ordering and convective motion regions coexist. Chain-like ordering remains only in the lower part of the structure and orientations of the chains were changed – the farther the chain from the discharge axis, the greater its inclination to the axis. Decreasing of interparticle distances were observed until discharge became unstable when there was no possibility to hold dust particles at the same discharge current – they were falling downwards on the discharge tube bottom. At temperatures lower then 30 K observations were made after decreasing of discharge current to 0.2 mA, when the discharge glowing was stabilized. Structures observed at about 30 K and lower exhibited liquid-like behaviour. The increasing of the dust density was observed until helium condensation inside inner Dewar (4.2 K). At that moment observation conditions became insufficient for recognizing the individual particles, and interparticle distances were no more than about 30 μm. In spite of significant measurement errors due to by poor observation conditions, obtained experimental results give us a right estimate about dust structure density increase caused by cooling of a discharge down to low (cryogenic) temperatures.

3. Numerical simulations. Decreasing of the gas temperature leads to the fact that at low gas temperatures IVDF can be significantly differed from equilibrium distribution. Model and algorithm of ion-atom collisions in dusty plasma were developed and calculations of IVDF in a discharge at experimental conditions were performed. Numerical simulations of dust charging and screening of particle charge in plasma of cryogenic gas discharge were conducted [4].

Ion	He^+	He^+	He^+
T_a, K	293	77	4.2
T_i, K	687	565	540
T_{eff}, K	846	770	779

Table 1. Results of Monte Carlo calculations of the temperatures of He^+ in He at different gas temperatures (p = 1 Torr at 300 K, E = 20 V/cm, E/n_a = 61 Td). $T_{eff} = <\varepsilon> 2/3$

Complete problem of plasma dynamics around a macroscopic body in the presence of plasma flows is highly nonlinear and therefore its numerical analysis is of major importance. Direct integration of the equations of motions of plasma particles represents a numerical experiment whose significance approaches experiments in the laboratory. The effect of collisions on the ion velocity distribution was estimated by performing relevant

Monte Carlo simulations, in which the applicability of different approximations was also analized.

The problem was studied by using the PIC and molecular dynamics simulation method. The dynamics of plasma electrons and ions as well as the charging process of the dust grain are simulated self-consistently. Grain charge, fluctuation, distributions of electron and ion number densities, and the electrostatic plasma potential are obtained for various pressures and temperatures of gas [4].

On the basis of the calculation results the conclusion was made stated that screening of dust particles is fulfilled by ions with effective temperature defined by energy reached in electric field of a striation an by ion resonant recharging on the cold atoms. Thus, it was obtained that at the experimental conditions the effective ion temperature is changed. It is a result of the ion “heating” in the strong electric field of the discharge. It means that cooling of the neutral component of a gas discharge do not lead to strong cooling of ions and, consequently, to significant decrease of ion Debye radius. Therefore, decrease of the interparticle distance observed in the experiments can not be explained by decrease of ion temperature.

It was shown that thought collisions with atoms usually improvable, collision channel of dust charging is principal. Screening characteristics strongly depends on collision relaxation even in the case of infinitely small collision rate. Results of the calculations demonstrated the importance of rare ion collisions for dust particle charging even for gas discharge at room temperature. Accordingly, the effect of bounded ion cloud is also sufficient and results in additional screening of negative dust particle charge.

At cryogenic gas temperatures and strong external field collision ion flow to down the finite orbits around dust particles rises sufficiently and charge of bounded ion cloud can achieve the value of the order of 0.3-0.4 of dust particle charge. Besides, screening of negative dust particle charge becomes more intensive and, consequently, interparticle distance decrease occurs.

Simulation of dust particle charging in cryogenic discharge at experiments was carried out. Calculations made by PIC method with ion-atom collisions taking into consideration revealed significant effect of the gas temperature on dust particle charge. It should be noted that with gas temperature decrease and significant (almost two times) decrease of dust charge the increase of absolute value of charge fluctuation is observed.

Therefore, decrease of the dust particle charge due to ion-atom collisions is an important mechanism in dense dust structure formation at cryogenic temperatures.

In order to study the mutual effect of dust particles and their charges in cryogenic discharges, calculations of dust particle charging were made by PIC method at various numbers of ions in calculated cell. It corresponds qualitatively to various dust density (to various distance from the nearest particle in cubic lattice). The mutual effect of dust particles and their charges is described by Havnes parameter, which is equal to the ratio of sum of charges on dust particles to the overall charge of electrons in plasma. From the calculations performed it is follows that at the Havnes parameter of the order of 1 rapid decrease of dust particle charge in the structure is occur. Thus the process of closing in of dust particles is accompanied by decrease of their charge. It facilitates the formation of dense dusty plasma structures at cryogenic temperatures.

4. Summary. So in the present work the results of the experiments on dusty structure formation in dc glow discharge at cryogenic temperatures in the range of 4.2-77 K were reported. On the basis of ion kinetics investigation in cryogenic gas discharges the theoretical reasoning of the cooling effect of discharge plasma neutrals on dust density increase was made. Analysis of the kinetic processes of dust particle interaction with plasma allows us to assign main mechanisms leading to dust density increase: cooling of the discharge tube walls causes the decrease of neutral atom temperature, consequently, collision effect become sufficient and lead to dust particle charge decrease and bounded ion cloud enlargement.

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