Reasons for rotating of dust structure in a highly non-uniform magnetic field

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Abstract. A study of a dust trap in a glow discharge in highly non-uniform magnetic field is carried out. The trap is near the end of the solenoid on the side of the anode part of the discharge; it exists only in the magnetic field and it is resistant to its change. In the trap a volume dust structure is formed and comes into rotation with angular velocity of about 10 rad/s depending on the conditions. The interpretation of the reasons of rotation of the dust structure in the detected dust trap is given. Four physical processes known from literature are considered; numerical estimates are made. A feature of the dust trap being studied is a highly non-uniform magnetic field in which the discharge current channel expands and its radial component appears. Ampere force action due to radial component of current and longitudinal component of magnetic field is taken as the reason of dust structure rotation. The numerical estimate for the average section gives the value from 2.5 to 10 rad/s depending on the assumption of the radial component of the current.

1. Introduction

When studying dust plasma [1–3] for engineering and technological applications, the study of bulk plasma-dust formations localized at the walls of a plasma installation in the presence of a strong magnetic field is of particular interest. Among experimental studies of dusty plasmas in the strong magnetic field, for example, [4–8], only two works were carried out with volumetric dust structures [7, 8]. But all studies were performed in the uniform magnetic field. In this work, dusty plasma in the form of a bulk dusty structure created in a highly non-uniform strong magnetic field is studied for the first time.

2. Experiment and results

The following results were obtained using the experimental setup described in [7–9] and shown schematically in figure 1. When scanning the dust structure along the axis of the discharge tube, it is found that a standing striation is formed outside the solenoid near its end on the anode side in the strong magnetic field. The volumetric dust structure is formed inside and comes into a sufficiently fast rotation on the order of 10 rad/s depending on the conditions. Angular velocity is directed opposite to magnetic induction vector. The detected dust trap is the significantly distorted striation (see figure 1). It is in an area of a strongly declining magnetic...
The described pattern of the dust structure formation and its rotation remains stable until the maximum of magnetic field in the superconducting solenoid.

The horizontal sections of the dusty structure were scanned in a magnetic field (at the center of solenoid of 7500 G) under conditions: neon gas, pressure $p = 0.63$ Torr, discharge current 1.5 mA, tube radius 10 mm. The angular velocity of rotation depending on the vertical coordinate $h$ was determined by the video records [see figure 2(a)]. Coordinate $h = 0$ corresponds to the centre of solenoid. Dependence of dust structure diameter on vertical coordinate is shown in figure 2(b). Points 1 and 2 on the plots of figures 2(a) and 2(b) correspond to horizontal sections shown on the scheme of the experimental setup. The dust trap was located in the varying magnetic field; an example of the longitudinal gradient of the magnetic field is shown in figure 3(a). It is found that in the central part of the section where the discharge tube is located, the radial gradient of the longitudinal magnetic field is very small [see figure 3(b)]. Additionally, measurements of the radial component of the magnetic field have shown that it is more than an order of magnitude smaller than the longitudinal component of the field in the area of the dust structure. The steady-state value of the rotation velocity [for example, in figure 2(a) it is of 5 rad/s at maximum] did not change at increasing of the magnetic field in the solenoid center up to 20000 G (at increasing up to 2000 G at the solenoid end respectively).

3. Discussion

Note that the detected dust trap was stable when the magnetic field changed. It does not exist in its absence. This finding is the only possibility today to create dusty plasma in the strong but highly non-uniform magnetic field. Without discussing the formation of standing striation in the non-uniform magnetic field, we will try to interpret the reason of rotation of the dust structure in the detected dust trap. It appears that four physical processes known from the literature can be considered.

First, it is the ion drag force in striation. It is possible that distortion of the shape of the striation in this region results in the dominance of the rotation mechanism associated with the ion drag force at greater values of magnetic induction than is generally observed. Ion drag force can act when radial ion flow in the longitudinal magnetic field exist (with radial current and
Figure 2. (a) The dependence of angular rotation velocity of horizontal section of dust structure on vertical coordinate. (b) The dependence of diameter of horizontal section of dust structure on vertical coordinate. The upper end of the solenoid is located at $h = 100$ mm. Conditions: neon at pressure 0.63 Torr, discharge current 1.5 mA, magnetic field 7500 G. Polydisperse particles of quartz. Points 1 and 2 correspond to horizontal sections shown on the scheme of the experimental setup.

