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Detection of eddy current in the striation

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Abstract – The dynamics of the dust structures created in striations in the glow discharge in a magnetic field has a complex character which is shown in the inversion of the direction of the movement. The hypothesis of existence of eddy current in the striation which in the magnetic field causes the rotation of dust structures by means of the Ampère force has been offered and developed in the recent works of Nedospasov *et al.* and Dyachkov *et al.* In the present work, the experiment in which eddy current in various phases of striations is registered by means of probing dust particles is carried out. It is shown that for various discharge conditions and various magnetic fields the dragging by the rotating gas and the ion drag are the dominating forces defining the dynamics of dust structures in striations.

Introduction. – Complex plasma is an example of collectively interacting system in which the self-organization occurs [1–4]. The study of dynamics in such system has a great interest for a number of reasons: the investigation of the self-organization process, the diagnostics, the study of the mutual influence of a low-temperature plasma and dusty subsystem. One of the productive methods of studying a complex plasma consists in imposing an external influence and an observation of the response of the system. Imposing a magnetic field on low-temperature plasma with the dusty component has revealed new mechanical and thermodynamic properties, namely, change of the order of the system and kinetic temperature of the particles, of viscosity [5–8], as well as the magnetic properties because the dusty component possesses paramagnetism [9–11]. Probably the most interesting feature of dusty plasma in magnetic field is the complex dynamics of the rotational motion which shows an inversion of the direction angular velocity of the rotation of dust structure. A discovery of this phenomenon in the stratified glow discharge stimulated the emergence of a number of articles discussing possible mechanisms of the inversion of the rotation direction [12–16].

As a rule the magnetic field affects the dust particles through the plasma fluxes and the ion drag force is the dominating force. The electron component does not transfer a big impulse to dust particles but the magnetized electrons change the properties of the discharge and operate the fluxes of the heavy component of the gas discharge. For example, the change of the direction of the diffusive flux in [6] and the drift in the radial direction in [5] led to the change of the direction of the rotation of the dust structure in the magnetic field. In the stratified glow discharge the role of “hot” electrons in discharge processes is very important [17–19]. In the recent articles by Nedospasov *et al.* [12–14] the existence of electron eddy current in the moving and standing striations was predicted on the basis of [17]. In the magnetic field the eddy current forces the discharge gas to rotate and the dusty plasma is involved in this rotation. In [15] it is shown that this effect is capable to explain the results of the experiment [8] but the agreement with the experiment [7] turned out to be only approximate. The unambiguous explanation of the inversion of the rotation direction of dust structures in striations in the magnetic field is not present yet; therefore, the confirmation of the existence of eddy current in an experiment is an actual problem. Besides, the eddy current was investigated theoretically within the hydrodynamics model and the complete description of the processes in low-temperature plasma is possible only on the basis of the kinetic approach [18,19]; in this case the dusty plasma can serve as the method of diagnostics of kinetic processes in the glow discharge.

In the head of striation the eddy current is directed radially to the axis of the discharge tube [12]. In this area the electron temperature has the maximum value and it is possible to expect the maximum of the Ampère force causing the rotation of gas with the positive projection of the angular velocity to the direction of the magnetic field. In complex plasma the direct measurement of this predicted rotation is impossible because the dust structure levitates in the trap which is placed above the given area. In the area of levitation of the dust structure there can be two mechanisms causing the rotation of the dust particles with the angular velocity having a negative projection to the direction of the magnetic field. These are the ion drag force and the dragging by the rotating gas owing to the Ampère force associated with the component of eddy current directed radially from the discharge axis. The experiment [20] in which the ion drag force was varied allows us making the choice between the models in this area of the discharge.

It was implemented by probing the whole area of the striation including parts where the dust structure does not levitate but the gas rotation can exist owing to the eddy current. Gravity-driven dust particles were used for probing the discharge.

Experiment. – The search of eddy current was carried out in the area of the discharge where the first striation and the lower part of the second ones were situated. The stratified positive column of the DC discharge was placed in the vertical magnetic coils, the experimental setup was the same as in [7]. The probing was done by dust particles falling through the discharge. The radial coordinate r of the probing dust particle is defined by the balance of the thermoforetic and radial electric forces. In experimental conditions it was $1.5 < r < 5.5\,\text{mm}$ for the particles of the minimum size and $6 < r < 11\,\text{mm}$ for the particles of the maximum size depending on the h. The fact that the radial coordinates of the probing particles are not equal to zero allowed to determine the angular velocity from the trajectory of particles. The area of probing was illuminated from the side in a gap between coils. The observation of the azimuthal movement of dust particles was done from above through the end face optical window of the tube. The quantitative measured value was the angular velocity of particles. It was defined depending on the vertical h and radial r coordinates under the chosen conditions of discharge and the induction of the magnetic field. A video filming of the azimuthal projection of the movement of the probing particles was made with a frequency of 25 frame/s. The investigated area was illuminated with the help of the parallel beam of the laser with thickness of 3 mm which lit the whole horizontal section of the tube. The examples of images of the section are presented in fig. 1. After the measurement at the certain vertical coordinate h was done, the illumination was shifted by 3 mm for the following measurements.

