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Dynamics of dust structures in a dc discharge under action of axial magnetic field

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Abstract – Results of experiments on the formation of dusty plasma structures in a stratified dc discharge in axial magnetic fields up to 2500 G are presented. The rotation of the rather small and planar dusty plasma structures has been observed. As the field increases, the inversion of the structure rotation occurs, and when it reaches 700 G, the displacement of dust particles from the axial region of the discharge to the periphery, along with the rotation continuation, is observed. The explanation of the features in the dynamical behavior of the dust particles in the discharge, in particular the rotation inversion, is proposed.

A characteristic feature of dusty (complex) plasmas is the strong interaction between dust particles, which may lead to the formation of ordered liquid-like and crystal-like structures [1,2]. The investigation of the response of the dusty plasma to various external influences is of great interest, as one can control the spatial position, order degree, and dynamics of dusty plasma structures. Dusty plasmas may be affected by an external magnetic field. The axial magnetic field can lead to the rotation of the dusty plasma structures due to the tangential component of the ion drag force [3–12]. Experiments [3–12] were performed with high frequency and dc discharges in magnetic fields up to 400 G. However, Sato *et al.* [9] studied the effect of magnetic fields up to $4 \cdot 10^4$ G on dusty plasma clouds in an rf discharge and pointed to difficulties in obtaining a stable dc discharge in magnetic fields of about 10^3 G.

In this letter, we consider our experiment [13] on the formation of dusty plasma structures and investigation their dynamics in a dc glow discharge in axial magnetic fields up to 2500 G presenting some new details. The observed dynamics of the dust structures in magnetic fields is explained using improved version of our theoretical model [13] taking into account effect of neutral gas on the rotation of dust particles according to Nedospasov [14]. This effect was also recently investigated by Carstensen *et al.* [15].

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The experimental setup shown in fig. 1 was developed to investigate the effect of the magnetic field on dusty plasma structures. A stratified dc glow discharge was created in a vertically oriented cylindrical glass gas discharge tube with cold electrodes. The inner diameter of the tube was 36 mm and the distance between the electrodes was 600 mm. Spherical melamine formaldehyde particles 5.5 μm in diameter were used. The particles were placed in a container that had a mesh bottom and was located in the upper part of the discharge tube. They were injected into the discharge by shaking the container with the use of a piezoelectric plate. Experiments were carried out in noble gases (largely in neon) and hydrogen at pressures ~ 0.1 torr with discharge currents ~ 1 mA. Dust particles levitating in discharge striation were found to form bulk or rather planar structures. The electric field in a striation has an intricate configuration [16], and in fact each striation is an electrostatic trap, which can confine micron-sized particles in the axial region of the discharge.

A superconducting cylindrical solenoid located in a liquid-helium cryostat was used to generate a magnetic field. The gas discharge tube was placed in a so-called "warm hole" 150 mm in diameter at the center of the cryostat. A system of two identical monocular optical periscopes was developed for observation and diagnostics of dusty plasma structures in the discharge inside the warm hole. Each periscope is a cylindrical tube with glass

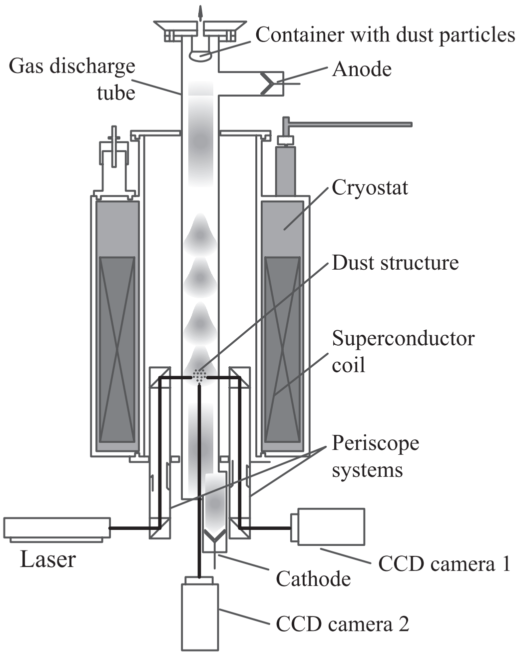

Fig. 1: Scheme of the experimental setup.

