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DUST TRAP IN A GLOW DISCHARGE IN THE REGION OF A STRONGLY INHOMOGENEOUS MAGNETIC FIELD

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INTRODUCTION

In the study of dust plasma [1-3] for engineering and technological applications, it is of particular interest to study volumetric plasma-dust formations localized near the walls of plasma installation in the presence of a strong magnetic field. Among experimental studies of dusty plasma in the strong magnetic field, for example, [4-6], only two works were carried out with volumetric dust structures [7-8]. But all studies were performed in the uniform magnetic field. This paper first studies dusty plasma in the form of the volume dust structure created in the highly non-uniform strong magnetic field.

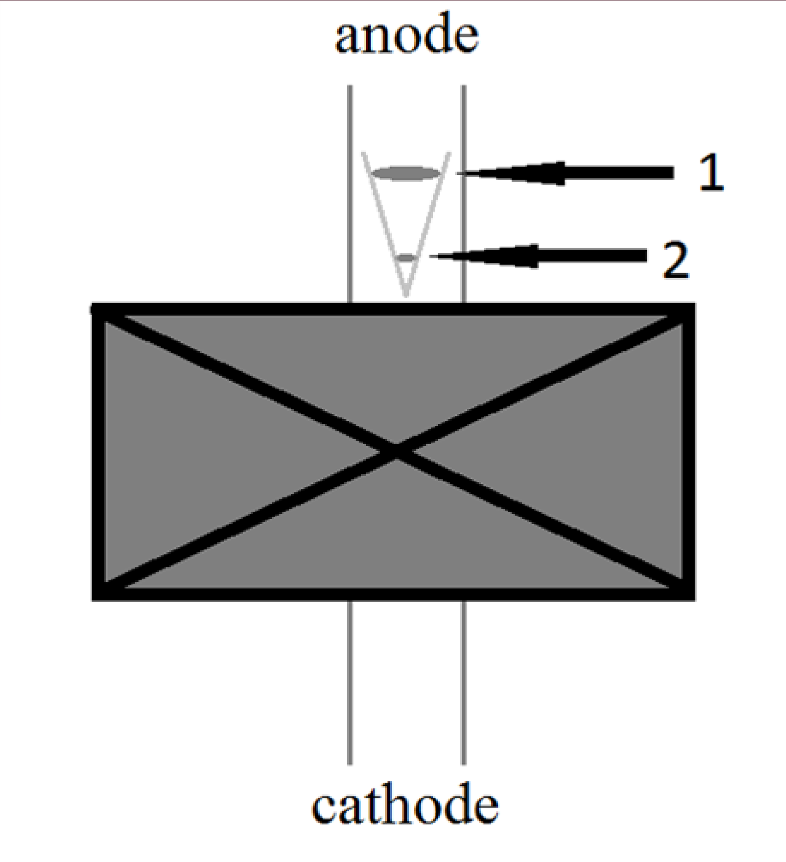

Fig. 1.Scheme of the experiment. The numbers indicate horizontal sections corresponding to angular velocity and diameter measurements in Fig.2 and 3.

EXPERIMENT

The following results were obtained on the experimental setup described in [7-9] and schematically shown in Fig. 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 from the anode part 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 (Fig.1). It is in the region of the strongly declining magnetic field (at the end of the solenoid from 1000 G to 50 G). 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 dust structure were scanned in magnetic field in 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 was determined by the video records, Fig.2. Change of dust structure diameter from vertical coordinate is shown in Fig.3. The dust trap was located in the varying magnetic field; an example of the longitudinal gradient of the magnetic field is shown in Fig.4a. 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, Fig.4b. 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 Fig.2 it is of 5 rad/s at maximum) did not change at increasing of the magnetic field in the solenoid center up to 2 T (at increasing up to 2000 G at the solenoid end respectively).

