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Motion of plasma-dust structures and gas in a magnetic field

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Numerous studies have revealed that the superposition of magnetic field causes plasma-dust structures to rotate in the plane normal to the field. The only explanation for this rotation found in the literature is that the plasma-dust structures are acted upon by the forces of ion entrainment (ion drag forces) from ions moving under the effect of the magnetic field in the azimuthal direction. However, this study demonstrates that the experimentally observed motion of plasma-dust structures cannot be explained by the forces of ion entrainment alone. We show that the observed motion of plasma-dust structures is further affected by their entrainment by gas rotating under the effect of the moment of force $\mathbf{I}\times\mathbf{B}$, which exists in regions of discharge with nonuniform magnetic field in the vicinity of solenoid end faces, as well as at the narrowing of cross section of the discharge channel. An eddy electric current exists in a discharge with strata in a uniform magnetic field; this current causes the rotation of gas and is associated with the noncollinearity of the gradients of plasma density and temperature. Estimates are provided for the density of this current and for its impact on the rotation of gas in a magnetic field. Recent experimental data by Karasev *et al.* [Phys. Rev. E **74**, 066403 (2003)] are discussed.

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I. INTRODUCTION

The investigations of plasma-dust structures (PDSs) usually involve the use of a striated discharge, in which the gravitational force acting on negatively charged dust particles is balanced by the electric field at the beginning of the stratum [1]. It is revealed by numerous investigations that the superposition of magnetic field causes the PDS to rotate in the plane normal to the field [2–8]. The only explanation for this rotation given in published papers is that the PDSs are acted upon by the ion drag forces from ions moving under the effect of a magnetic field in the azimuthal direction. This explanation further holds for uniform positive columns of discharges in tubes with glass walls parallel to a uniform magnetic field. In particular, a large amount of new and valuable information is provided by the review [7] on a series of studies performed in stratified positive columns of discharges in a longitudinal magnetic field.

It is demonstrated in this paper that the experimentally observed motion of PDSs cannot be explained by the forces of ion entrainment alone. In a number of cases, such explanation may lead to wrong conclusions. We argue that the observed motion of plasma-dust structures is further affected by their entrainment by rotating gas. Observations of the behavior of dust particles in plasma opened up new possibilities for fine measurements of gas and plasma motion in a positive column of discharge.

The hypothesis of rotation of a neutral gas in a discharge upon superposition of a magnetic field was suggested by Granovskii and Urazakov [9,10]. They found that a light rod with two wings at the ends, suspended from an elastic filament in a vertical positive column, turned through some angle when a permanent longitudinal magnetic field was switched on. The direction of the turn changed its sign with variation of the direction $\mathbf{B}$, but was independent of the direction of the current $\mathbf{I}$ in the column. Granovskii and Urazakov [9,10] inferred from this that the rotation of gas is not associated with the Ampére force $\mathbf{I}\times\mathbf{B}$, but is an intrinsic property of positive columns. They named this phenomenon the magnetomechanical effect and associated the rotation of gas with the Hall diffusion of ions and electrons transmitting different momenta to neutral gas in the azimuthal direction. The magnetomechanical effect was subjected to numerous investigations [11–14]; however, no physical explanation has yet been provided. No radial electric current is present in an axisymmetric discharge with dielectric walls, and the moment of force is $\mathbf{I}\times\mathbf{B}=0$ [11]. In this case, no rotation of gas and plasma will take place if we can only ignore the inertial drift of ions arising upon ionization of a gas in a magnetic field. In the experiments discussed here, the frequency of ion-atom collisions is much higher than the cyclotron frequency of ions, $\omega_i\tau_i \ll 1$; therefore, the disregard of inertial drift is valid.

It will be demonstrated below that the rotational moment of force $\mathbf{I}\times\mathbf{B}$ exists in regions of discharge with nonuniform magnetic field in the vicinity of solenoid end faces, as well as in the vicinity of the narrowing of cross section of the discharge channel. In addition, an eddy electric current exists in a discharge with strata in a uniform magnetic field; this current causes the rotation of gas and is associated with the noncollinearity of the gradients of plasma density and temperature in the strata.