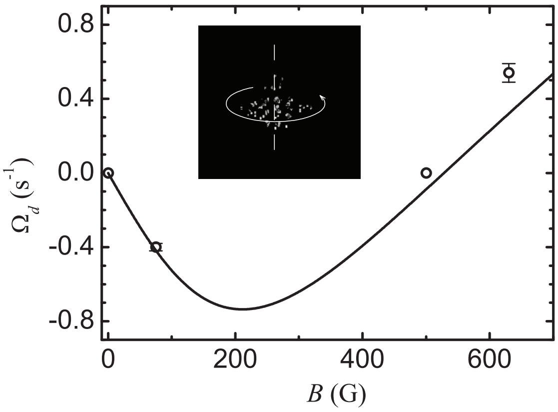

Fig. 2: Dependence of the angular velocity of a dust structure on the axial magnetic field, as experimentally observed (○) and as estimated by eq. (13) (- -). The inset shows the view of the structure rotation at $B = 630$ G.

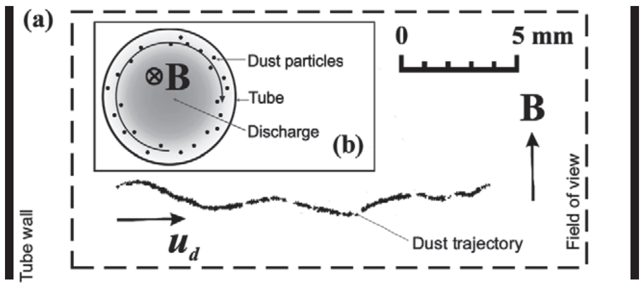

Fig. 3: Typical trajectory of the dust particle motion in the periphery of the discharge at 700 G: a) the superposition of consecutive video frames captured by the side view camera (the dashed rectangle represents the field of view of the periscope system in the central (axis) region of the discharge); b) sketch of the bottom view.

prisms located at its upper and lower ends. To observe the desired region of gas discharge plasma, each periscope can be vertically displaced by a distance equal to its working height (300–450 mm). The particles were illuminated with 532 nm laser radiation introduced into the warm hole via one of the periscopes. The dusty plasma structures were recorded by means of two CCD video cameras via the other periscope and via the lower flat end of the discharge tube. In this way the system allowed us to obtain images of both a side view and a bottom view of the dust structure.

The maximum value of the axial magnetic field, at which fixed striations were retained, was attained in hydrogen at a pressure of several tenths of a torr and was equal to 2500 G. However, no dust particles injected into the discharge could be registered in the observation region at this field. Structures of dust particles in a discharge in hydrogen were observed only in fields up to 10^3 G in the form of planar monolayers consisting of a small number of particles (up to 10^2).

Structures of different sizes were formed in neon, both almost planar and bulk ones (the results obtained for other noble gases were close to those for neon). Small and rather planar structures containing up to $\sim 10^2$ particles rotated about the vertical symmetry axis of discharge under the action of the axial magnetic field. In a field of 75 G, the rotation was counterclockwise if viewed in the direction of the magnetic field. As the field was increased, the rotation decelerated and then ceased at $B = B_0 \approx 500$ G. In a field of 630 G, the dust structure rotated in the opposite direction. Figure 2 shows the experimental angular velocities of the dust cloud in the stratum of the dc glow discharge for various magnetic fields. With the further increase in the field to 700 G, the particles forming the structure in the axial region of the discharge were displaced towards its periphery, *i.e.* towards the walls of the discharge tube (fig. 3). In this case, the angular velocity of the particles did not change and was found to be 1–2 rad/s. Small oscillations of the dust particles in the vertical direction were observed. These oscillations are likely caused by the instability of the glow discharge in the magnetic field. We have not observed any changes in the discharge structure, that is in agreement with experimental data for rf discharges [17], where the discharge filamentation was observed under the action of much more intense magnetic fields, $B \sim 10^4$ G. Bulk structures containing 10^3–10^4 dust particles were obtained in experiments with neon in fields below 300 G, however, their rotation was not observed. Further increase in magnetic field resulted in the degradation of the structure which lost most of the particles, became plane with the number of particles of $\sim 10^2$, and only after that began rotating.

