Formation of the structures from dusty clusters in neon dc discharge under cooling

D N Polyakov, V V Shumova and L M Vasilyak
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13
Bldg 2, Moscow 125412, Russia
E-mail: cryolab@ihed.ras.ru

Abstract. The formation of structures consisted of dusty clusters in plasma at the discharge tube cooling to a temperature of liquid nitrogen was discovered. The dependence of the reduced electric field in the positive column of a discharge on gas temperature was experimentally measured. Depending on the pressure of neon were observed the different structural transitions in the regions of growing current-voltage characteristics at low discharge currents ≤ 1 mA. It was found that the regions of existence of structured clusters and the regions of structural transitions were characterized by the higher values of the reduced electric field than the regions of destruction of ordered structures.

1. Introduction
The dusty plasma cooled to cryogenic temperatures is a subject of fundamental interest in studies of strongly coupled systems [1]. The review of current state of the studies of the cryogenic dusty plasma and the technological aspects of application of the cryogenic plasma with a dust component is represented in [2]. Cryogenic plasma with dust particles was experimentally obtained for the first time comparatively recently [3,4]. Cryogenic dusty plasma was investigated at the boiling point of liquid nitrogen (T = 77 K) in rf and in dc discharges in air [3] and at the boiling point of liquid helium (T = 4.2 K) in dc discharge in helium [4]. There were observed the dense dust structures consisting of micron size dust particles with the distances between particles about the Debye ion radius (10–30 µm). Cryogenic dusty plasma in neon was obtained experimentally for the first time at 77 K [5]. There was found, that distances between dust particles, types and shapes of dust formations complexly depend on gas temperature, pressure and discharge parameters.

The structural transitions characterized, for example, by a change in dust particle number density, lead to self-consistent changes in parameters of background plasma.

The longitudinal electric field is one of the fundamental plasma characteristics that determine the electron temperature and the rates of ionization in plasma. The ionization processes and losses on the dust particles in neon plasma may proceed with the participation of metastable atoms [6,7]. The concentration of metastable atoms is strongly influenced by gas and by electron temperatures and can be significant at cryogenic temperatures [2]. The electron temperature also determines the charge of dust particles that defines the internal structure of dust formations, their geometrical shape and size. Hence, the study of change of an electric field in plasma is...
Figure 1. The schemes of electric measurements (a), the optic setup scheme (b) and photo of the experimental setup (c).

The aim of this work is to study in more detail the internal structure of complex dust clusters, depending on gas pressure and the value of reduced electric field. The represented in this article experimental data may provide an information on the fundamental interactions in dusty plasmas.

2. Experimental

The glow discharge was initiated in a discharge tube by means of a high-voltage generator operating in a current stabilization mode. The formation of dust structures was studied at discharge current $I$ in the range of 0.01–1 mA and neon pressure $P$ in the range of 0.14–1.4 torr, measured at 295 K. The glass discharge tube (1) was of 16.5 mm i.d. The distance between the hollow cathode (2) and the ring anode (3) was 18.4 cm (figure 1a). The 4.14 $\mu$m dust particles (4) of melamine formaldehyde were injected in the discharge from the container (5), located above the top electrode.

After ignition of glow discharge, the emission of a portion of particles from the container was organized, and the formation of dust structure followed. The discharge luminescence and images of dust structures were registered optically (figure 1b). The photo of the experimental setup is represented in figure 1c.

Were measured the temperatures of a discharge tube wall and the values of gas pressure and electric characteristics of a positive column where dust structures were localized. To control and maintain the desired gas temperature, the discharge device was enclosed in optic cryostat (6), represented in figure 1b. The discharge tube was cooled from the temperature of external air 295 K down to 77.4 K in a stream of evaporating liquid nitrogen (LN2).

The temperature of the discharge tube wall was measured in three positions: on the half of its length and in the vicinity of cathode and anode, as shown in figure 1a. The signals from thermocouples (7) were outputted to the temperature measurement block, located in the block of cryostat management. The accuracy of maintenance of temperature was $\pm 0.5$ K at peak heat release of the discharge. The accuracy of heat stabilization without a heat release was $\pm 0.05$ K in a temperature range from 4.2 to 50 K and $\pm 0.1$ K at higher temperature. The gas temperature was accepted to be equal to the temperature of tube wall, which was considered as an average over the length of electric measurements. The neon pressure was registered by
the controller. Following [6], the concentration of neon was determined from the corresponding values of temperature and pressure.

