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Dynamic Behavior of Polydisperse Dust System in Cryogenic Gas Discharge Complex Plasmas

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Complex (dusty) plasmas of micron-sized CeO_2 polydisperse particles in dc glow discharges at 77 and ∼10 K were experimentally investigated. It was obtained that dust structure in cryogenic gas discharge plasma can be a mixture of two fractions (components) with completely different dust ordering and dynamics. We observed under some specific conditions that fast-moving particles of one component diffuse through another component consisted of dust particles arranged in linear chains (strings). From experimental data analysis particle velocity distribution functions for each dust component were obtained. The possible nature of two-component dust structure formation was discussed.

1 Introduction

Cryogenic complex (dusty) plasmas, i.e. complex plasmas in cryogenic discharges, have received increasing interest over the last decade [1–12]. The interest has been largely motivated by extremely low temperature conditions (to several Kelvins) at those dust structures can exhibit unique structure properties such as very high dust concentration, the formation of compact dust spheres, etc. As to dust dynamics, an increase in dust kinetic energy during neutral gas cooling was observed. Unfortunately, the nature of these remarkable features is still almost unclear mostly because of the lack of reliable experimental data. As it was obtained in numerical simulations (see, for example, [3]), at cryogenic temperatures of the discharge tube walls strong anisotropy of ion velocity distribution function takes place, which in turn can cause considerable change of structure and dynamic properties of a dusty plasma.

In laboratory experiments, dust particles commonly form structures consisted of ordered fraction of chain-like clusters and/or disordered fraction (liquid- or gas-like) of moving particles. The fractions are always separated in space and consisted of particles of the same size. At cryogenic temperatures we found another type of dust behavior — formation of polydisperse dust systems which are two-component dust mixtures. Using polydisperse micron-sized particles of irregular shapes in cryogenic experiments, we can achieve free-moving dust particles levitating in the same region as particles arranged in linear chains/strings and the particles of one fraction/component diffuse through another with relatively high velocities. In other words, binary-like dust structures in cryogenic gas discharges were observed.

The investigations presented in this paper are interesting, in particular, because of possible application in a wide range of biological systems involving clustering and migration. Related transport phenomena represent characteristic aspects of many nonequlibrium processes and are essential features of most living systems.

2 Experimental setup

At present, development of the diagnostic techniques providing direct measurements of quantitative characteristics of dusty plasma structures at cryogenic temperatures is still an actual problem. In this work, the optical

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diagnostic system was improved for investigation at liquid helium temperatures. The experiments were conducted using dc glow discharge generated in a vertical glass tube placed inside specially designed metal cryostat (see Fig. 1). In order to illuminate and register dust structures at cryogenic temperatures, the cryostat is supplied with four flat round windows of 3 cm in diameter.

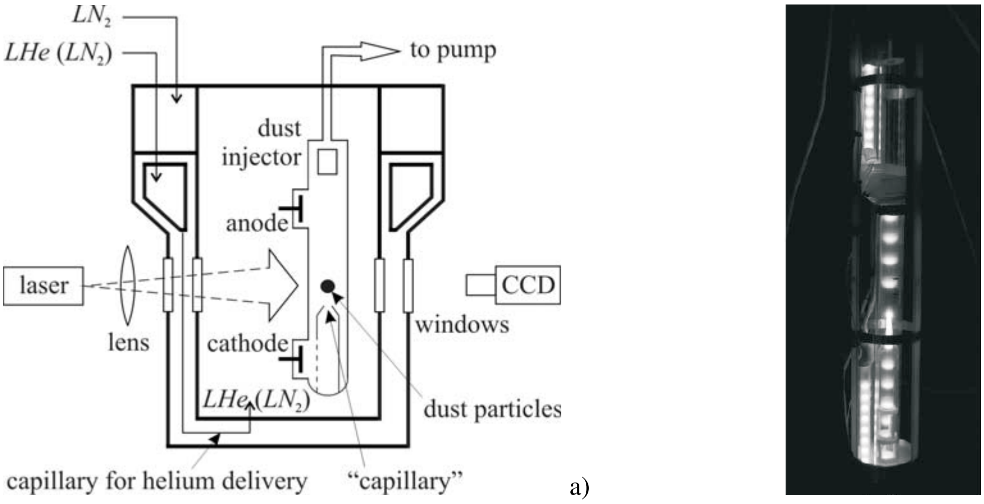

Fig. 1 a) Schematic of the experimental setup. b) Image of the stratified dc discharge in the tube at room temperature (tube inner diameter — 1.5 cm, interelectrode distance — 34 cm).