Next we consider the cause of the inversion of the dust structure rotation. Dust particles are acted by the magnetic field through the discharge plasma, their rotation in the axial magnetic field occurs due to the ion

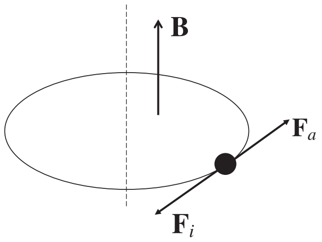

Fig. 4: Forces driving a dust particle in azimuthal direction under action of axial magnetic field.

drag forces [3–12]. The ion drag force in the uniform rotation is balanced by the force of friction against neutral gas atoms (see fig. 4). These forces, F_i and F_a, applied to a dust particle of radius a and charge $Z_d < 0$, can be estimated as [1]

$$F_i \cong \frac{8}{3}\sqrt{2\pi T_i m_i} a^2 n_i \left(1 + \frac{1}{2} z\tau + \frac{1}{4} z^2 \tau^2 \Pi\right)(u_i - u_d), \tag{1}$$

$$F_a \cong \frac{8}{3}\sqrt{2\pi T_a m_a} a^2 n_a (u_a - u_d), \tag{2}$$

where m_α, T_α, n_α and u_α are the mass, temperature, number density and velocity of particles α ($\alpha = i,\ a$); u_d is the dust particle velocity; $\tau = T_e/T_i$ is the electron to ion temperature ratio; $z = |Z_d|e^2/aT_e$ is the dimensionless charge of the dust particle, and Π is the modified Coulomb logarithm integrated over the ion velocity distribution function. From eqs. (1) and (2) and the equation $F_i + F_a = 0$ (which is the condition for the uniform rotation of the dust particle through a circle of radius r) and assuming that $u_d \ll u_i$, $T_i \approx T_a$ and $m_i = m_a$, we obtain

$$u_d(r) \cong \frac{n_i}{n_a}\left(1 + \frac{1}{2} z\tau + \frac{1}{4} z^2 \tau^2 \Pi\right) u_i(r) + u_a(r). \tag{3}$$

The ion azimuthal velocity u_i (we take $u_i > 0$ if the vector of corresponding angular velocity $\boldsymbol{\omega}_i$ is directed in the directions of magnetic field) is defined by two mechanisms (see, *e.g.*, [18]),

$$u_i(r) = \frac{-eE_r(r) + n_i^{-1}(r)\,\mathrm{d}(n_i T_i)/\mathrm{d}r}{m_i \omega_{iB}(1 + \nu_{ia}^2/4\omega_{iB}^2)}. \tag{4}$$

The first term in eq. (4) is due to the ion drift in the crossing radial electric E_r and axial magnetic B fields, and the second term is associated with the radial gradient of the ion pressure (diamagnetic ion current). It should be noted that the ion and electron drifts occur in the same direction with the same velocity, while the motion associated with the diamagnetic current has different directions for ions and electrons. Since the electron mass is much less than the ion one, the electron drag can be disregarded. It should be noted that we use here the approximation of uniform positive column disregarding stratification and assuming that the plasma parameters depend only on the radial coordinate. In the case of rather plane dust structure, this is acceptable. Ambipolar electric field orthogonal to the magnetic field is expressed by [18]

$$E_r(r) = -\frac{T_e}{e}\frac{1 - \beta(B)/\tau}{[1 + \beta(B)]n_i(r)}\frac{\mathrm{d}n_i}{\mathrm{d}r}, \tag{5}$$

