

## Dense dust structures in cryogenic complex plasma

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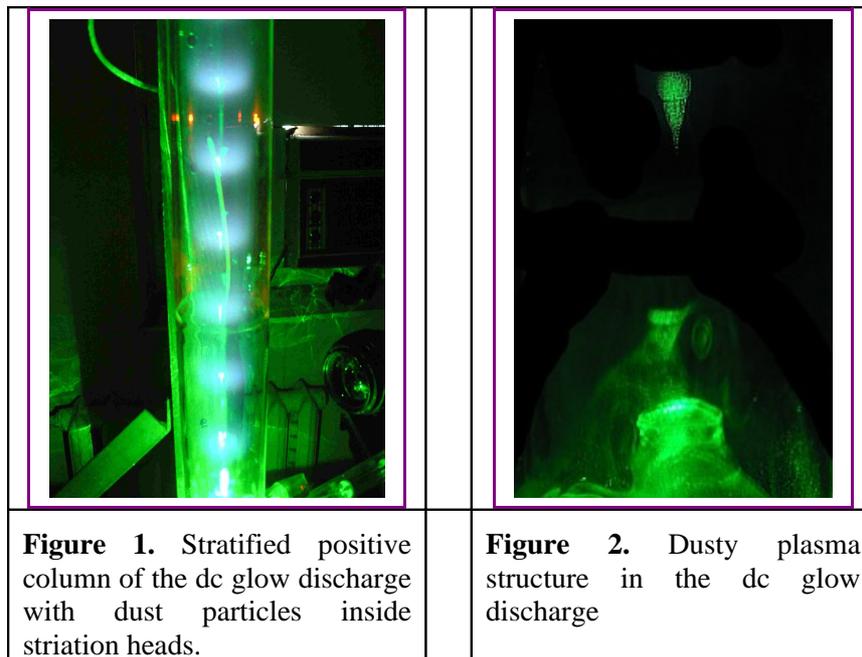
**Abstract.** In the previous researches of cryogenic complex (dusty) plasma [1] we observed experimentally complex plasma systems formed in cryogenic environments. Particularly it was revealed from the experiments that dust structures with high concentration of macroparticles can be formed. So-called super dense dusty plasma structures in which interparticle distance is comparable with particle size were also observed. Thus concentration of particles was close to concentration of background plasma. Similar formations had unusual properties (sphere-like form, free boundaries, etc.) and represent new object in dusty plasma researches. In the present work new results on experimental investigations of dense dust structures at cryogenic temperatures were presented. The experiments were made by means of recently developed techniques and cryogenic facilities (optical cryostat). Possible nature of the unusual properties of super dense dusty plasma structures was discussed.

### 1. Introduction

In recent years, plasma with macroparticles, or dusty plasma, has been the subject of extensive investigations. Experiments have revealed various dusty plasma structures in which the observed ordering has been attributed to the Coulomb interaction. This work is devoted to the investigation of a dusty plasma in a dc gas discharge under the conditions where the walls of a gas-discharge tube are cooled to cryogenic temperatures. The experiments performed with a glow-discharge plasma in helium at temperatures of atoms below 100 K have revealed that the specific features of this plasma become more pronounced with decreasing temperature. The first experiments revealed the possibility of forming considerably denser dust structures in the cryogenic plasma as compared to those observed in the discharge at room temperature. Recently, the authors put forward the assumption that the ion Debye length substantially decreases in the cryogenic plasma; furthermore, this phenomenon, in the authors' opinion, is the main factor responsible for the observed approach of dust particles to one another.

This paper reports on the results obtained from the experiments on the generation of dusty plasma structures in a dc glow discharge at cryogenic temperatures in the range from 4.2 to 77 K. The effect of cooling of the neutral component of the gas-discharge plasma on the increase in the density of dusty plasma structures was justified theoretically by analyzing the kinetics of ions in the cryogenic gas discharge. The dependences of the dust particle charge on the gas temperature and the density of the dusty plasma component were calculated using the molecular dynamics method.





