Creation of stable dust structures in the glow discharge in magnetic fields of up to 15000 G

S I Pavlov, L A Novikov, E S Dzlieva and V Yu Karasev

1 St. Petersburg State University, 7/9 Universkaya Emb., St. Petersburg, 199034
Russia

2 E-mail: s.i.pavlov@spbu.ru, plasmadust@yandex.ru

Abstract. The dusty plasma created in the dust trap in strata of the glow discharge in the strong magnetic field was studied. The conditions were found that make it possible to avoid the development of instabilities in the glow discharge plasma in the magnetic field. For the first time, in the magnetic field range of higher than 10000 G, the dust structures were obtained. The rotational speed as a function of the magnetic field induction was studied. The experimental conditions were discussed under which the stable dust structures can be created.

1. Introduction
When studying the dusty plasmas in the DC discharges in the strong magnetic fields of the order of 10000 G, the researchers meet the problems of the discharge burning stability and the dust structures stability in the dust traps. In [1, 2], the DC discharge was replaced by the RF discharge, the discharge chambers being similar for both types of discharge. The authors of [3] also met the problem of creating dusty plasmas in the glow discharge in the strong magnetic field. In a series of new studies of dusty plasmas in the magnetic field which appeared in the last 10 years [4–9], only the RF discharges were used, in which the dusty plasma is created in the form of monolayers perpendicular to the magnetic induction vector. However, in the RF discharge in the magnetic field, the dust layers lose their stability, as well as homogeneity. Thus, due to the discharge filamentation, the uniform dust disk becomes divided into the fragments with sizes of several millimeters, which are comparable to the width of the volumetric dust structures formed in the glow discharge [4].

In the magnetic field range under consideration, the current-convective instability develops in the homogeneous glow discharge [10–12]. This process is studied in detail and can be taken into account in research. In the case of studying the dusty plasmas, the stratified discharge is used. Currently, the runaway and standing strata formation in the magnetic field is an unsolved problem. The reliable data are available only on discharges in light gases and in the limited range of magnetic fields [13–14]. In recent works [15–17] we have successfully created the stable traps in the stratified glow discharges in the strong magnetic field. In this paper, we will discuss some technical problems and experimental conditions, under which it was possible to create the stable dust trap. The rotational motion dynamics in it is studied in the magnetic field range of up to 15000 G that, currently, is a unique achievement.

2. Experiment
The cryomagnet creating the magnetic field was described in detail previously [15–17]. The peak magnetic field created in the center of the solenoid reaches 2.7 \(10^4\) G at a current of 55 A.
The magnetic field homogeneity in the central region is 0.1% within one cubic cm. The magnetic induction vector is directed vertically. Liquid helium is required to provide the phase transition in the solenoid to the superconducting state. The liquid helium vessel is placed inside the liquid nitrogen vessel in order to reduce the liquid helium loss. All these elements are installed inside the chamber, pumped to high vacuum (up to $10^{-5}$ Torr) that is necessary to reduce the liquid nitrogen loss. Inside the cryomagnet, there is a cylindrical channel (warm hole) with a diameter of 59 mm, which is isolated from the facility units cooled to low temperatures. Through this channel, the object under study can be placed inside the homogeneous magnetic field. During the cryomagnet operation, the temperature inside the warm hole was 281 K.

A discharge tube with an inner diameter of 22 mm and a length of 1.5 m was installed inside the cryostat coaxially with the warm hole. The tube can be displaced along the cryostat, so that the observed dusty structure is always in the central part of the solenoid (in the homogeneous magnetic field). Both of the electrodes were installed outside the cryomagnet (outside the magnetic field region); the cathode was installed under the solenoid. The dust particle injection was performed using the container with a fine mesh at its bottom. It was fixed in the side branch pipe of the discharge tube at a distance of 1 m or more from the superconducting solenoid. The injection was performed by means of shaking the container with dust particles with the help of the external magnet. To ensure the stable stratification, the dielectric insert was installed inside the discharge tube that narrowed the current channel. The observations were carried out in the first stratum, as counted from the insert in the direction of the anode.

