Creation of dust structures and clusters in a glow discharge in a strong magnetic field

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Abstract. During the last 5 years, the range of magnetic field applied in the studies of dusty plasmas extended to the strong field. In particular, it became possible to generate dusty plasma in a glow discharge in a standing striation in a field of 1 T. Features of the formation of dusty plasma in a strong magnetic field, such as its geometric shape, the size of the dust structure and its stability are discussed in this report. Additionally, the dust component is used for the diagnosis of the glow discharge, because it reflects the geometric size of the dust trap. Experiments showed the tendency of the generated dust clouds to compress in the direction perpendicular to the magnetic field and lengthen along the magnetic field.

1. Introduction

Since the first experimental studies of dusty plasma [1–3] in a magnetic field, the results were found to be closely related to the geometric parameters of the dust structures. The type of gas discharge (DC or RF) was found to be essential for the type of geometry of the generated structures because it shapes a three-dimensional or a two-dimensional plasma-dust object even in the absence of a magnetic field.

The works [4–6] were devoted to the studies of flat dust clusters in a magnetic field. In these works, 2D objects were generated in the plane perpendicular to the magnetic field. In small systems [5, 6], it was found that the number of dust grains in the cluster affects the plasma flows and, consequently, the force characteristics and the dynamics of the cluster rotation. In [4], both small clusters and large dust formations were created. Ring-shaped structures were found and the melting of the dust cluster due to the viscous flows in its different regions was observed in the presence of a magnetic field.

In DC discharges, both in dust traps of special design [7, 8] and in striations of the glow discharge [9–12], spatial dust structures are formed. The application of a magnetic field causes a change in the discharge parameters and consequently, the changes in the geometric shape of the spatial dust formations. In this case, the visualization of the boundary of the dust structure shows the line of the force equilibrium and the equipotential surface. The changes in the profile of the dust structure, i.e., its transition from convex to concave, are clearly seen in a weak magnetic field in the striation, Fig. 1.

In this paper, a comparative analysis of the geometric parameters of dust structures created in a DC discharge in a strong magnetic field with induction up to 1 T is carried out [13–16].

2. Experiment

An experiment on creation of dusty plasmas in a strong magnetic field was carried out using a cryomagnet. A 20-cm-long superconducting solenoid generated a magnetic field of up to 1 T with
a degree of uniformity of 0.1% in the observation region. The glow discharge was ignited in a discharge tube with an inner radius of 1 cm using cold nickel electrodes placed outside the magnetic field region. The working gas was neon. To realize the stratified mode, a dielectric insert was placed in the discharge tube, which narrowed the current channel. The discharge tube was placed inside the warm hole of the cryostat of the superconducting magnet. On the side of the tube, a periscope system used for the illumination of the discharge region was placed. Observations of the horizontal cross section of the dust structure were made through the optical window on the upper end of the discharge tube. The video recording of the discharge was realized from a distance of 135 cm using a video camera with a 25 fps shooting frequency.

Figure 1. The changes in the shape of the dust structure in the striation with increasing magnetic field. Conditions: working gas neon, pressure 0.7 Torr, magnetic field: 0 T (a), 0.034 T (b), 0.04 T (c) at a discharge current of 2 mA and 0.04 T at a discharge current of 3 mA (d).

The experiments were carried out as follows. The discharge was ignited without a magnetic field, then dust grains were injected into it. When using a polydisperse quartz powder, dust structures formed in the glow discharge in two types of traps: in the striations and in the area of the discharge over the narrowing of the current channel (typically in the shape of a ring) and inside the narrow cone of the insert, similarly to [17]. When using calibrated grains from melamine–formaldehyde with a diameter of 4.1 µm, the structures formed in striations and inside the insert. When using 1.1-µm-diameter melamine–formaldehyde grains, the structures were formed in all of these dust traps. In the magnetic field range up to 1 T, the experiment could be carried out only with quartz grains.