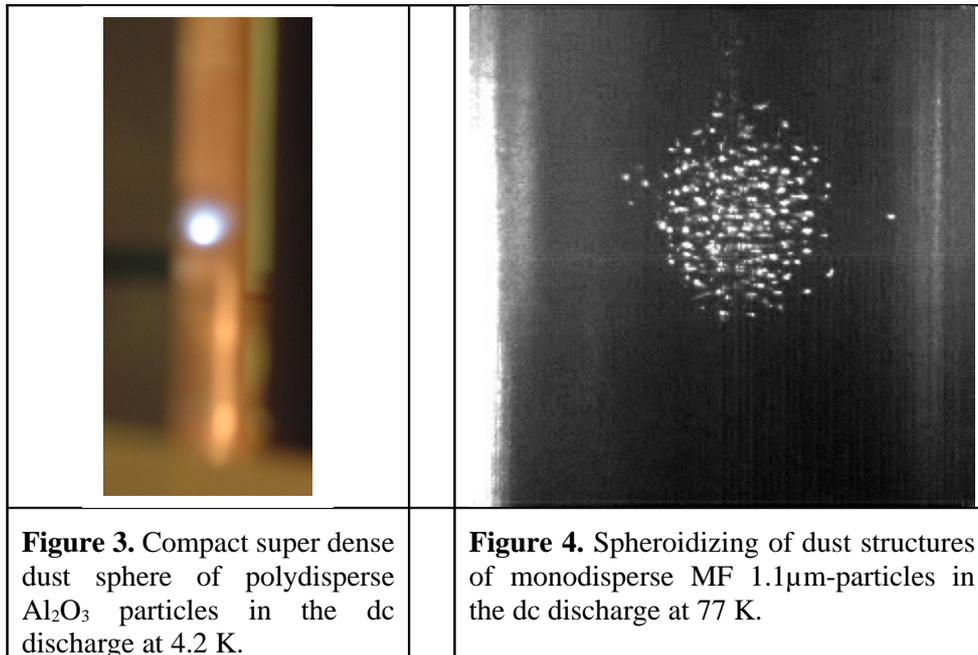
## 2. Results of the experimental investigations

In a dc glow discharge, the dust particles acquire a negative charge and are held in standing striations (ionization waves) of the positive column of discharge (Figure 1). An additional glass tube with a narrowing (Figure 2) was placed above the cathode in the lower part of discharge for generation of stable standing striations in a wide range of parameters. Because the function  $E/N(NR)$  in a dc glow discharge decreases rapidly in the region of low values of  $NR$  ( $E$  is the electric field of discharge, and  $R$  is the discharge radius), a potential jump arises in the region of narrowing, this jump promotes the emergence of striations in the positive column of discharge. Each striation is a cylindrical potential well in a horizontal plane; in the vertical direction, it is characterized by an abrupt increase in the electric field, which is accompanied by only an insignificant decrease in the electron concentration. The electrostatic force acting on the dust particles in a striation may compensate for the force of gravity and cause the particles to levitate. For the given parameters of discharge, the number of dust particles contained in the striation is limited. In the experiments considered in this paper, the particles were injected until their number in the striation became maximal.

The first cryogenic experiments were performed with a dc glow discharge generated in a vertical glass tube placed inside a cryostat designed in the form of a cylindrical system consisting of two glass Dewar vessels. The outer Dewar vessel served as a heat shield and was filled with liquid nitrogen. The glass discharge tube was located in the inner Dewar vessel under the cover of the cryostat. The upper electrode was a hollow cylindrical anode through which dust particles were injected into the discharge. Dust particles were stored in a container with a perforated bottom and positioned above the anode. The discharge was generated in helium at pressures of the order of 1 Torr (hereafter, the density of the neutral component will be given in terms of a pressure at room temperature) and at discharge currents of the order of 0.1 mA. The scheme of the experimental measurements was described in detail in our previous papers [1, 2], in which we also reported the results of the first experimental observations at temperatures of 77 and 4.2 K. The experimental setup had the possibility of continuously varying and controlling the temperature conditions. The blowing of liquid helium vapors through the inner Dewar vessel made it possible to controllably change the temperature of the walls of the gas-discharge tube in the range from 4.2 to 77 K. The temperature was controlled using a silicon sensor mounted on the outer surface of the wall of the gas-discharge tube near the region of the generation of dust structures.