Were measured the current-voltage characteristics (CVC) of the glow discharge and CVC of the section of positive column, where the dust structures were localized. The voltage drop in a positive column was measured between the ring electrodes (8) located as represented in figure 1a. The influence of a measuring circuit on discharge plasma was excepted because the voltage on the discharge was measured using the voltmeter (9) with high input resistance. The hit of dust particles on the cathode and the binding of the discharge strata between ring electrodes was prevented with the dielectric insert (10) located over the cathode.

The registration of an integral luminescence of the discharge plasma in an optic range was carried out by means of video camera. For the optic measurement of size of dust structure (11) and the discharge luminescence in the axial and transverse sections, the cryostat was supplied with flat quartz windows (12) at the end surface and along the cryostat length (see figure 1). The images of dust structures were registered in a reflected light of a flat laser beam (13) with the help of a microscope and video camera (14). The flat laser beam was formed after a passage of radiation from laser through the optical system consisting of two cylindrical lenses (15). The images of dust structures in the transverse section were registered by video camera after the rotation of image in the mirror. The vacuum jacket of the cryostat and the discharge tube were evacuated to $10^{-1}$ Pa and $7 \times 10^{-5}$ Pa respectively.

The electric and optic measurements were carried out with time synchronization recording the dust structure images, luminescence and discharge parameters in the video file on PC. Two video cameras and the diagnostic laser (16) were settled down on the uniform platform (17) which allowed us carry out 3D scanning of dust structures.

3. Results and discussion
Earlier we revealed [2, 8], that the distances between the dust particles and the shapes of dust structures show the complex dependence on neon temperature, pressure and discharge parameters. In the present study, the distances between the dust particles in dust structures at 295 K were of 140 to 310 $\mu$m depending on discharge current, and they varied along the dust structure. The typical dust structure images are represented in figure 2c.

At cooling to 200 K, the structural phase transition was observed. The clustering of dusty plasma was observed, i.e. the formation of clusters formed by dust particles. In the center of dust structure the formation of a dense nucleus appeared, similarly to the process of self-organizing of dust structures around the center of crystallization, observed in [9]. At cooling below 200 K the processes of self-organizing could proceed in two directions, the formation of a highly ordered and weakly ordered structures consisting of dust clusters was observed. At the temperature of liquid nitrogen, depending on the parameters of the plasma in the first case, the formation of simple 1D clusters (threadlike clusters, dust strings) and multi-dimensional clusters (2D or 3D multiple chains) and disordered structures consisting of them (figure 2b) take place. In second case the formation of ordered structures consisting of multi-dimensional clusters was observed. The fragment of such structure is represented in figure 2a, where the ordered structures formed by the ordered multi-dimensional clusters, which constitute a hexagonal lattice, are shown with circles.

The temperature decrease was accompanied by the decrease of inter-particle distances to values of 10–40 $\mu$m (figure 3). The distance between chains (threadlike 1D clusters) was of 40–100 $\mu$m. These experimental data demonstrate that the self-organization of dust structures at cryogenic temperatures appears to be more complicated than we supposed earlier. Depending on the plasma parameters, there may be transformations from the second order transitions up to melting and the transition to a state of vapor cloud with the random motion of individual particles. In this study, the formation of complex cluster structures [5] consisting of simple
1D clusters was observed (figures 3). The similar clusters (dust strings) were found at room temperature in rf discharge in argon [10] and in dc discharge in neon [11]. The threadlike aggregates (dust chains) were discovered in helium dc discharge at 77 K [12].

The various phase transitions can be realized in dust structure formed by clusters. Depending on gas pressure, were observed the structural second order transitions from chain structures formed by multi-dimensional clusters (figure 3a) to homogeneous structures formed by simple 1D clusters (figure 3b), which were in a liquid state.

Under the presence of dust particles the electric field increases in the whole range of gas temperature when maintaining the total discharge current. While the dust particle number density in cryogenic plasma is high, their total number $N^d$, maintained in a discharge, is small, because the dust structures formed at cryogenic temperature are of the smaller sizes than that at room temperature.