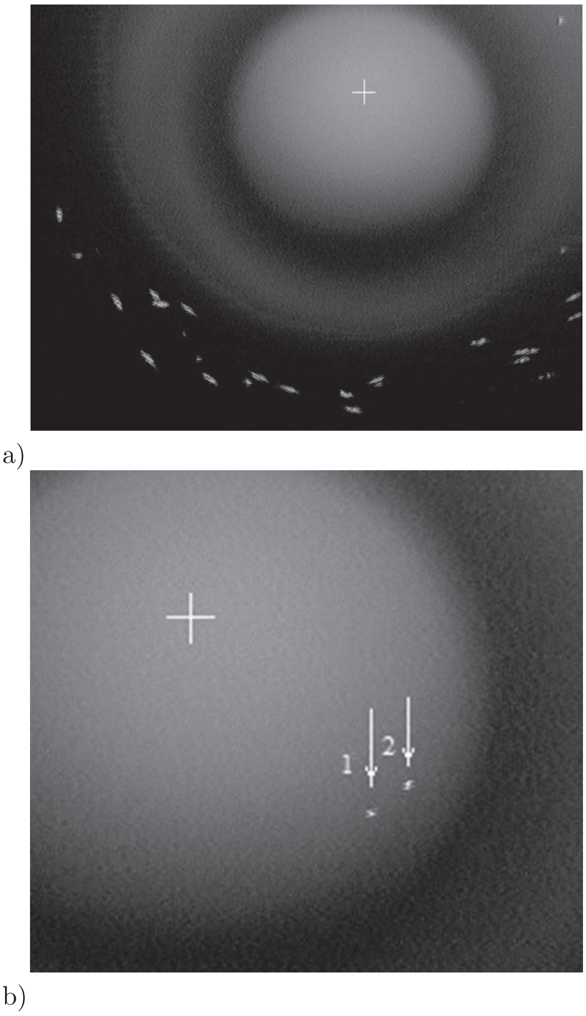

Fig. 1: Determination of the angular velocity of falling particles. The discharge axis is denoted as a cross. Conditions: neon, $P = 2\,\text{torr}$, $I = 1.6\,\text{mA}$, particles $1.1\,\mu\text{m}$. (a) Seven consecutive frames are presented. The particles fall at the average distance from the axis $\langle r\rangle = 5.5\,\text{mm}$ and have the average angular velocity $\langle\omega\rangle = (0.3 \pm 0.1)\,\text{rad/s}$. (b) Two frames where the initial (1) and final (2) positions of particle are shown. The particle falls at the distance from the axis $r = 2.4\,\text{mm}$ and has angular velocity $\omega = (0.90 \pm 0.08)\,\text{rad/s}$.

For an evidence of the applicability of the probing technique for the measurement of the gas rotation velocity we will do an assessment of the time during which the probing particle gets the gas velocity. Under the conditions of the experiment the particles are dragged by the gas because of an action of the friction force of Epstein [1]. Solving the equation of the movement of the particle with size a and mass m in the azimuthal direction

$$m\frac{\mathrm{d}v_\varphi}{\mathrm{d}t} = -\frac{8\sqrt{2\pi}}{3}a^2 P\frac{v_\varphi}{v_T}, \tag{1}$$

where v_φ is the azimuthal velocity of the particle relatively to the gas, P is the pressure, v_T is the thermal velocity of the gas, we receive the expression for the dependence of the velocity of the particle on time. According to this equation we have the expression for the time during which the particle velocity will change in e times,

$$t = \frac{3mv_T}{8\sqrt{2\pi}a^2 P}. \tag{2}$$

The assessment shows that the time is about 1 ms for the particle with size $1\,\mu\text{m}$ in neon with pressure 2 torr.