The temperature sensor was thermally insulated from the outer cooling medium and could measure the temperature of the discharge tube wall with an accuracy of no worse than 1-2 K. In order to illuminate the dust particles, radiation from a diode-pumped solid-state laser with the wavelength 532 nm was introduced into the cryostat through an optical fiber. The observations were performed in the Dewar vessels with a CCD video camera. In order to generate stable striations over a wide range of parameters, the discharge was locally constricted with the use of an additional glass cylinder located in the lower part of the discharge tube. In the upper part, the cylinder narrowed to a capillary with an inner diameter of 0.1 cm. The results of the experiments demonstrated that, both in the discharge at room temperature and in the cryogenic discharge, the dusty plasma structures were formed in the stationary striations generated above the capillary. The observations were carried out in the first striation over the capillary. In the experiments performed at room temperature, we observed the formation of anisotropic crystalline dust structures, which are typical of dc glow discharges and have a preferred direction along the axis of the discharge. The dust particles in this case are ordered in the vertical direction, thus forming threadlike aggregates (dust chains) containing from two to ten particles. The number of chains can vary from several units to several tens, and the total number of particles usually does not exceed  $10^2$ . Figure 2 shows a similar structure formed at the discharge current  $I = 0.5$  mA and the gas pressure  $p = 2$  Torr. The interparticle distance  $l_p$  for these parameters is equal to 500–750  $\mu\text{m}$ . Upon changing over to cryogenic temperatures, both the pattern of the dust structure and the dynamics of dust particles in it become different. At a temperature of 77 K, we observed the formation of large scale dusty plasma structures (with sizes of the order of  $10^3$  particles) made up of long chains (containing 15-20 particles). The interparticle distance in the chains amounted to 200–250  $\mu\text{m}$ . This circumstance indicates that, compared to the density of dust structures at room temperature, the density of the dust structure at 77 K increases by at least one order of magnitude at the same values of the density of the neutral gas and the discharge current. A further continuous cooling of the discharge is accompanied by a further decrease in the interparticle distances in the dust structure, a transformation of the pattern of the dust structure, and a change in the dynamics of dust particles in it. At temperatures in the range from 30 to 50 K, the interparticle distances decrease to 120–160  $\mu\text{m}$  and the dust structure occupies the entire volume of the striation head. In this case, the dust structure consists of a complex aggregate involving regions of crystalline ordering and convective motions. The chain ordering of dust particles is retained only in the lower part of the structure, and the orientation of the chains is changed in such a way that the larger is the distance between the chain and the axis of the discharge, the greater is the tilt of the chain with respect to the vertical axis (the discharge axis). Upon cooling of the discharge, the interparticle distances decrease until the discharge becomes unstable. The development of discharge instabilities at the aforementioned discharge current prevents the confinement of dust particles in the discharge, and they are deposited on the bottom of the discharge tube. At temperatures below 30 K, the observations of particles were performed after the discharge current was decreased to 0.2 mA, when the discharge was stabilized. The structures formed under these conditions are characterized by a liquid-like behavior. An increase in the density of the dusty plasma structures is observed until the helium is completely condensed in the Dewar vessel, i.e., when the cooling helium vapors transform into the liquid state (4.2 K). Note that, in this case, the conditions of observation of dust particles are substantially deteriorated (the measurement of interparticle distances is strongly complicated). The distances between the dust particles at a temperature of 4.2 K do not exceed 30  $\mu\text{m}$ . The first experimental results obtained provide a qualitatively correct pattern of the variation in the density of the dusty plasma structures during cooling of the discharge to low (cryogenic) temperatures. The data obtained demonstrate a strong nonlinear dependence of the interparticle distance  $l_p$  in the dusty plasma structures on the temperature  $T$  of neutral atoms. An analysis of the mechanisms of the phenomena under consideration should include a thorough examination of the transformation of the ion velocity distribution function at low temperatures of the gas atoms with the proper allowance made for the ion–atom collisions.

As it was obtained from the first experiments the cooling of the discharge down to very low temperatures (4-5 K) can lead to formation of very dense structures in which interparticle distance is



comparable to the plasma screening length and even to the size of the particles. Figure 3 shows such structure of polydisperse  $\text{Al}_2\text{O}_3$  particles observed at 4.2 K. The specific feature of this structure is compact spherical form and extremely high concentration of dust particles. Unfortunately, obtained images could not allow as obtaining any structural and dynamic structure characteristics because of the poor conditions for observation. For the purpose of observing individual particles in super dense dust structures at cryogenic temperatures the new optical cryostat with flat round windows was developed. By means of the new cryostat we observed the phenomenon of spheroidizing of dust structures at the discharge cooling (Figure 4). Such a sphere-like structure was obtained as a result of decreasing of pressure and current of the discharge at 77 K. Here the interparticle distance is about 100  $\mu\text{m}$ . Thus, one can expect the formation of superdense compact dusty plasma structures (spheres) of monodisperse particles at 4.2 K.

For the estimation of the dust charge in super dense structure at 4.2 K we can use the quasineutrality condition:

$$n_d Z_d + n_e = n_i,$$

where  $n_i \sim 2 \times 10^9 \text{ cm}^{-3}$  for the experimental conditions [1]. Assuming that the conditions  $n_e \ll n_i$  is valid (because of the energetic ( $\sim 1 \text{ eV}$ ) electron loss on the dust particles) we can achieve

$$Z_d \sim 20.$$

This result seems to be rather realistic since such a small dust charge does not lead to sufficient Coulomb repulsing of dust particles. Since plasma parameters in the dc discharge striations are anisotropic, such sphere-like form can be result of surface tension of the structure caused by forces of non electric nature (ion drag force, thermophoretic force, etc.).

This study was supported by the Program ‘‘Thermal Physics and Mechanics of Intense Pulse Actions’’ of the Presidium of the Russian Academy of Sciences, by the NWO Project No. 047.016.020 and by the CRDF Project No. RUP2-2891-MO-07

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