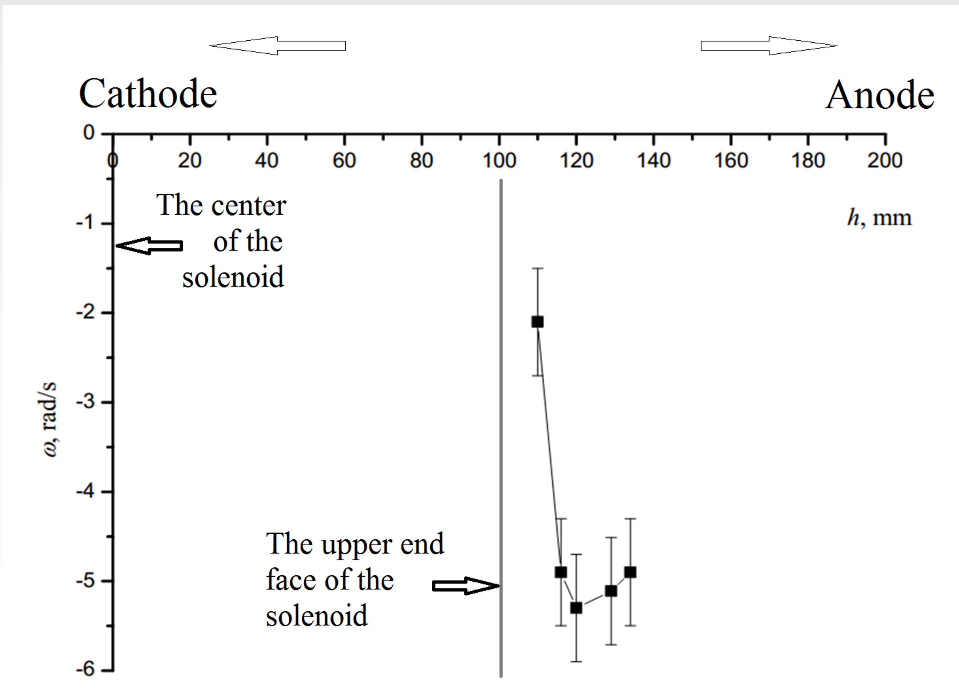

Fig. 2.The dependence of angular rotation velocity of horizontal section of plasma-dust structure on vertical coordinate. Conditions: neon at pressure 0.63 Torr, discharge current 1.5 mA, magnetic field 7500 G. Polydisperse particles of quartz.