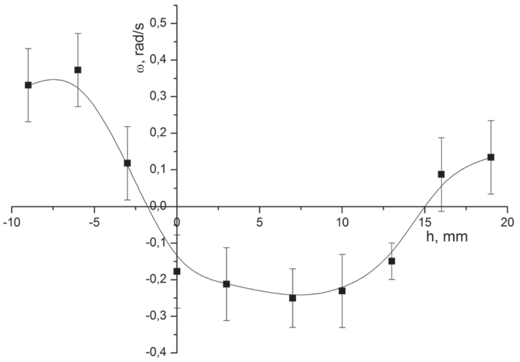

Fig. 2: The dependence of the projection of the angular velocity of rotating probe particles on the vertical coordinate along striations. Conditions: neon 2 torr, $I = 1.6\,\text{mA}$, $B = 120\,\text{G}$, melamine-formaldehyde particle with diameter $4.1\,\mu\text{m}$. As a starting point we consider the border of the luminous region of the first striation. The angular velocity is averaged over the probing cross-section ($6 < r < 10.5\,\text{mm}$).

Particles which cross the laser highlighting (3 mm) during three frames or 120 ms and more are registered in the experiment. Thus it is possible to claim that the azimuthal velocity of the probing particles will equal the gas rotation velocity. The experiment was carried out in neon with a pressure of 2 torr, discharge current of 1.6 mA and the magnetic field of 120 and 160 G. The calibrated monodisperse melamine-formaldehyde particles with diameters (1.10 ± 0.04) and $(4.10 \pm 0.14)\,\mu\text{m}$ were used as probing particles. The sharp standing striations existed under these parameters and the azimuthal movement of particles was observed during the necessary number of video frames. We have chosen the value of the magnetic field in which the competing processes defining rotation according to [7,8] could work.

Results and interpretation. – Figure 2 represents the results of probing of the hole investigated area of the discharge in the form of dependence of the angular velocity of particles with size $4.1\,\mu\text{m}$ on the vertical coordinate which counted from the shining border of striations to the anode side. It is visible in the schedule that in the center of the striation (in the area where particles levitate in [7], $h = 0$–$5\,\text{mm}$) the projection of the angular velocity of the probing particles to the direction of the magnetic field has negative sign. In the areas under and over the striation, the projection of the angular velocity has positive sign.

Then the part of the investigated area which is situated under the striation from the cathode side was studied in detail. The dependence of the angular velocity of particles with size $1.1\,\mu\text{m}$ on the vertical coordinate h in the area under the first striation is presented in fig. 3, for various radial coordinates r. Particles of smaller sizes probed the sections on smaller radial coordinates. The peak of angular velocity is present on the dependence under the first striation at the vertical coordinate $h = -(15$–$5)\,\text{mm}$. A similar peak is present in fig. 2, under the second striation at the vertical coordinate $h = 15\,\text{mm}$.

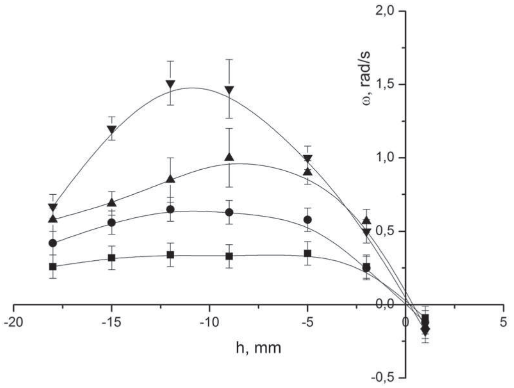

Fig. 3: The dependence of the projection of the angular velocity of rotating probe particles on the vertical coordinate in the head of striations for different radial coordinate r: ▼: $r = 1.5\,\text{mm}$; ▲: $r = 2.5\,\text{mm}$; ●: $r = 3.5\,\text{mm}$; ■: $r = 5.5\,\text{mm}$. Conditions: neon 2 torr, $I = 1.6\,\text{mA}$, $B = 120\,\text{G}$, melamine-formaldehyde particle with diameter $1.1\,\mu\text{m}$.

The probing shows that along one striation, fig. 2, the various mechanisms forcing particles to rotate in different directions work. For the interpretation we will execute estimates of the angular velocity of the rotation in areas with the maximum (the head of striations) and the minimum (the body of striations) of electron temperature. The mechanism associated with the dragging of the particles by the gas rotating under the influence of the Ampère force caused by the radial component of eddy current directed to the tube axis operates in the area in the head of striations. The value of the angular velocity of the particles can be estimated by the formula from [12–15],

