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# Rotation inversion of dust plasma structures in magnetic fields in a dc discharge

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Effect of magnetic field on formation and dynamical characteristics of dust plasma structures confined in electrostatic trap in the axial region of strata in dc glow discharge has been investigated. Experiments were carried out in discharge tube of inner radius 1.8 cm filled with neon at pressures ~$10^{-1}$ Torr with discharge currents ~$10^{-4}$ A. Spherical melamine formaldehyde grains 5.5 μm in diameter levitated in axial region of the vertical dc discharge and formed ordered structures. In the axial magnetic field, they rotate in the horizontal plane about the vertical symmetry axis of the discharge. The rotation seems to be a rigid-body one: the angular velocity of all the grains is the same. The rotation velocity depends on the magnetic field $B$. In low magnetic fields ($B \sim 10^2$ G) the angular velocity of the dusty cloud is directed against the magnetic field. With increase in the field, rotation is decelerated and terminated at 500 G. In the field $B \approx 600$ G the dusty structure was rotated in opposite direct. The dependence of the angular velocity of the dust plasma structures is presented in Fig. 1. With the further increase in the magnetic field up to 700 G dust grains went from the axial region to the discharge periphery with the continuation of the movement around the axis.

An explanation of the rotation inversion of the dust plasma structures in axial magnetic fields in dc glow discharge is the aim of the present paper.

The ions azimuthally drift in the crossed axial magnetic field and radial electric field, and the dust plasma structure rotation is due to the ion drag force [1,2]. In the uniform rotation, the ion drag force is balanced by the friction one with the neutral gas of atoms. These forces for the dust grain of radius $a$ can be estimated as [1]

$$F_i = -\frac{8}{3}\sqrt{2\pi T_i m_i}\, a^2 n_i \left(1 + \frac{1}{2} z\tau + \frac{1}{4} z^2\tau^2 \Pi\right) u_i \qquad F_a = -\frac{8}{3}\sqrt{2\pi T_a m_a}\, a^2 n_a u_a\,, \qquad (1)$$

where $n_\alpha$, $T_\alpha$, $m_\alpha$, $u_\alpha$, are the density, temperature, mass, and velocity of particles $\alpha$ ($\alpha = i, a$); $\tau = T_e/T_i$; $z = |Z_d| e^2 / aT_e$, $Z_d$ is the charge number of the grain, $\Pi$ is the modified Coulomb logarithm integrated with the velocity distribution function of ions. The magnetic field direction is taken as the positive angular velocity direction. Then, the angular velocity of the azimuthal drift is [14]

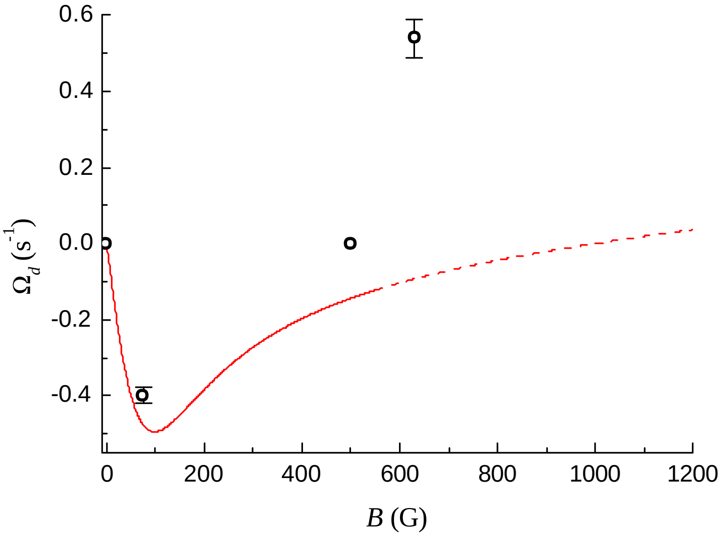

Fig. 1. Dependence of the angular velocity of the dust plasma structure on the axial magnetic field. Comparison of the theoretical estimation (5) given by curve with experimental data.

$$\Omega_i(r) = \frac{u_i(r)}{r} = -\frac{cE_r(r)}{rB\left(1+\nu_{ia}^2/4\omega_{iB}^2\right)}, \tag{2}$$

where $c$ is the speed of light in vacuum, $\nu_{ia}$ is the transport frequency of ion–atom collisions, and $\omega_{iB} = eB/cm_i$ is the ion cyclotron frequency in the magnetic field $B$. The radial electric field $E_r(r)$ is ambipolar and is determined by the expression [3]

$$E_r(r) = -\frac{T_e}{e}\frac{1-2\dfrac{T_I}{T_e}\dfrac{\omega_{iB}\omega_{eB}}{\nu_{ia}\nu_{ea}}}{\left(1+2\dfrac{\omega_{iB}\omega_{eB}}{\nu_{ia}\nu_{ea}}\right)}\frac{1}{n_i(r)}\frac{dn_i}{dr}. \tag{3}$$

As a result we get the expression for the angular velocity of the grain

$$\Omega_d \approx \frac{4T_e\omega_{iB}}{m_i\nu_{ia}^2}\left(1+\frac{1}{2}z\tau+\frac{1}{4}z^2\tau^2\Pi\right)\frac{1-2\dfrac{\omega_{iB}\omega_{eB}}{\tau\nu_{ia}\nu_{ea}}}{\left(1+2\dfrac{\omega_{iB}\omega_{eB}}{\nu_{ia}\nu_{ea}}\right)\left(1+4\dfrac{\omega_{iB}^2}{\nu_{ia}^2}\right)}\frac{dn_i/dr}{rn_a(r)}. \tag{4}$$