II. PROCESSES OF TRANSPORT IN POSITIVE COLUMNS IN A LONGITUDINAL MAGNETIC FIELD

If the PDSs transfer the momentum they received from ions to the gas, it would seem that the gas must rotate at some low velocity. However, in the absence of the moment of forces, the rotation of PDSs and slow rotation of the viscous gas would contradict the laws of mechanics. Therefore, more detailed analysis is required of the impact made by the PDSs on a discharge in a magnetic field.

We will first consider an axisymmetric discharge without dust particles in a uniform longitudinal magnetic field in a glass tube of radius a with the walls parallel to $\mathbf{B}$. The stationarity of the discharge is provided by the balance of ion-

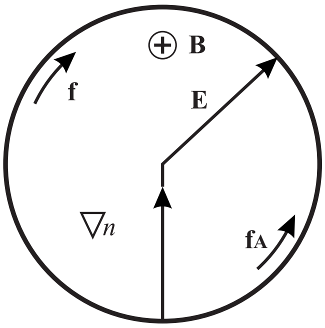

FIG. 1. Relative positions of magnetic fields (**B**), of the radial electric field (**E**), of the gradient of plasma density ($\boldsymbol{\nabla} n$), and of the forces acting on the gas ($\mathbf{f}, \mathbf{f}_A$).

ization in the bulk and by the recombination on the walls; the Joule heating is spent by electrons for ionization, radiation, and heating of gas. We will use right-handed cylindrical coordinates, in which the electric field **E** has components with respect to r and z; the uniform magnetic field is directed along the z axis. The concentrations of electrons and ions are equal ($n_e = n_i = n$); in so doing, $dn/dr < 0$. It is assumed that the electron and ion temperatures T_e and T_i are constant over the pipe cross section. For simplicity, we restrict ourselves to the conditions $(\omega_e \tau_e)^2 \gg 1$, where $\omega_e = e_0 B/m_e$ is the cyclotron frequency, and τ_e is the mean free time of electrons between collisions with atoms. For ions, $(\omega_i \tau_i)^2 \ll 1$, i.e., the effect of magnetic field on the radial ion motion may be ignored. The radial ion flow is defined by the equality

$$n v_{ir} = b_i n E_r - b_i T_i \nabla n / e_0. \tag{1}$$

Here, $b_i = e_0 \tau_i / m_i$ is the ion mobility, and T_i is the ion temperature. The radial ion current is acted upon by the Ampère force of volumetric density $\mathbf{f}_A = \mathbf{j}_{ri} \times \mathbf{B}$ directed in the azimuthal direction (counterclockwise in Fig. 1). It is transferred to the neutral gas by collisions.

Given the magnetization of electrons, an important part in their motion is played by the diamagnetic current due to incomplete mutual compensation of the electron rotation currents in the presence of gradient of n, as well as by the drift in the crossed **E** and **B** fields. The density of the diamagnetic current is

$$\mathbf{j}_{\mathrm{dia}} \times \mathbf{B} = \boldsymbol{\nabla} p_e, \tag{2}$$

where p_e is the electron gas pressure. The velocity of diamagnetic electron drift is $\mathbf{v}_{\mathrm{edia}} = (T_e / e_0 n)(\boldsymbol{\nabla} n \times \mathbf{h}/B)$, $\mathbf{h} = \mathbf{B}/B$. The velocity of azimuthal electron drift is $\mathbf{v}_{\mathrm{ed}} = (\mathbf{E} \times \mathbf{B})/B^2$. The azimuthal electron motion acts on the neutral gas by the friction force. The density of this force is

$$\mathbf{f} = n(\mathbf{v}_{\mathrm{edia}} + \mathbf{v}_{\mathrm{ed}}) m_e / \tau_e \tag{3}$$

(in Fig. 1, this force is directed clockwise).