Fig. 2 Magnified views of CeO_2 irregular particles (scale — 10 μm).

The discharge tube can be cooled by liquid nitrogen/helium (77/4.2 K) or liquid helium vapors ($\sim$10 K). In the last case, level of liquid helium on the bottom of cryostat is lower than the position of the tube in cryostat shaft. The discharge was generated in helium gas at pressures of about 10^{-2}–10^{-1} Torr and discharge currents of about 0.1–1 mA. The estimations of plasma density for the similar experimental conditions (in particular, tube size and geometry, discharge parameters, etc.) give the values of several units of 10^8 cm^{-3} at 77 K and about 10^9 cm^{-3} at 4.2 K [2]. We assume that temperature of ions is approximately equal to the temperature of the tube walls and the temperature of electrons was not changed during the cooling of ions. Irregular particles of CeO_2 polydisperse powder of about 2-5 μm in effective size (see Fig. 2) were injected in discharge plasma from the container positioned above the stratified discharge positive column. Levitation of dust particles in the field of gravity was carried out by means of a double electric layer created in the bottom part of the discharge tube using an additional glass tube with narrowing of 0.1 cm in diameter (so-called "capillary"). The results of the experiments demonstrated that both in the discharge at room temperature and in the cryogenic discharge, the dusty plasma structures were formed in the heads of stationary striations. Our observations were conducted in the first striation over the "capillary". In order to illuminate dust particles, diode-pumped solid-state laser with the wavelength 532 nm and variable power (up to 300 mW) was used. The scattered laser light from particles was registered by means of high-speed CCD video camera at a frame rate 100 fps and 640$\times$480 pixels resolution. From video frames the interparticle distances were measured.

3 Experimental observations and discussions

Let us now present the results of experimental investigations. As it was mentioned above, dust structures consisting of particles of two non-separated fractions combined in two-component mixtures were obtained in the experiments at 77 and ∼10 K. These components differ in both dust ordering and dynamics — particles of one component are localized in chain-like dust clusters (background component), particles of another component move with relatively high velocities, while diffusing through this background. These diffusing particles have finite (orbital) trajectories with predominant horizontal component of velocity.

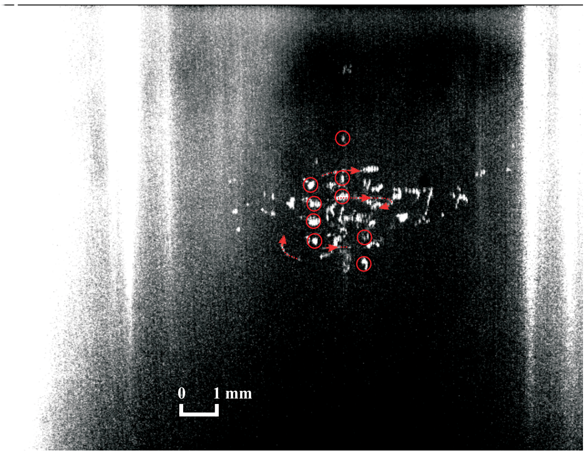

Fig. 3 Side view of typical two-component dust structure in dc discharge striation at 77 K (gas pressure 0.3 Torr, discharge current 1.1 mA). The image is the result of superposition of 13 consequent frames. Circles indicate some particles in dust chains, arrows indicate the movement of some orbiting particles.