It is seen from (4) that the rotation inversion can be caused by (i) magnetization of electrons to a degree such that their mobility becomes lower than the ion mobility ($\omega_{iB}\omega_{eB} > \tau\nu_{ia}\nu_{ea}/2$) and (ii) a change in the sign of the radial component of the ion density gradient $dn_i/dr$, We now estimate the dependence of $\Omega_d$ on $B$ from (4) for the experimental conditions. Let us assume that the radial distribution in the stratum region near the discharge axis, where the dusty structure is located, has the Bessel profile, which does not contradict the measurements in [3]. The substitution of the experimental parameters $T_e \approx 3$ eV, $T_i \approx 300$ K, $\nu_{ia} \sim 10^6$ s$^{-1}$, $\nu_{ea} \sim 10^8$ s$^{-1}$, $n_a \approx 8\times10^{15}$ cm$^{-3}$. $z \sim 1$ yields the approximate dependence of $\Omega_d$ on $B$:

$$\Omega_d \approx -10^{-2} B \frac{1-10^{-6}B^2}{1+10^{-4}B^2}, \tag{5}$$

which is shown by the curve in Fig. 1. Since the effect of the magnetic field and dusty structure on the $n_i(r)$ distribution is disregarded in (5), this equation is valid only for small structures and low magnetic fields $B \sim 10^2$ G. Equation (5) provides a qualitatively correct magnetic field dependence of the angular velocity of the dusty structure and velocity values (for $B < 500$ G) close to the experimental data. Note that the rotation inversion following from (5) at $B \approx 1000$ G, is attributed to the magnetization of electrons (their lower mobility as compared to ions). However, in this case, the destruction of the potential trap confining the dusty structure should be expected, but this destruction is observed at higher magnetic fields ($B \approx 700$ G) than $B \approx 500$ G at which the rotation inversion occurs.

The rotation inversion is likely attributed to a change in the direction of the diffusion plasma flux: the derivative $dn_i/dr$ near the structure becomes positive. In this case, $dn_i/dr$ outside the dusty structure remains negative and the trap continues to exist. It is known that plasma recombination occurs on the surface of dust grains; i.e., the plasma is absorbed by the dusty structure. If the ionization rate $I_i$ in the volume, where the grain structure is located, exceeds the rate of recombination on the dust grains $I_d$, then we have the diffusion plasma flux $I_0 = I_i - I_d$ from this volume and $dn_i/dr < 0$. In the opposite case $I_i < I_d$ we have the flux into this volume and $dn_i/dr > 0$. Thus, we should compare the rates $I_i$ and $I_d$. In the first approximation the ionization rate is independent on the grain structure and without the structure

$$I_i = I_0 = -2\pi rhD_{rA}\frac{dn_i}{dr}, \qquad D_{rA} = \frac{T_e + T_i}{\mu_{ia}\nu_{ia}\left(1+2\frac{\omega_{iB}\omega_{eB}}{\nu_{ia}\nu_{ea}}\right)}, \tag{6}$$

where $r$ and $h$ are the radius and height of the structure, respectively, and $D_{rA}$ is the ambipolar diffusion coefficient $D_{rA}$ in the radial direction perpendicular to the magnetic field [4]. We can estimate $I_d$ in the orbit motion limited approximation [1]:

$$I_d = \sqrt{8\pi T_i / m} a^2 n_i (1 + z\tau) N_d \,, \tag{7}$$

where $N_d = \pi r^2 h l_d^{-3}$ is the number of the dust grains in the structure, $l_d$ is the mean intergrain distance. So we can compare $I_0$ and $I_d$. It should be noted that the flux $I_0$ has the radial direction, while the plasma absorption by the grains occurs in different directions. So the effect of the magnetic field on $I_0$ is much stronger.

In low magnetic fields $B \sim 10^2$ G the ionization rate $I_i$ prevails over the rate of recombination on the grains. As the magnetic field increases, the plasma is magnetized and the radial flux toward the wall $I_0$ decreases, consequently the ionization rate $I_i$ is also decreases when the discharge current is unchanged. As a result, at a certain $B$ value (at $B \approx$ 500 G in our experiment), the total plasma flux on the dust grains becomes larger than the charged-particle flux generated in the discharge near the dusty structure. Therefore, the inversion of the radial plasma flux occurs in the central discharge region and leads to the change in the rotation direction of dust grains. Comparing (6) and (7) we fined that $I_i = I_d$ at $B \approx 300$ G that is close to the experimental value 500 G corresponding to the rotation inversion.

With the further increase in $B$, the inversion region of the diffusion flux is expanded, the potential trap disappears, and the dusty structure decays at $B \approx 700$ G. According to the experimental results, the trap disappears incompletely and is shifted to the peripheral region of the discharge.

Thus, we can conclude that the inversion of the rotation of the dusty plasma structure is a result of the competition of two the plasma fluxes: to the wall and to the grain surface. For low magnetic fields the first prevails. With the increase in $B$, the second becomes predominant as a result of the plasma magnetization.

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