where $\beta(B) = 2\frac{\omega_{iB}\omega_{eB}}{\nu_{ia}\nu_{ea}}$; $\nu_{\alpha a}$, and $\omega_{\alpha B}$ are the transport frequency of collisions with atoms, and the cyclotron frequency of ions ($\alpha = i$) and electrons ($\alpha = e$). We substitute eq. (5) into eq. (4) and assume that the ion temperature T_i be constant along the radius. Then we find the angular velocity of ions

$$\Omega_i(r) = \frac{u_i(r)}{r} = \frac{4\omega_{iB} T_i (1 + \tau)}{m_i[1 + \beta(B)](\nu_{ia}^2 + 4\omega_{iB}^2)}\frac{\mathrm{d}n_i/\mathrm{d}r}{r n_i(r)}. \tag{6}$$

In a first approximation, the radial density gradient of the ions $\mathrm{d}n_i/\mathrm{d}r$ may be estimated by assuming a Bessel profile of the radial distribution of charged particles in the striation [19] which does not contradict the measured data [16]. Then

$$\frac{\mathrm{d}n_i}{\mathrm{d}r} \approx -\frac{2.9 n_i(0)}{R^2} r, \tag{7}$$

where R is the radius of the discharge tube. We assume here that the radial distribution of charged particles is independent of the presence of small planar dust structures. Thus, $u_i < 0$, and the dust particles rotate counterclockwise (if viewed in the direction of the magnetic field) relative to the neutral gas.

Inserting eqs. (6) and (7) into (3), we find

$$\Omega_d \approx -\frac{n_i}{n_a}\left(1 + \frac{1}{2} z\tau + \frac{1}{4} z^2\tau^2\Pi\right)\frac{2.9}{R^2} \times \frac{4T_i(1+\tau)\omega_{iB}}{m_i(4\omega_{iB}^2 + \nu_{ia}^2)[1 + \beta(B)]} + \Omega_a. \tag{8}$$

In our paper [13] (see also review [20]), we assumed that the rotation inversion is associated with the change in direction of the radial diffusion flux of plasma, which occurs when the rate of plasma recombination on the dust particles becomes higher than that on the tube wall because of the plasma magnetization. However, such a cause would be more significant for rather large bulk structures, while in the case of small planar structure, the radial flux to the dust structure is not so important in comparison with the axial one. Here, therefore, we take into account the motion of neutral gas, and to estimate $\Omega_a = u_a/r$, we consider the mechanism discussed in recent paper by Nedospasov [14]. If the direction of the current in neutral gas is different from that of magnetic field, the gas is acted by the Ampere force (due to the collisions with charged particles), the density of which is $\mathbf{j} \times \mathbf{B}$, where $\mathbf{j}$ is the current density. So, in uniform column of a dc discharge in a tube with insulating wall under action of axial magnetic field, this force is absent. It can arise at the solenoid end faces, where the magnetic field has radial component causing the azimuthal Ampere force, and the torque can be transferred along the tube by the viscosity of gas. If this effect is significant, variations in the dust structure rotation should be noticeable when the discharge tube is shifted along the solenoid. However, we did not observe any similar variations. Such variations were not observed by Karasev *et al.* [12] too. It should be noted that even in uniform column of a discharge, neutral gas can rotate due to the interaction with plasma drifting in the crossing radial electric E_r and axial magnetic B fields. However, the corresponding velocity u_a is very small and can be disregarded (according to our estimations it is two or three orders smaller than u_d).

Another possible cause of the gas rotation can be associated with the nonuniformity of stratified dc discharge and modulation of plasma parameters along the tube [14]. Noncollinearity of gradients of electron density and temperature gives rise to eddy currents [21] which can be described by the following equation [14]:

$$\frac{e}{m_e\nu_{ea}}\nabla n_e\times\nabla T_e=-\mathrm{curl}\,\mathbf{j}. \tag{9}$$

The gradient of the electron density always has a radial component, and the gradient of the electron temperature in a stratified discharge has a longitudinal component since in the stratum head T_e is considerably higher than that between strata. Therefore, according to eq. (9), above and under the stratum head, there are axisymmetric circulations of radial and longitudinal currents. On the level of the stratum head this additional electric current is directed from the wall toward the axis, while in the region of lowest value of T_e it flows toward the wall. The density of the circular current is an order of magnitude lower than that of discharge current; consequently, it leads to a slight modulation of the main discharge current [14]. It should be noted that eq. (9) is derived without account of the magnetic field; however, it is enough for estimations, since the terms associated with the magnetic field have not appreciable azimuthal components.