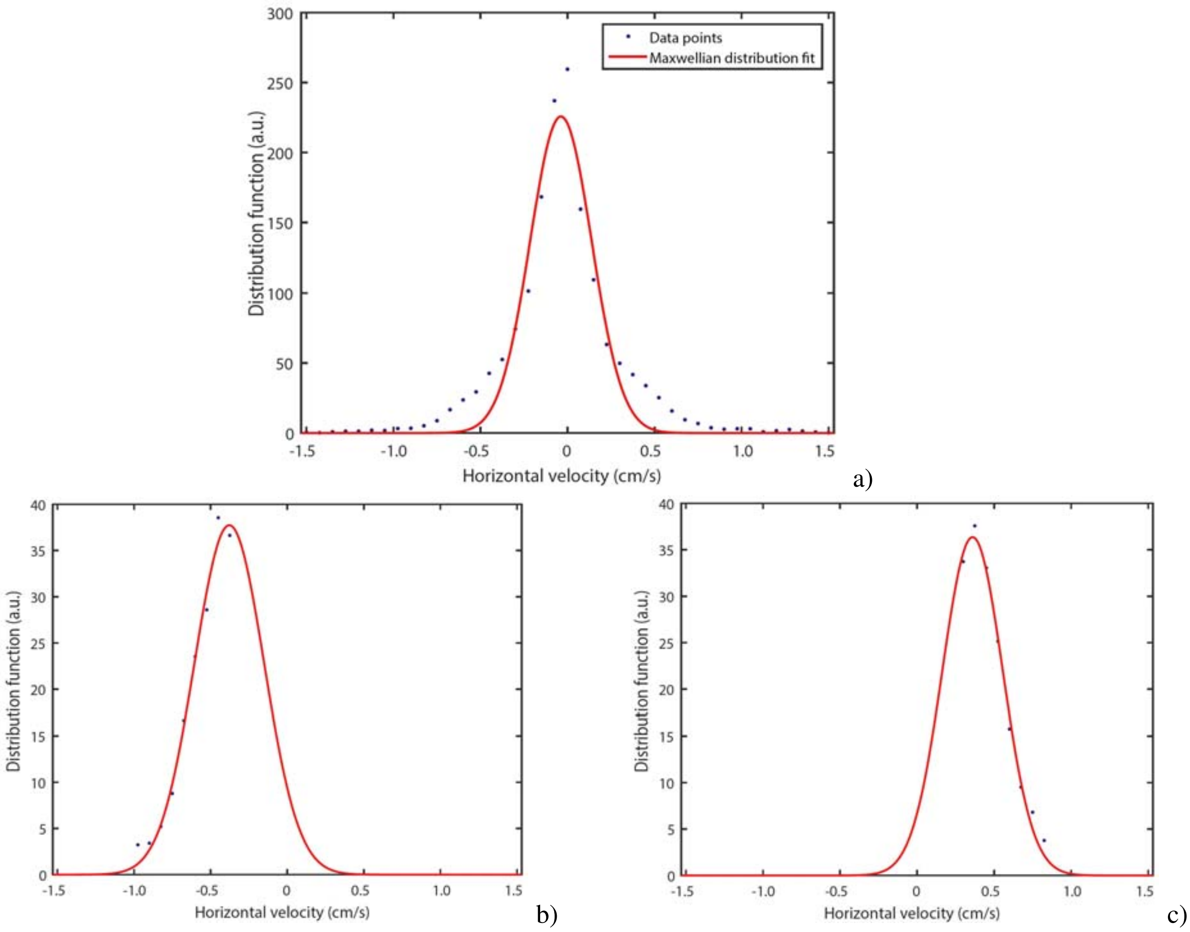

Fig. 4 Dust particle distribution functions for velocity horizontal projections on side view of dust structure on Fig. 2 (dots — experimental data, line — Maxwell distribution): a) total velocity distribution, b) velocity distribution for particles with negative velocities (moving to the left), c) velocity distribution for particles with positive velocities (moving to the right).

At 77 K, relatively small two-component structures consisted of about several tens of particles were observed (Fig. 3). In such a structure the measured interparticle spacing for particles in chains (chain period) is about 500 μm. From video frames received dust particle velocity distribution functions were obtained (Fig. 4). As it is shown in Fig. 4a, Maxwell's function well approximates a maximum of distribution of velocity horizontal projections. On the contrary, "wings" of this distribution fall several times slowly (it looks like the existance of salient/inflection points in Fig. 4a). We assume that such distribution function is a mixture, i.e. sum, of normal distributions, where the central part of function corresponds mainly to the dust chains, and "wings" — to the particles having directed velocities (orbiting particles): $NF(v) = n_1 f_1(v) + n_2 f_2(v)$. Now, in order to find orbiting particle velocity distribution function, we propose the following procedure: one can subtract the background component Maxwell function, which is close to the central part of the distribution, from full distribution. The received values will lie on the following distributions (Fig. 4b,c): left values — on the left part of the distribution for particles with negative velocities (moving to the left), right values — on the right part of the distribution for particles with positive velocities (moving to the right): $2f_2(v) = f_+(v) + f_-(v)$. The distributions received have almost identical view and are symmetrically positioned about zero:

$$f_{\pm} = \sqrt{\frac{m_2}{2\pi k T_2}} exp \left(\frac{-m_2(v \mp V)^2}{2kT_2} \right). \tag{1}$$

Here $V \approx 0.4$ cm/s is treated as side view drift velocity of orbiting particles. It was obtained that the kinetic temperature of the orbiting particles exceeds the temperature of particles in chains approximately by 1.5 times: $T_2 = 1.5T_1$.