The influence of dust structures with such quantity of particles on the CVC is minor [13, 14]. Still, the discharge voltage drop $\Delta U$ related to the total number of dust particles $N^d$ measured on the identical length of discharge, is much higher at cryogenic temperature, than at room temperature: $\Delta U/N^d_{\text{room}} \approx 10^{-5}$ V/particle, $\Delta U/N^d_{\text{LN2}} \approx 10^{-3}$ V/particle.

The dependence of the reduced electric field $E/N$ on neon temperature is represented in figure 4. One can see that with the decrease of temperature from room to the temperature of liquid nitrogen, the reduced electric field $E/N$ decreased by more than 1.5 times.

At cooling from the room temperature to the temperature of liquid nitrogen, the border of the transition of CVC to the normal glow discharge, shifts towards the smaller discharge current, and it approximately coincides with the border of the melting of structured clusters. Figure 5 represents the diagram of dusty plasma in neon at a temperature of liquid nitrogen with the

Figure 2. The reduced electric field $E/N$ in a positive column of glow discharge in neon versus the reduced pressure $Pr$ at room temperature (green) and at temperature of liquid nitrogen (red, blue and magenta) at discharge current of 0.5 mA. Fragments (a–c) represent the images of dust structures (axial cross section) that correspond to colored parts of the curves (a–c).
Figure 3. The scheme of structural transitions in dependence on pressure for cryogenic dusty plasma at the boiling point of liquid nitrogen for discharge current $\leq 1$ mA and fragments of dust structures (axial cross section) consisted of clusters: multi-dimensional (a) and simple (b).

Figure 4. The surface of the reduced electric field $E/N$ in a positive column of glow discharge in neon at room temperature (a) and at temperature of liquid nitrogen (b) versus the reduced pressure $Pr$ and the discharge current $I$.

isolines of the reduced values of the longitudinal electric field, determining the phase transition. The higher is the electric field, the higher is the degree of dust structure order. The regions of existence of structured clusters are characterized by the higher values of the reduced electric field than the regions of their melting and the regions of homogeneous structures formed by threadlike clusters. At low current, i.e. to the left from the vertical border of melting, the melting is governed by the value of the electric field strength, to the right by the discharge current.

It is worth to note that the vertical border of melting coincides with the border of the transition to the normal glow discharge (2), where the electric field strength slightly depends
Figure 5. The diagram of state of dusty plasma in neon at a temperature of liquid nitrogen with isolines of the reduced electric field, the border of melting (1) and of transition to the normal glow discharge (2).

upon the discharge current. To the left from the vertical border of melting (1), the ordered structures are formed by ordered multi-dimensional clusters.

Thus, the structural transitions proceed with the change of gas pressure and discharge current. When pressure increases, the multi-dimensional clusters reconstruct into threadlike clusters. The four specific regions of structural transitions are observed. In the region 1 there appear the ordered structures with the lattice similar to the hexagonal with multi-dimensional clusters located in the sites of lattice. The dust particles forming multi-dimensional cluster, in turn, are in the ordered state. In the region 2 the destruction of crystals consisting of multi-dimensional clusters and the destruction of ordered multi-dimensional clusters into individual threadlike clusters is observed. In the region 3 the dense disordered structures consisting from threadlike clusters are observed. With an increase in the discharge current, the melting of the ordered structures and the increase of distances between dust particles and between clusters is observed (to the right from the vertical border in the region 4). At room temperature, the boundary of the structural transition is mainly determined by the discharge current. With an increase in discharge current the structural transition associated with the restructuring of the lattice was earlier observed in [15].

4. Conclusion

The internal structure of dust formations was studied at cooling of the discharge. The types of dust structures formed at cooling differ from those at room temperature. The clustering of the dust cloud was observed. At room temperature the dust structures were formed by dust particles, while at cryogenic temperature the dust structures were formed by clusters. The melting of clusters and changes of their structures were observed at change of gas pressure. The low-temperature border of the melting of dust structure in a direction of gas density change was found. At room temperature, the border of the structural transition was mainly governed by the discharge current, while at cryogenic temperatures this border was determined by gas pressure,
the discharge current and the value of the electric field. The electric field determined the degree of ordering of dust structures at such values of discharge current, where their melting was not observed.

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