Plasmas and dusty plasmas at temperatures of liquid helium

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Abstract. Recent studies of dusty plasma structures formed by polydisperse CeO\textsubscript{2} particles in a dc glow discharge at a temperature $T > 1.6$ K were shown to be the first experiments on dusty plasma in an exotic dark glow discharge mode. The properties of cryogenic helium plasmas at $T \sim 1$ K are summarized and discussed.

1. Introduction

The constantly growing interest in plasma science and technology for many years is associated with the numerous applications of plasma in materials science, electronic industry, medicine, biotechnology and environmental protection and others. The properties and potentials of plasmas maintained at temperatures below 10 K were intensively studied last years in researches on plasma decay and corona discharge in liquid helium \cite{1–4}, radiofrequency discharge afterglow \cite{5, 6}, and dielectric barrier discharge (dbd) \cite{7, 8}.

Cryogenic plasma cooled by liquid helium was first investigated by Kirillin and Markovets \cite{9}. The first publication on experiments with cryogenic dusty plasma structures appeared in 2002 \cite{10}. Later investigations of dusty plasma systems were continued at lower temperatures down to the liquid helium temperature $T = 4.2$ K \cite{11–15}. It was suggested that a decrease in the discharge temperature to 2 K under cooling of the dust component (if other conditions being the same) would lead to a more than twofold increase of the plasma non-ideality (coupling) parameter. However, temperatures lower than 4 K were not reached till recent works \cite{16–18}.

It should be noted that the gas discharge itself at temperatures below 5 K has not been studied comprehensively as yet. In particular, the reasons for the hysteresis and a discontinuity of the current–voltage characteristic of the direct current (dc) glow discharge, as well as complete absence of positive column glow at currents lower than 0.2 mA, remain unclear \cite{19, 20}. Analysis of these phenomena suggests the existence of a new state of the cryogenic plasma with a fundamentally new conduction mechanism, which remains unknown till now \cite{20}. This fact also stimulates the interest for investigation of cryogenic gas-discharge plasma itself and dusty plasma structures at temperatures lower than 5 K. In this case, dust particles can be treated as auxiliary probes for studying cryogenic plasma.

Here we review the experimental results of investigation of dusty plasma structures formed by polydisperse cerium dioxide particles in the dc glow discharge at temperature $T > 1.6$ K.
The phenomena related to nanoparticles and filaments formed in the cryogenic discharge due to efficient sputtering of dielectric material [17, 18] will be out of scope of this paper.

2. Experimental setup
The experimental setup for investigation of cryogenic helium plasma and dusty plasma structures has been described in detail elsewhere [16]. It was based on a Janis SVT-200 optical cryostat. The temperature of liquid helium inside the cryostat could be lowered down to 1.5 K by pumping helium gas away. Experiments with the dc glow discharge were carried out in a vertically oriented glass tube located in the inner channel of the cryostat. The lower end of the discharge tube (up to the position of dusty plasma structure) was immersed into liquid helium at temperatures below 4.2 K. The inner diameter of the tube was 20 mm and the distance between electrodes was about of 600 mm. Two thermometers were used for temperature measurements: the former was next to the lower end of the discharge tube; the latter was fixed on the outer surface of the discharge tube approximately at the height of dusty plasma structure. We suggest that the temperature of helium gas inside the discharge tube, \( T_g \), was equal to the temperature of the tube wall.

Temperatures below 4.2 K were reached in a regime with the minimal heat release (discharge current of 20–50 µA at the voltage applied up to 3.2 kV. This regime, we will call it as the dark mode, was characterized also by the low helium pressure (4–6 Pa) in the discharge tube and complete absence of any emission from the discharge area. Dusty plasma structure was formed injecting polydisperse CeO\(_2\) powder. Powder particles fell into the positive column of the discharge, where their charging and trapping in ionization regions (striations) occurred. The dusty plasma structure trapped in a striation was recorded by a digital video camera at the rates up to 300 frames/s. Dusty plasma structures were visualized with a laser knife introduced into the cryostat through an optical window at right angle to the observation axis the video camera.

3. Results
The development of the glow discharge was accompanied with very unstable conditions at the current values within the range of 50–80 µA: we observed fast sporadic displacements up to 2 mm along the tube axis of the dusty plasma structure within the times of \( \sim 0.01 \) s. A dusty plasma structure formed at \( T_g = 1.6 \) K is shown in figure 1(a). One can see also the level of the superfluid helium (HeII) filling the space around the discharge tube.