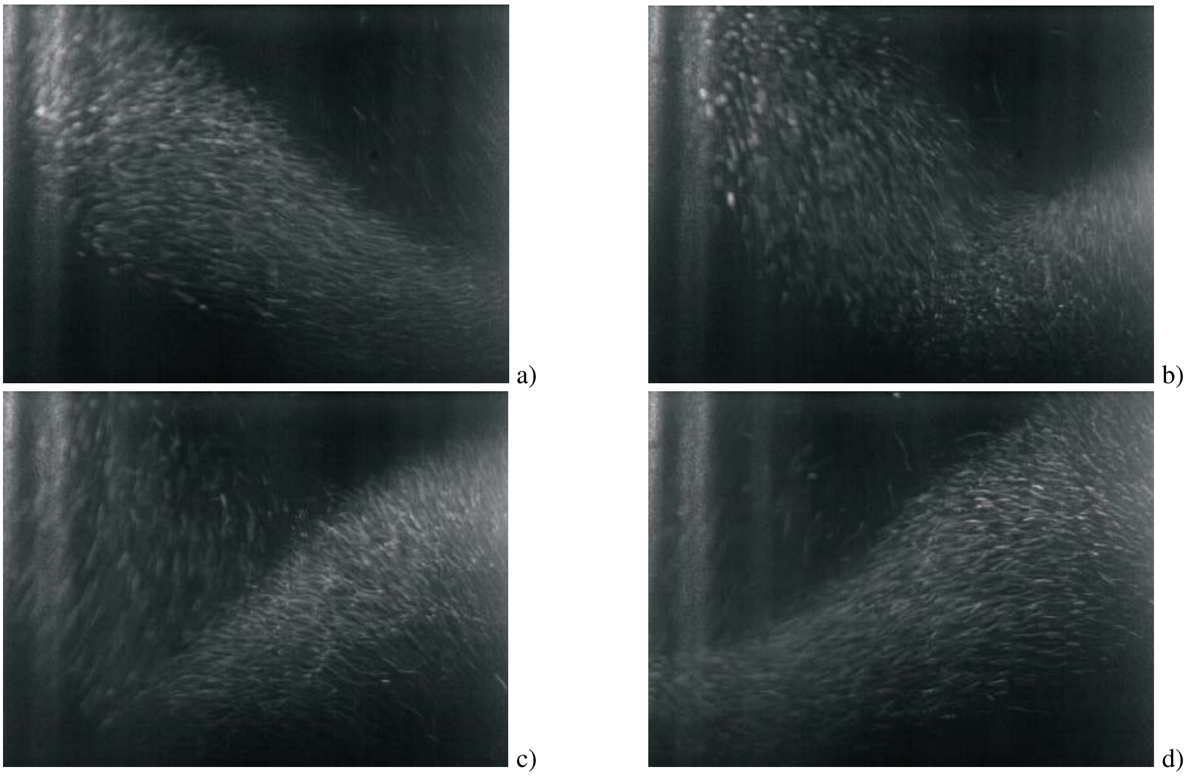

Fig. 5 Self-oscillation of dust structure at temperatures of several kelvins (side view). The interval between the frames is 0.04 s.

At cooling by liquid helium, dust self-oscillations can be excited (Fig. 5). The oscillations were caused by discharge temperature increase to $\sim$10 K after decrease of liquid helium level. As it was observed, the oscillations have a form of tidal waves with frequency of 3–4 Hz. The oscillations fade away after a couple of minutes and two-component structure remains (Fig. 6). Further temperature increase leads to falling of particles and dust structure degradation.