The electrons are acted upon by a force $(-f)$ which develops a radial drift of velocity

$$\mathbf{v}_{er} = (\mathbf{f} \times \mathbf{B})/e_0 n B^2. \tag{4}$$

Hence the density of electron current to the tube walls, $-j = f/B$, which corresponds to the impact made on gas by the specific force $\mathbf{f} = \mathbf{j}_{er} \times \mathbf{B}$. Because the sum of currents to the insulating wall is $\mathbf{j}_{er} + \mathbf{j}_{ir} = 0$, the moments of Ampère forces from electrons and ions, which cause the rotation of neutral gas, are equal in magnitude and opposite in direction, as would be expected. This equality is further valid for positive columns under conditions of developing current-convective instability [15,16]. In the case of a turbulent positive column with magnetized ions [17], additional analysis is required. The polarization current must be taken into account, because the resultant ion during transition to motion in the crossed **E** and **B** fields shifts along the radius in the direction of the electric field.

In the absence of radial electric current, the intensity of the radial electric field is found from Eqs. (1) and (4),

$$E = -\frac{\nabla n [T_e - T_i (\omega_e \tau_e)(\omega_i \tau_i)]}{e_0 n [1 + (\omega_e \tau_e)(\omega_i \tau_i)]}. \tag{5}$$

In accordance with Eq. (5), the radial electric field may change its sign in strong magnetic fields. In the discharges discussed by us, $T_e \gg T_i$, and the change of sign requires an appreciable magnetization of ions $\omega_i \tau_i \approx 1$. In fact, when the magnetic field intensity increases due to end effects and current-convective instability, formula (5) ceases to be valid before the change of sign of E_r.

We will now return to the question of the forces acting on the gas in the azimuthal direction. Disregarding the ion diffusion in Eq. (1) ($n E_r \gg T_i \nabla n / e_0$), the ratio of azimuthal ion velocity $v_{i\varphi}$ to v_{ir} is equal to $\omega_i \tau_i$,

$$n v_{i\varphi} = b_i n E_r \omega_i \tau_i. \tag{6}$$

The friction force acting on the gas on the ion side is

$$f_A = b_i n E_r \omega_i \tau_i m_i / \tau_i = e_0 b_i n E_r B. \tag{7}$$

The azimuthal electron velocity according to Eqs. (3) and (5) will be written as

$$v_{e\varphi} = (-E_r / B) \omega_e \tau_e \omega_i \tau_i. \tag{8}$$

Relations (6) and (8) yield the ratio

$$|v_{e\varphi} / v_{i\varphi}| = \omega_e \tau_e / \omega_i \tau_i = b_e / b_i. \tag{9}$$

The ratio of azimuthal velocities of electrons and ions rotating in different directions is equal to the ratio of their mobilities, and the forces with which they act on a gas are mutually balanced.

We will now consider plasma with the addition of a number of charged microparticles, the negative charge of which is largely shielded by positive ions. It is assumed that the motion of electrons does not act on the particles (although the azimuthal velocity of electrons is two or three orders of magnitude higher than the ion velocity), and the ions act with ion drag forces proportional to the velocity of ion motion [1]. The addition of dust particles causes an increase in the average collision frequency of ions and a decrease in their mobility. Relation (9) of the equality of friction forces remains valid. However, if we assume that the electrons drifting in the azimuthal direction collide only with gas atoms, the ions transfer the momentum to gas partly through the intermediary of dust particles which are decelerated by the friction forces. The gas remains stationary by virtue of the fact that the motion of dust particles partly maintains the equilibrium of forces acting on the gas. Under these conditions, the measurement of the velocity of PDS motion could serve to test the validity of the theory of ion drag forces. However, violations of uniformity of discharge exist, the reasons for which are considered below.

III. IMPORTANCE OF END EFFECTS AND NARROWINGS OF THE CHANNEL

Experiments with discharges in longitudinal magnetic field are usually performed in tubes with the central part located on the solenoid axis and the ends outside the magnetic field. *At the solenoid end face on the anode side*, where the tube leaves the region of magnetic field, the longitudinal current crosses the lines of magnetic flux confined in the tube. The moment of force $\mathbf{I}\times\mathbf{B}$ exists here, which causes the plasma to rotate counterclockwise if viewed in the direction $\mathbf{B}$. It was this direction of rotation that was observed by Granovskii and Urazakov [9]. As a result of variation of its direction, the current on the "new" anode end face interacts with the field which has radial component of opposite sign. In so doing, the direction of the moment of force $\mathbf{I}\times\mathbf{B}$ is retained. It was the fact that the sign of rotation of gas is independent of the direction of current that misled Granovskii and Urazakov [9] and their followers. The rotation under the effect of $\mathbf{I}\times\mathbf{B}$ is transferred along the tube by the viscosity of gas and by closed currents. The counterclockwise rotation of dust structures was observed in weak magnetic fields [7].