The liquid-like structures consisted of fast and slow particles moving chaotically. Their velocities differed by about an order of magnitude, from some tenths up to 10 mm per second. Some of fast particles formed vortices over the structures. The average distance between particles in the structure was usually within the range from 100 up to 200 µm. The structure sizes after its formation varied from 3 to 5 mm, its height was usually larger than the diameter. Therefore we can estimate the total number of dusty particles forming such a structure as \( 10^4 \)–\( 10^5 \) particles. Dusty plasma structures encompassed much less particles at temperatures above 4 K.

It was found that plasma dusty structures in the dark mode of the dc glow discharge could be maintained up to temperatures as high as 10 K. A dusty plasma structure at \( T_g = 9.8 \) K is shown in figure 1(b). Destruction of dusty structures occurred because of the glow discharge decay and sometimes the structures were thrown on the tube wall by electric field. We have collected the cerium dioxide particles stuck to the wall and analyzed them using scanning electron microscopy: the initially very broad size distribution of particles (from 0.1 to \( \sim 100 \) µm) was significantly narrowed (from 1 to 20 µm).

4. Discussion
We have estimated the particle charge in plasma dusty structures for a particle of the diameter about 1 µm from the balance of the gravitational and electrostatic forces as \( 250e \), where \( e \) is
elementary charge. Bearing in mind the typical interparticle distance of 120 µm, we can obtain a value $\sim 10^8$ cm$^{-3}$ for the average density of positive ions from neutrality of plasma. The coupling parameters $\Gamma \sim 10$ were determined for the dusty plasma structures and their values comply very well with the liquid-like type of the structures observed. The particle densities, $\sim 10^9$ cm$^{-3}$, in the structures studied in our experiments [16–18] are much lower than those in dense dusty structures, $10^8$–$10^9$ cm$^{-3}$, observed earlier [11, 12, 14]. We have to consider the principally different experimental conditions in those experiments: the higher values of the discharge currents, $>0.2$ mA, and bright emission from the discharge. Thus, we can conclude that our works [16–18] were the first studies of dusty plasma carried out in the dark mode of the dc glow discharge [9,19,20]. This mode is poorly studied yet and we can only to summarize some important parameters of cryogenic plasma at 4.2 K. It is well known that the density of the triplet metastable helium atoms can be so high as $10^{13}$ cm$^{-3}$ at gas temperatures $<10$ K [19, 21]. Moreover, the electron density in cryoplasma generated at atmosphere pressure in He dbd increases synchronously with the atom density and reaches $3 \times 10^{11}$ cm$^{-3}$ at the gas temperature 5 K, while the electron temperature drops from 13 eV at $T_g = 50$ K down to 2 eV at $T_g = 5$ K [22]. At the same time, the ratio $T_e \gg T_i = T_g$ right for low temperature plasma transforms into $T_e \gg T_i \gg T_g$ in cryogenic plasma because the positive ion temperature, $T_i$, becomes higher than $T_g$ due to ions heating in strong electric field of the cryogenic discharge [23]. It is worth noting also the decreasing of the charge value acquired by dusty particles in cryogenic plasma at temperatures below 100 K [13, 23]. The particle surface heating at temperatures $< 10$ K and pressure $\sim 1$ Pa, is very obvious due to ion-electron recombination: it was shown that the temperature of the dust particle surface can be significantly higher than that of neutral gas in cryogenic dusty plasma [24].
We have to mention also that the specific heat of solids is many times less at low temperatures. For instance, the specific heat of alumina (Al$_2$O$_3$) and polystyrene is decreased from 2941 and 1210 to 0.4 and 31 J/(kg K), respectively, upon cooling from 300 to 10 K. The particles made of these materials were used, for example, in the experiments presented in [11, 12, 14]. In such a case, not only the ion recombination, but even small absorption of light used for particle visualization can greatly warm up the particles and transform them into active hot particles in cold environment. The absence of emission from the discharge area along with the discontinuity of the current–voltage characteristic of the discharge point to switching the energy transfer processes and the conductivity mechanism in helium cryogenic plasma [20].

5. Conclusions

We have shown that dusty particles can be used as probes for studying properties of plasma in the dark mode of the dc glow discharge cooled by superfluid helium.

It has been found that the dark mode of the dc glow discharge, with no light emission from plasma, may be maintained within the temperature range 1.6–10 K keeping very low values of the current, $\sim 10 \mu$A, and the specific heat release along the discharge tube, $\sim 1$ mW/cm.

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