Setting $|\nabla n_e|\approx n_e/R$ and $|\nabla T_e|\approx T_e/l$ (l is the length of the stratum, $l\approx 2R$) in eq. (9), Nedospasov has obtained the estimates for radial current and driving force and, as a result, the estimate for the neutral gas rotation velocity [14]

$$\Omega_a\approx\frac{1}{3}n_e\tau\sigma_a\frac{\omega_{eB}}{\nu_{ea}}\sqrt{\frac{T_a}{m_a}}, \tag{10}$$

where σ_a is the gas-kinetic atomic scattering cross-section. This equation is a crude approximation and overestimates the gas rotation velocity in the region where the dust structure is placed. Indeed, it estimates the gas velocity in the horizontal layer where T_e is maximal (stratum head) and circular electric current is directed towards the axis. Here the gas rotates clockwise if viewed in the direction of magnetic field, while in the region where the circular current is directed towards the wall, the rotation direction is opposite. But the dust structure levitates some higher the stratum head, and here the gas velocity should be some slower than that given by eq. (10). Moreover, eq. (10) does not take into account the gas viscosity which apparently decreases the gas velocity. Thus, one should insert into eq. (10) an additional factor $b<1$.

Allowing for that $n_e=n_i=n$, $\Pi\sim 1$, $\tau\gg 1$, and $z\sim 1$, we get from eqs. (8) and (10) the approximate expression for the angular velocity of the dust structure

$$\Omega_d\approx n\tau\sqrt{\frac{T_a}{m_a}}\left[\frac{b\sigma_a\omega_{eB}}{3\nu_{ea}}-\frac{2.9z^2\tau^2\omega_{iB}\sqrt{T_i/m_i}}{R^2n_a(4\omega_{iB}^2+\nu_{ia}^2)[1+\beta(B)]}\right]. \tag{11}$$

It is constant along the radius that is in accordance with the observations. If the condition

$$\frac{b\sigma_a}{3m_e\nu_{ea}}>\frac{2.9z^2\tau^2\sqrt{T_i}}{R^2m_i^{3/2}n_a\nu_{ia}^2} \tag{12}$$

is valid, only clockwise rotation of the dust particles should be observed for all values of magnetic field.

For our experimental conditions $T_i\approx 300\,\mathrm{K}$, $n_a\approx 8\cdot 10^{15}\,\mathrm{cm^{-3}}$, $n\approx 10^8\,\mathrm{cm^{-3}}$, $\sigma_a\approx 2\cdot 10^{-15}\,\mathrm{cm^2}$, $\nu_{ia}\approx 2\cdot 10^6\,\mathrm{s^{-1}}$, $\nu_{ea}\approx 10^9\,\mathrm{s^{-1}}$, $\tau\approx 10^2$. Orbit motion limited approximation yields $z=2.2$ for neon. The value of the factor b is unknown, let us set $b=0.5$. Then we obtain

$$\Omega_d\approx 10^{-3}B\left[2-\frac{8}{(1+2\cdot 10^{-7}B^2)(1+10^{-5}B^2)}\right], \tag{13}$$

where B is in gausses. As is seen from fig. 2, this expression provides a good agreement with experimental data.

The comparison of the theoretical estimation given by eq. (11) with measured results by Karasev *et al.* [12] is presented in fig. 5. In this case

$$\Omega_d\approx 10^{-2}B\left[0.8-\frac{0.9}{1+1.3\cdot 10^{-6}B^2}\right], \tag{14}$$

and we have a qualitative agreement between theoretical estimation and experimental data and considerable quantitative difference. However, it should be noted that the dust particles used in experiment [12] were polydisperse and arbitrary in shape, so, the use of our estimations may be questionable.