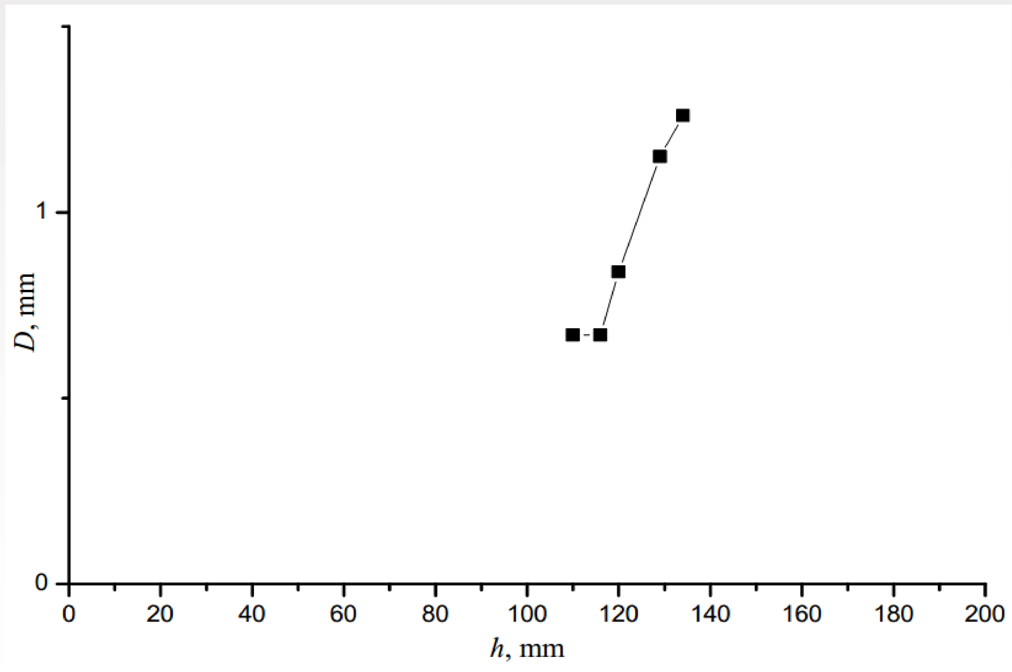

Fig. 3.The dependence of diameter of horizontal section of plasma-dust structure on vertical coordinate. Conditions: neon at pressure 0.63 Torr, discharge current 1.5 mA, magnetic field 7500 G. Polydisperse particles of quartz.

DISCUSSION

Note that the detected dust trap was stable when the magnetic field changed. It doesn't 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 can act when radial ion flow in the longitudinal magnetic field exist (with radial current and 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, Fig. 2.

Second, it is a dragging by the rotating gas in the striation. This mechanism causes the 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 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. In this area there is an azimuthal movement of ions caused by their gradient drift in ∇B (directed radial) and in vertical B. The expression describing the velocity of ion drift:

$$v_{\nabla B} = \frac{1}{2} v_{\perp} \rho \frac{\mathbf{B} \times \nabla \mathbf{B}}{B^2}, \qquad (1)$$

where ρ 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 ∇B, B and the angular velocity of dust particles rotation ω, is presented in Fig.5. But, according to the measurements made, the radial gradient of the longitudinal component of the field is extremely small, Fig.4. 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. Expression (2) defines the M_B value:

$$\mathbf{M}_B = (\mathbf{j}_r \times \mathbf{B}) S \Delta r r_{cp}, \qquad (2)$$

where $\mathbf{j}_r$ is the radial component of the vector of current volume density, S is the area of a cylindrical surface of radius of $r_{cp} = \frac{r_1 + r_2}{2}$, $\Delta r = r_2 - r_1$ is the change of radius of cross section of the discharge.

The expression (3) defines the value of the M_η:

$$M_\eta = 2\pi \eta \omega r_{cp} R_0 h, \qquad (3)$$

where R_0 is the radius of the tube, ω is the angular velocity of the gas, η is the viscosity of the gas.

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

$$\omega_\eta = \frac{j_r B r_{cp} \Delta r}{\eta R_0}. \qquad (4)$$

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

The measurements of the longitudinal component of magnetic field in the superconducting solenoid