At the solenoid end face on the cathode side, the electrons move in increasing magnetic field. When their motion becomes magnetized ($\omega_e\tau_e>1$), the current continues to flow along converging magnetic lines of force. In so doing, the cross section of the discharge decreases, and the discharge is focused on the tube axis. In the region of focusing, the radial electric field may become negative, because the magnetized electrons are largely held by the magnetic field, and the ions by the electric field. The region of negative field elongates with increasing intensity of magnetic field; in strong fields, the negative radial field exists over the bulk of the length of turbulent positive column [18,19]. In the adjoining part of the tube outside the magnetic field, the radial electric field defined by ambipolar diffusion is positive. Therefore, regions of plasma with different signs of E_r exist on both sides of the cathode end of the solenoid. Because the circulation of E in a closed circuit (along the discharge axis, in the radial directions, and along the walls) is zero, the electric current developing an additional moment of Ampère force flows in this circuit.

The focused current channel within the solenoid in uniform magnetic field gradually expands because of collisional or turbulent diffusion of electrons along the radius. The radial component of electric current directed toward the center causes the gas to rotate clockwise relative to the direction $\mathbf{B}$. Note that, even in the absence of longitudinal magnetic field, plasma disturbances in the positive column of low-pressure discharge propagate through a significant length toward the anode. The time of plasma departure to the walls is $\tau\cong a^2/5D_a$ [a is the tube radius, $D_a\cong b_i(T_e+T_i)/e_0$ is the ambipolar diffusion coefficient, and the numeral 5 is defined by the boundary condition]. The ions depart to the walls in the vicinity of the point where they appear, and the electrons drift along the tube in an electric field to a distance $L=a(b_e/5b_i)(e_0aE/T_e)$. The factor (e_0aE/T_e) turns out to be of the order of unity in inert gases and of the order of several units in molecular gases. Because $b_e/b_i\approx10^2-10^3$, we have $L/a\gg1$. In a strong magnetic field, the negative radial field exists over the bulk of the length of turbulent positive column.

The method of elimination of end effects at the cathode end was employed in [18,19]. A severalfold increase in the diameter of the cathode end of the tube before the solenoid inlet made it possible to obtain the cross section of focused discharge of the tube radius. In so doing, the radial electric field remains positive in all modes of discharges.

IV. STRATA IN MAGNETIC FIELD

It is known that moving and standing strata are concentration and temperature waves of plasma of ionization-diffusion nature [20,21]. In the strata, the modulation of electron temperature along the discharge is combined with the radial gradient of plasma density defined by diffusion. Additional electric current exists in the positive column with strata; the circulation of this current is defined by the noncollinearity of gradients of electron concentration and temperature [22]. For estimating this current, we will write the equations of motion for electrons and ions as follows:

$$e_0n\mathbf{E}+\nabla(nT_e)+\frac{m_en}{\tau_e}(\mathbf{v}_e-\mathbf{v})=\mathbf{0},\tag{10a}$$

$$e_0n\mathbf{E}-\frac{m_in}{\tau_i}(\mathbf{v}_i-\mathbf{v})=\mathbf{0}.\tag{10b}$$

Here, $\mathbf{v}$ is the velocity of neutral gas; and τ_e^{-1} and τ_i^{-1} are the frequencies of collisions of electrons and ions with atoms, respectively, which we will assume to be independent of n and T_e. It is assumed that $T_i\ll T_e$. We apply the curl to Eq. (10a),

$$e_0n\ \mathrm{curl}\ \mathbf{E}+e_0\nabla n\times\mathbf{E}+\frac{m_e}{\tau_e}[n\ \mathrm{curl}(\mathbf{v}_e-\mathbf{v})+\nabla n\times(\mathbf{v}_e-\mathbf{v})]=\mathbf{0}.$$