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

where n_e is the concentration of electrons (which strongly depends on the vertical coordinate h [18,19]), $\tau = T_e/T_i$, σ_a the gas-kinetic section of scattering of the atom, ω_{eB} is the cyclotron frequency of the electron, ν_{ea} is the transport frequency of the collision of electrons with atoms. We will execute the numerical assessment of the angular velocity of the gas rotation using the following values of the parameters: $n_e \approx 3 * 10^8\,\text{cm}^{-3}$, $\tau \approx 100$, $\sigma_a \approx 2 * 10^{-15}\,\text{cm}^2$, $\omega_{eB} = 2.8 * 10^9\,\text{rad/s}$ (at $B = 160\,\text{G}$), $\nu_{ea} = 1.4 * 10^9\,\text{s}^{-1}$. The assessment gives the average value of the angular velocity of the radial coordinate $+0.43\,\text{rad/s}$. As the dependence of the angular velocity on the radial coordinate is not predicted in the models [12–15], we can compare the calculated value with the angular velocity observed for the radial coordinate close to the average, $r = 5.5\,\text{mm}$ in fig. 3, and the values are close. The angular velocity caused by another mechanism associated with ion drag can be estimated by the formula from [20],

$$\omega = \frac{U_{ir}}{r} \frac{\omega_{iB}}{\nu_{ia}} \frac{n_i}{n_a} \sqrt{\frac{T_i}{T_a}} \sqrt{\frac{m_i}{m_a}} \left(1 + \frac{z\tau}{2} + \frac{z^2\tau^2}{4}\Pi\right), \tag{4}$$

where U_{ir} is the radial speed of the flux of ions, r is the radial coordinate of the probing particle, ω_{iB} is the cyclotron frequency of an ion, ν_{ia} is the transport frequency of the collision of ions with atoms, $z = \frac{Z_d e^2}{aT_e}$ is the dimensionless charge of the particle, Z_d is the charging number of a particle, Π is the modified Coulomb logarithm integrated over the ion velocity distribution function. The assessment gives the value $\omega = -0.005\,\text{rad/s}$ for the studied area at parameters $U_{ir} \approx 300\,\text{m/s}$, $r \approx 5 * 10^{-3}\,\text{m}$, $\omega_{iB} \approx 0.75 * 10^5\,\text{rad/s}$, $\nu_{ia} \approx 1.5 * 10^7\,\text{s}^{-1}$, $n_a \approx 7 * 10^{16}\,\text{cm}^{-3}$, $Z_d \approx 10^3$ (for particles with $1.1\,\mu\text{m}$), $\Pi \approx 1$. Under these conditions the value of the ion drag force is very small because the pressure is increased in comparison with the pressure regularly used for the research of dusty plasma. In the examined area of the striations the dragging of particles by the rotating gas dominates. In the area located in the center of striations (the body of striations) at coordinates from $h = 5\,\text{mm}$ to $h = 10\,\text{mm}$ in fig. 2 both mechanisms lead particles to rotating in the same direction with negative projection of the angular velocity since eddy current in this area has the component directed radially to the wall of the tube [12–15]. The assessments of the rotation velocity owing to eddy current and ion drag give the values $-(0.15\text{–}0.20)\,\text{rad/s}$ and $-0.01\,\text{rad/s}$ (for particles of $4.1\,\mu\text{m}$). The dragging by the rotation gas dominates over the ion drag force. We will notice that in the area where the dust structure levitated in [7] ($h = 0\text{–}5\,\text{mm}$ of fig. 2) because of great values of n_e [18,19] and U_{ir}, the ion drag causes the angular velocity to be about $-0.1\,\text{rad/s}$ (for particles of $4.1\,\mu\text{m}$) so both mechanisms become comparable in action.

Conclusion. – The method of experimental detection of the action of eddy current in the striations of the glow discharge is presented. The technique is realized by means of the probing dust particles in the magnetic field under the pressure which is increased in comparison with the pressure used for the research of complex plasma. The dependence of the azimuthal projection of the particles velocity in a striation on longitudinal and radial coordinates is measured. Numerical estimates of the angular velocity of the rotation of the particles which are dragged by the rotation of gas because of the eddy current and ion drag force for various areas of striations are done. They revealed that under the conditions of the experiment in all areas of striations the rotation of gas owing to the Ampère force dominates over the ion drag force except for the area where the dust structure levitates (where n_e is maximum). In this area the dragging of particles by the rotating gas is comparable in magnitude with the action of the ion drag force. The ion drag force can dominate over dragging by gas at smaller pressure or in smaller magnetic fields as was observed in [7,8].

The detected action of the eddy current allows to define unambiguously the mechanism of the inversion of the rotation of dust structures in the striation; also it allows to use the dusty plasma as the instrument for studying the kinetic processes in striations.

* * *

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