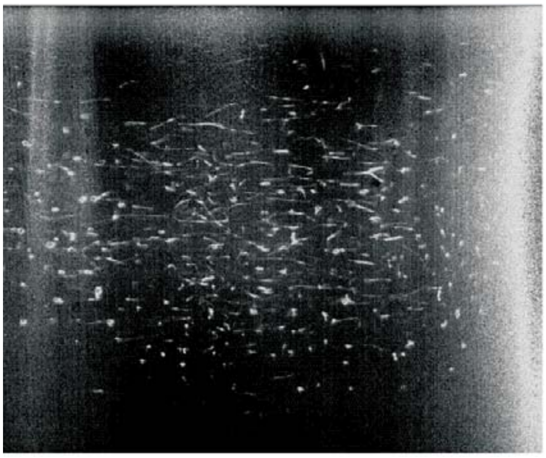

Fig. 6 Side view of the typical two-component dust structure in dc discharge striation at $\sim$10 K (image is the result of superposition of 11 consequent frames).

As one can see, formation of two components is more visible at lower temperatures ($\sim$10 K), where dust cloud is several times larger and denser comparing with 77 K. Note that two-component dust mixtures were never observed in laboratory experiments before — particles were always separated in space into fractions according to their size. At cryogenic dusty plasmas we observe the mixtures of fractions of particles having irregular shapes. Thus, we can propose that formation of such dust mixtures is caused by both cryogenic and shape factors. For example, one component may consist of particles of approximately symmetric shape, another — from strongly asymmetric particles, such as elongated dust rods or discs. In this case the term "binary-like dust structures" can be introduced analogously to binary systems in colloids and chemical compositions.

We assume that one of the mechanisms responsible for the orbiting particles acceleration may be in deformation of ion distribution function due to ion-atom collision effect at cryogenic temperatures. In theoretical studies [13, 14] it was showed that even rare collisions of ions can substantially change the characteristics of screening and charging of dust particles. Since ion-atom collision cross sections increase with a decrease in collision energy, the decrease in temperature of atoms leads to an enhancement of the influence of ion-atom collisions on many characteristics of dusty plasma. In particular, this enhancement manifests itself in a drastic change in the ion velocity distribution and an increase in the ion current per dust particle. Moreover, the collisions caused by the resonant charge exchange of ions with atoms of the parent gas can also affect the force of the interaction with the ion flow (there arises so-called reactive force accelerating the particle in the direction opposite to the flow [14]). The effect of appearance of reactive force accelerating dust particle against the ion flow was considered for the first time by Prof. Maiorov [15,16]. The mechanism of this force rests on resonance charge exchange collisions of ions of the flow with buffer gas atoms and on momentum transfer from the flow of ions accelerated additionally in dust particle field to the buffer gas atoms (upon resonance charge exchange collisions of ions with gas atoms). As a result, from "ions + dust particle" system the atoms (that were ions before resonance charge exchange) take off a larger momentum than they had brought in, which creates a reactive force directed against the flow (negative friction force). But there is also a serious question to mechanism discribed above — how it can lead to particle acceleration in the directions observed in the experiments (horizontal drift of particles)? This problem still remains unclear and requires an explanation.

It should be noted that the motion of orbiting particles is very similar to the motion of fast-moving particles in dc discharge in mixtures of "light" (helium) and "heavy" (krypton) inert gases studied by the authors at room temperature [17]: the anomalous heating of dust particles in the discharge in mixture gives rise to the dust fraction containing particles orbit with high velocities (up to 10^3 eV) around the axial region of the structure. This fact may indicate a similar origin of such orbiting dust particles in both the discharges. Moreover, the phenomenon of appearance of ensemble of diffusing particles with directed velocities inside background dust was considered in experiments performed under microgravity conditions onboard the International Space Station (ISS) (for example, see [18, 19]). Such fast-moving particles received the name "crazy particles".

4 Summary

In conclusion, we experimentally investigated cryogenic dc discharge dust structures consisting of micron-sized dust particles of irregular shapes. The specific feature of dust structures obtained is the formation of two dust fractions (components) combined in binary mixture containing linear chain-like dust clusters as a background and ensemble of fast-moving particles diffusing through the background dust. We propose that the mechanism responsible for this phenomenon involvs both dust shape irregularities (form factor) and considerable deformation of the ion velocity distribution function from an equilibrium distribution at cryogenic temperatures (cryogenic factor). This remarkable phenomenon may lead to deeper understanding of physical processes which take place in nonequlibrium systems, typical in natural and social environments.

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