In a standing stratum, curl $\mathbf{E}=0$. We express $\mathbf{E}$ from Eq. (10a) to derive

$$-b_e\nabla n\times\nabla T_e+e_0n\ \mathrm{curl}(\mathbf{v}_e-\mathbf{v})=0.\tag{10c}$$

It follows from Eq. (10b) that curl $\mathbf{v}_i$=curl $\mathbf{v}$. We eliminate the velocity of gas $\mathbf{v}$ in Eq. (10c) and derive the following equation for current density $\mathbf{j}=e_0n(\mathbf{v}_\mathrm{i}-\mathbf{v}_e)$:

$$b_e\nabla n\times\nabla T_e=-\mathrm{curl}\ \mathbf{j}.\tag{11}$$

It follows from Eq. (11) that an axisymmetric circulation of radial and longitudinal currents is formed in the stratum. This circulation is caused by the fact that the stratum has at its beginning a region with elevated electron temperature and radial electric field exceeding the field in regions with lower temperature. Additional electron current flows under the effect of this potential difference; in the region of maximum of T_e in this current, the electron velocity is directed from the axis toward the wall along the radius. The electron gas expands in the regions of maximum of T_e, with a part of its thermal energy converted to electric energy. This energy dissipates in Joule losses under conditions of flow of eddy current. As a result, the thermal energy flux turns out to exceed by one-third the flux transferred by electron thermal conductivity alone [22]. The density of the eddy current is an order of magnitude lower than the density of the discharge current. Therefore, on being added to the main discharge current, the additional current modulates its radial profile only slightly.

The effect of longitudinal magnetic field on the radial component of eddy current sets the gas to rotation about the discharge axis. In the region of high values of T_e, where the electric current is directed toward the axis, the rotation is clockwise if viewed in the direction $\mathbf{B}$. In the bulk of the stratum, the gas rotates in the opposite direction.

We use Eq. (11) for estimating the order of magnitude of the velocity of rotation. We set $|\nabla n| \approx n/a$ and $|\nabla T_e| \approx T_e/l$ on the left-hand side of the equation; here, a is the tube radius, and $l=ka$ is the size of the order of length of the stratum, which is equal to approximately $2a$ in standing strata. On the right-hand side of Eq. (11), we estimate the current density j from the relation $\int_S \mathrm{curl}_n \mathbf{j}\, dS = \oint_L j_s ds$, where $S \cong al$ and $L \cong 2(a+l)$, $|\mathrm{curl}\, \mathbf{j}| \approx |\mathbf{j}| 2(1+k)/ak$. We equate the estimates of both parts of equality (11) and derive

$$j_\perp \approx \frac{b_e n T_e}{a\xi}, \tag{12}$$

where $\xi = 2(1+k) \approx 6$.

The formula for the azimuthal velocity of rotation of a gas in a uniform column of discharge was suggested by Zakharova *et al.* [11]; in this formula, the moment of force $\mathbf{j}_\perp \times \mathbf{B}$ is balanced by friction against the walls with gas viscosity $\eta = \frac{1}{3} m_a n_a v_T \lambda$,

$$v_\varphi \approx 3 \frac{e_0 B}{m_a} \frac{n}{n_a} \frac{v_r}{v_T} \frac{a^2}{\lambda}. \tag{13}$$

The following notation is used in Eq. (13): $v_T = (2T_a/m_a)^{1/2}$ is the thermal velocity of the gas, $\lambda = (n_a \sigma)^{-1}$ is the mean free path, σ is the gas-kinetic atomic scattering cross section, and v_r is the radial velocity of electrons. The velocity of rotation of gas in strata is limited by its longitudinal and transverse viscosity. Therefore, the application to strata of formula (13), which does not include longitudinal viscosity, results in significant overestimation of the value of the rotation velocity. According to Eqs. (12) and (13), this estimate will be written as

$$v_\varphi \approx \frac{2(\omega_e \tau_e)}{\xi} n a \sigma \left(\frac{T_e}{T_a}\right)^{1/2} \left(\frac{T_e}{m_a}\right)^{1/2}. \tag{14}$$