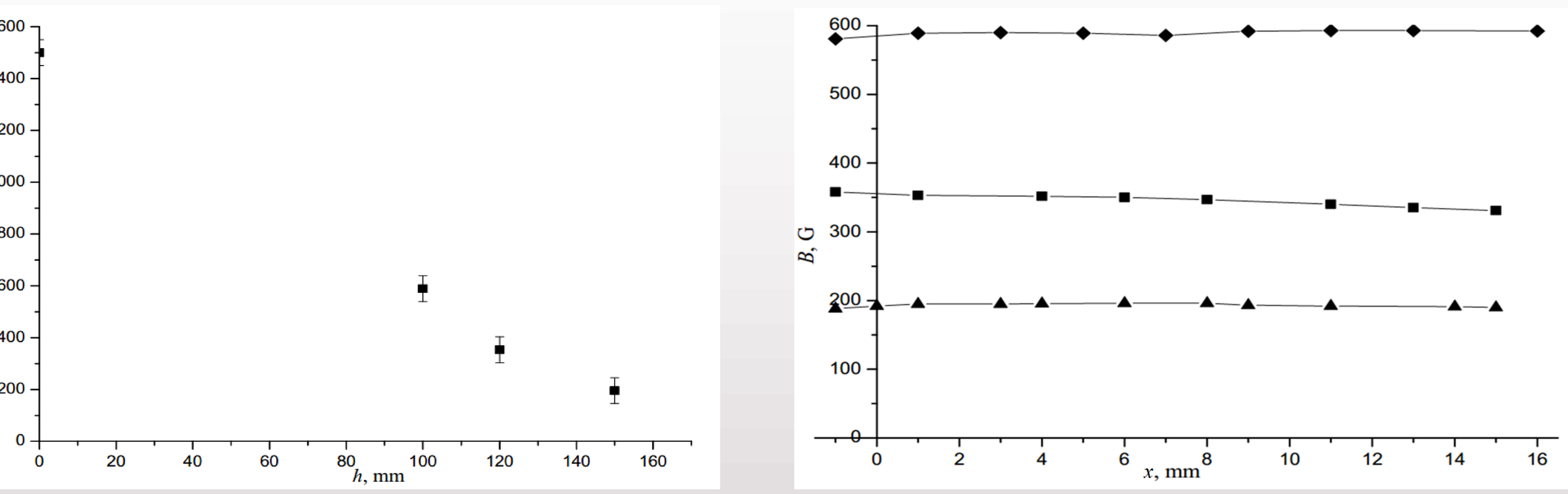

Fig. 4. (a) Measured values of the vertical component of the magnetic field on the axis of the discharge tube in the area of structure levitation. The upper end of the solenoid is located at h = 100 mm, the center of solenoid is located at h = 0. (b) Measured values of the vertical component of the magnetic field depending on the radial coordinate (x = 0 in the center of discharge tube). Rhombs: on h = 100mm, squares: on h = 120 mm, triangles: on h = 150 mm.

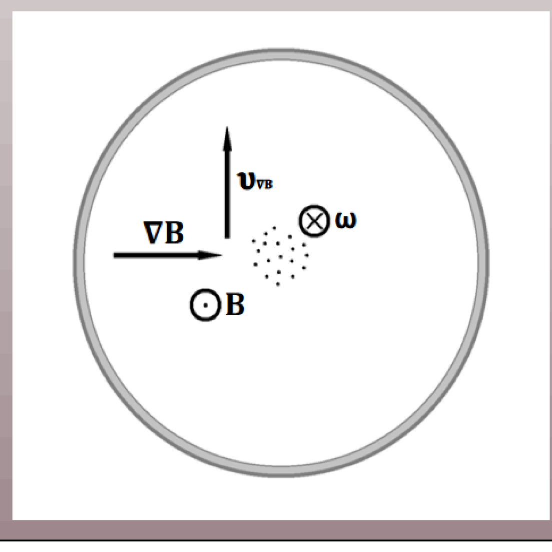

Fig.5. The scheme explaining the mechanism of dust structure rotation caused by gradient drift of ions.

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.

REFERENCES

1. Fortov V E and Morfill G E 2010 Complex and dusty plasmas: from laboratory to space (New York: Taylor & Francis Group)
2. Tsytovich V N, Morfill G E, Vladimirov S V and Thomas H M 2008 Elementary Physics of complex plasmas. (New York: Springer)
3. Bonitz M, Horing N and Ludwig P 2010 Introduction to Complex Plasma. (Berlin Heidelberg: Springer-Verlag)
4. Thomas E J, Lynch B, Konopka U, Merlino R L and Rosenberg M 2015 Phys. Plasmas. 22 030701
5. Schwabe M, Konopka U, Bandyopadhyay P and Morfill G E 2011 Phys. Rev. Lett. 106 215004
6. Melzer A, Kruger H, Schutt S and Mulsow M 2019 Phys. Plasmas. 26 093702
7. Dzlieva E S, D'yachkov L G, Novikov L A, Pavlov S I and Karasev V Y 2018 EPL 123 15001
8. Dzlieva E S, D'yachkov L G, Novikov L A, Pavlov S I and Karasev V Y 2019 PSST 28 085020
9. Dzlieva E S, Novikov L A, Pavlov S I and Karasev V Yu Technical Physics Letters. 44(10)

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