Figure 3. (a) Measured values of the vertical component of the magnetic field on the axis of the discharge tube in the area of structure levitation. The upper end of the solenoid is located at $h = 100$ mm, the center of solenoid is located at $h = 0$. (b) Measured values of the vertical component of the magnetic field depending on the radial coordinate: $h = 100$ (rhombus), 120 (squares) and 150 mm (triangles).

without it in the case of ambipolar diffusion). Ion dragging is proportional to magnetic field and ion density. Both of these factors are enhanced near the magnetic coil (the compressing of the current channel and the increasing the longitudinal component of the field). Both qualitative and quantitative estimates contradict the measurements [see figure 2(a)].

Second, it is a dragging by the rotating gas in the striation. This mechanism causes rotation of another sign then the observed one. It can be assumed that the substantially distorted striation in the non-uniform magnetic field is the dust trap only in the upper (non-compressed) part. At
Figure 4. The scheme explaining the mechanism of dust structure rotation caused by gradient drift of ions.

The same time in the head part of the striation, where are both the discussed mechanisms, due to striation distortion there are no conditions for levitation of the dust structure.

Third, it is possible to consider the gradient drift of ions in the non-uniform magnetic field [10]. In this area there is an azimuthal movement of ions caused by their gradient drift in \( \nabla B \) (directed radial) and in vertical \( B \). The expression describing the velocity of ion drift is

\[
v_{\nabla B} = \frac{1}{2} v_{\perp} \rho \frac{|B \times \nabla B|}{B^2},
\]

where \( \rho \) is the cyclotron radius of ion, \( v_{\perp} \) is ion velocity in the plane perpendicular to direction \( B \). The scheme explaining the mutual direction of \( \nabla B \), \( B \) and the angular velocity of dust particles rotation \( \Omega \), is presented in figure 4. But, according to the measurements made, the radial gradient of the longitudinal component of the field is extremely small [see figure 3(a)]. The numerical evaluation of ion drag force with ion drift defined by formula (1) gives the rotational velocity one to two orders of magnitude less than that obtained in the experiment.

Fourth, a feature of the dust trap being studied is a highly non-uniform magnetic field in which the discharge current channel expands, its radial component appears. Here, the Ampere force is possible because of the radial component of the current and the longitudinal component of the magnetic field, as well as because of the effect of the radial component of the field on the discharge current. According to our estimates, the last reason leads to the rotation of the gas with the velocity that is an order of magnitude less.

We concluded that the observed rotation of the dusty plasma is caused by Ampere’s force when the longitudinal component of the magnetic field acts on the emerging radial current component near the end of the solenoid. The expression for angular rotation velocity can be obtained by equating the moment of Ampere force \( M_B \) to the moment of viscous friction force of the discharge gas against the discharge tube wall \( M_\eta \). Expression defines the \( M_B \) value:

\[
M_B = [j_r \times B] S \Delta r r_{av},
\]

where \( j_r \) is the radial component of the vector of current density, \( S \) is the area of a cylindrical surface of radius of \( r_{av} = (r_1 + r_2)/2 \), \( \Delta r = r_2 - r_1 \) is the change of radius of cross section of the discharge.

The expression defines the value of the \( M_\eta \):

\[
M_\eta = 2\pi \eta \Omega_\eta r_{av} R_0 h,
\]
where $R_0$ is the radius of the tube, $\Omega_\eta$ is the angular velocity of the gas, $\eta$ is the viscosity of the gas.

The rotational velocity of the gas (and the section of the dust structure) is given by

$$\Omega_\eta = \frac{j_r B r_{av} \Delta r}{\eta R_0}.$$  \hspace{1cm} (4)

The numerical estimate for the average section yields $\Omega_\eta$ from 2.5 to 10 rad/s depending on the assumption about the radial component of the current.

4. Conclusion

The dusty plasma in the glow discharge in highly non-uniform magnetic field was studied in the work. The stable dust trap containing the volume dust structure was detected. Quantitative measurements of the rotation velocity of the structure in the magnetic field were made, the geometry of the dust structure and the non-uniformity of the magnetic field were defined. Possible reasons of rotation were considered, quantitative estimates were carried out. Mechanism of dust structure rotation, which is connected with action of Ampere force due to radial component of current and longitudinal component of magnetic field, was chosen.

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