The observations were carried out of the dust structures formed from the polydisperse quartz powder. The noble gas neon was used in a magnetic field of up to 15000 G. We called the dust structure stable, if we observed its regular rotation in the magnetic field. The dust structure can be trapped in the stratum by the strong magnetic field, but be distorted or displaced from the discharge axis and stop its rotation. After passing the region with unstable magnetic induction, the dust structure either resumes its rotational motion, or escapes from the trap; we call this phenomenon the "breakdown". The Figures 1–3 give an idea of the stable structures and breakdowns observed. Figure 3 shows the stable rotation detected for the first time, and the dusty plasma observed in the glow discharge in the magnetic field higher than 10000 G.

**Figure 1.** Dependence of the rotational speed of the horizontal cross section of the dusty plasma structure formed in the glow discharge strata trap on the magnetic field induction obtained at the minimal pressure and current. Conditions are as follows: plasma is produced from neon, the discharge current is 1 mA, and the gas pressure is 0.2 Torr. In a magnetic field of 1500 G, the breakdown of the dust structure occurred in the trap.
Figure 2. Dependence of the rotational speed of the horizontal cross section of the dusty plasma structure formed in the striation trap of glow discharge strata trap on the magnetic field induction. Conditions are as follows: plasma is produced from neon, the discharge current is 1.4 mA, the gas pressure is (a) 0.6 Torr and (b) 0.66 Torr, and the polydisperse quartz particles with a typical size of 5–6 µm are injected. In the field ranges (a) from 3000 to 4000 G and (b) from 6000 G to 8000 G, the instability is observed, but there is no complete breakdown of the dust structure.

3. Discussion
Such experimental conditions were chosen that, for the first time, it becomes possible to produce the dusty plasma in the glow discharge in the strong magnetic field higher than 10000 G. In a considerable number of cryomagnet operating cycles, the dusty plasma in the strata experienced breakdowns, even if the discharge continued burning. At pressures decreased to 0.2 Torr or less, the breakdown of the structure was more probable (Fig. 1). We tried to compare our experimental observations with the data
on the homogeneous glow discharges in the magnetic field available in publications and to formulate the general recommendations for obtaining the stable dusty plasmas.

The current-convective instability develops in the glow discharge in the longitudinal magnetic field. The instability parameters can be estimated using data available in publications [10–12]. Despite the fact that we deal with the stratified glow discharge, this instability is clearly observed in some magnetic field ranges (2500–3500 G) (see Fig. 2a). And besides, in a number of the cryomagnet operating cycles, under the same conditions (neon, p = 0.66 Torr), there were two magnetic field ranges of the instability development: the first range is 1000–3500 G and the second one is 6000–8000 G (see Fig. 2b). The development of these instabilities was somewhat avoided, if the cathode was installed outside the magnetic field and the discharge tube diameter was reduced from 2 to 1.5 cm.

Figure 3. Dependence of the rotational speed of the horizontal cross section of the dusty plasma structure formed in the glow discharge strata trap on the magnetic field induction. Conditions are as follows: plasma is produced from neon, the discharge current is 1.9 mA, the gas pressure is 0.66 Torr, and the polydisperse quartz particles with a typical size of 5–6 µm are injected.

In the magnetic fields higher than 10500 G, the degradation of the dust structure was not observed, and, apparently, the discharge instability did not develop. When the magnetic field was increased and the discharge current was chosen to be 1.9 mA, the stable rotation of structure was observed. So, Fig. 3 shows that the rotational speed is almost constant for the magnetic fields of up to 15000 G. Comparison with the measurements [15] shows the following trend: when the magnetic field increases in the range of 1000–2000 G, the rotational speed also rapidly increases; as the magnetic field increases up to 10000 G, the growth rate of the rotational speed gradually decreases; and at the magnetic fields higher than 11500 G, the rotational speed becomes constant. We note the important fact that at the magnetic fields exceeding 10000 G, the voltage drop along the discharge tube did not change. In further interpretation of the rotation dynamics of the dust structure, the changes in the shape (length) of the dust trap (standing strata), as well as the changes in plasma density and potential distribution, which occur with increasing magnetic field, should be taken into account, thereby quantitatively developing the model [15].
4. Conclusions
By means of varying the experimental parameters (the gas pressure, the discharge current, the tube diameter and the cathode arrangement in the magnetic field), for the first time, we managed to create the stable dusty plasma in the glow discharge in the strong magnetic field (higher than 10000 G).

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