3. Results and conclusions
After the dust structure was formed, the selected cross section of the discharge was visualized by lateral horizontal illumination; it was photographed or a video of the discharge was recorded. Then a magnetic field was imposed or a new value of the magnetic field was set, and the horizontal illumination system was moved to the new position of the discharge section under study. Thus, in a certain range of the vertical coordinate \( h \), the described method was used to estimate the vertical size of the dust structure in the magnetic field. A longitudinal elongation of the dust structure was recorded, which could be of the order of the original structure length or significantly larger. For example, if the dust trap (striation) shifted and left the area of the highly uniform magnetic field at the new value of the magnetic field, the dust formation could acquire a longitudinal size of several
centimeters (the initial size being of 0.5 cm). Due to the technical difficulty of observations inside the cryomagnet, it is not yet possible to unambiguously relate the observed elongation of the dust structure to either the elongation of the striation or the appearance of a stable dust trap in the area between the striations.

In the magnetic field range 0.2–0.3 T, where the current–convective instability of a longitudinally homogeneous discharge [18–19] should exist, in a number of experiments, an instability of the dusty plasma and partial loss of the dust component were observed in striations. This was accompanied by a decrease in the angular velocity of the structure rotation in the magnetic field, which was studied in detail under identical discharge conditions in [13]. When the magnetic field was increased further, the discharge became stable again in all the studied magnetic field range up to 1 T. When the magnetic field was increased, the horizontal size the dust structure gradually decreased regardless of the initial size of the structure created without the magnetic field (100–1000 grains in the horizontal cross section), Fig. 2.

![Figure 2](image.png)

**Figure 2.** Horizontal cross sections of the dust structure in the striation. Conditions: pressure 0.6 Torr, discharge current 1.4 mA, magnetic field: (a) 0.09 T, (b) 0.25 T, (c) 1 T.

Thus, the observation of the size and shape of the dust formation in the striation in a strong magnetic field provides a qualitative picture of the change in the geometric shape and spatial position of the dust trap. The qualitative results obtained in this work are schematically presented in Fig. 3. The observed trends allow a qualitative interpretation of the dependence of the angular velocity of the dust structure rotation in the striation in a strong magnetic field measured in [13]. The deceleration of the increase in the angular velocity in the magnetic field region of 0.1 T is probably caused by the elongation of the dust structure and its rising over the head region of the striation, which moves the structure into a region of the striation where the effect of the eddy electron current is small.

The radial compression of the horizontal cross section of the dust structure in a glow discharge in a magnetic field can be compared with the data on the dust structures in an RF discharge found in literature. For example, in [14], the RF discharge in a magnetic field of the order of 1 T was divided into separate vertical "threads". The dust structure was divided into separate vortices, the size of which was comparable to the size of the compressed horizontal sections observed in the strata of a DC discharge. However, in the experiments in the glow discharge discussed above, we obtained not a monolayer of dust, like in the RF discharge, but a spatial dust structure.

Estimates of magnetization were performed for a magnetic field at which the change in the geometry of the structure was observed. At a magnetic field about 0.1 T (the dust structure was reconstructed, the angular velocity changed the magnetic field derivative), the magnetization of electrons is \( \omega_e \tau_e = 10 \) and the magnetization of ions is \( \omega_i \tau_i = 0.1 \). The full magnetization of the plasma is \( \omega_e \tau_e, \omega_i \tau_i = 1 \). This means that under our experimental conditions, starting with the magnetic field of 0.1 T, the ambipolar field and the coefficient of ambipolar diffusion, which depend on the total magnetization of plasma particles, begin to decrease:
This magnetization may be the cause of changes in the geometry of the dust trap.

**Figure 3.** Schematic of the shape of the dust structure in the striation. (a) without the magnetic field and (b) in a strong magnetic field.

**Acknowledgments**

The experiment was supported by RSF grant No. 18-12-00009, estimations of the magnetization were carried out with the support of RFBR grant No. 18-02-00113.

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