Thus, the inversion of rotation of dusty plasma structure with increasing axial magnetic field may be explained by the competition between two mechanisms. The first is the rotation of the dust particles together with the neutral gas, but due to the eddy currents the angular velocity of the gas in the region of the dust structure location is clockwise relative to the magnetic-field direction. The second is the rotation of the dust particles under the action of the ion drag force in the opposite direction. In weak magnetic

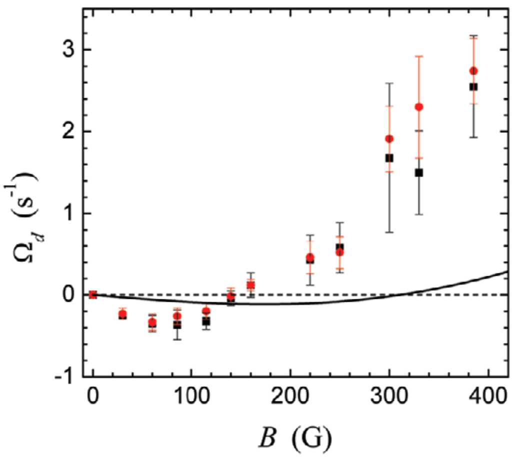

Fig. 5: (Colour on-line) The angular velocity of dust structure as a function of magnetic field in stratified glow discharge in neon at pressure of 0.7 torr and current of 2.5 mA [12]. The squares indicate the data for the top cross-section, and the circles for the bottom cross-section. The curve is the estimation by eq. (14).

fields, both the mechanisms cause velocities proportional to the field B, but the second predominates, and the rotation of the dust particles is counterclockwise. As the magnetic field increases, the second velocity decreases due to the plasma magnetization and becomes inversely proportional to B, then the first mechanism predominates, and rotation inversion occurs (in our experiment at $B = 500\,\mathrm{G}$).

With a further increase of the magnetic field, the radial electric field (5) decreases and cannot confine the dust particles at the axial region. Thus, they shift to the discharge periphery, as was observed in neon at $B \approx 700\,\mathrm{G}$. At still higher magnetic fields, the ions become more mobile than electrons (in eq. (5), the factor $1 - \beta/\tau \approx 1 - 10^{-6}B^2 < 0$), the wall acquires a positive charge, and the negatively charged dust particles stick to it. This result was apparently observed during experiments in hydrogen with magnetic fields $B > 10^3\,\mathrm{G}$. The stratification of discharge was still retained, but the injected particles were not found in the discharge volume. No charge exchange on the wall occurs in neon, because the discharge loses stability and decays before such a high magnetic field is reached.

The considered mechanism of the dust structure rotation can explain different angular velocities of different horizontal layers of the structure observed by Karasev *et al.* [12] (see fig. 4). In stratified dc discharge, the structure levitates above the region of the highest value of T_e (stratum head), where the gas rotates clockwise ($\Omega_a > 0$) with maximal angular velocity. Above the structure there is a region between the strata where the gas rotation is counterclockwise ($\Omega_a < 0$). So, in the region of the structure location, the vertical gradient $\mathrm{d}\Omega_a/\mathrm{d}h < 0$. Assuming that in the first approximation, azimuthal velocity of ions is independent of the vertical coordinate h, we obtain for the angular velocity of the dust structure $\mathrm{d}\Omega_d/\mathrm{d}h < 0$, that is in an agreement with observations [12].

To summarize, we have presented results of experimental investigations of the effect of axial magnetic fields on dusty plasma structures in stratified dc glow discharges in noble gases and hydrogen. We have observed the rotation of small structures (<10^2 particles). As the magnetic field increases, the rotation direction changes. When the field increases to 700 G, a displacement of the dust particles from the axial region of the discharge to its periphery, along with continued rotation, has been observed. An explanation of the rotation inversion of the dusty plasma structures and some other features in their dynamics has been proposed. The magnetic field at which the levitation of the dust particles in the discharge becomes impossible due to their falling on the wall of the gas discharge chamber has been estimated.

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