In moving strata, similarly to standing strata, the sign-variable azimuthal rotation of gas in a longitudinal magnetic field must be present. In these strata, the duration of the effect of eddy electric current is limited to the period of strata oscillation τ_B depending on the magnetic field. Estimates reveal that the maximal velocity of rotation $\Delta v \approx (dv_\varphi/dt)\tau_B$ turns out to be much lower than the velocity calculated by formula (14). In [23,24], the moving strata in magnetic fields were investigated in neon in a wide range of variation of gas pressure, current strength, and magnetic field intensity at $a = 1.1$ cm. For example, at $p \cong 0.4$ Torr, $j \cong 0.2$ A, and $B \cong 800$ G, the velocity is $\Delta v \approx 25-30$ cm/s. The rotation of gas was not measured in these experiments. At present, such measurements could be performed using plasma-dust structures.

V. DISCUSSION OF EXPERIMENTAL RESULTS

We will apply the foregoing results to the experimental data from studies involving the visualization of motion of PDSs in discharges in neon [7]. These data exhibited sign-variable deviation of incident particle paths in the azimuthal direction. The velocities of rotation of PDSs in different parts of the stratum turned out to be different. The angular frequency of azimuthal rotation of dust particles in the top part of the stratum was directed in opposition to the magnetic field, no deviation of particles was observed in the middle part, and motion in the opposite direction was observed in the bottom part. These observations agree with the foregoing results. We will apply formula (14) to a discharge with the following parameters: $p = 0.7$ Torr, $B = 350$ G, $\omega_e \tau_e \approx 2.6$, $a = 1.2$ cm, $(T_e/T_a) \approx 10^2$, $n \approx 10^9$ cm^{-3}, $T_e \approx 3 \times 10^4$ K, and $\sigma = 1.8 \times 10^{-15}$ cm^2. We substitute these values into Eq. (14) and derive the estimate of $v_\varphi \approx 7$ cm/s with angular velocity of rotation (on radius $a/2$) $\omega \approx 14$ rad/s. This value of angular velocity significantly exceeds the measured value of $\omega \approx 1.5-2$ rad/s. Estimation reveals that, even for the degree of ionization of gas of 10^{-7}, the observed rotation of PDSs may be attributed to their entrainment by gas rotating under the effect of the Ampère force from the current circulating in the stratum. Rather than being caused by the change of sign of the radial field (+3.3 and −0.8 V cm^{-1}), as was assumed by Karasev *et al.* [7], the observed variations of the direction of rotation of particles were caused by the effect of rotating gas. Such a sign-variable radial electric field would inevitably develop a radial current rotating the gas, with the density of this current being an order of magnitude higher than that estimated by Eq. (12). In reality, the radial electric field in different parts of the stratum remains positive.

In the case of low magnetic fields, the plasma-dust structures rotated counterclockwise within the entire stratum. The direction of this rotation was changed to the opposite with increasing intensity $\mathbf{B}$; however, the difference in the velocity of rotation between the upper and lower layers of stratum was retained [7]. This variation of rotation of PDSs within the entire stratum cannot be explained only by internal forces or by a change of sign of the radial electric field, which remains positive under the conditions of the described experiments. The counterclockwise rotation is apparently associated with the influence of the anode end face of the solenoid and with the effect of the forces of ion entrainment. The variation of the direction of rotation with increasing field intensity in this case was caused by the narrowing of the current channel, which develops the radial component of current.

The rotation in a magnetic field is further developed in the vicinity of narrowing of the discharge channel cross section. Karasev *et al.* [7] used a narrowing with the opening 5 mm in diameter (with the tube diameter of 24 mm) for the stabilization of standing strata. In a longitudinal magnetic field, the radial component of the current develops the moment of Ampère force in a restricted volume in the vicinity of the opening. The experimental results confirm that the direction of PDS rotation is defined by this moment of force and that the velocity of PDS rotation is maximal in the vicinity of the opening and decreases away from the opening [7]. The rotation proceeds in the direction opposite to that of the effect of ion drag forces from the ions diffusing in the radial direction to the tube walls.

Other experiments in investigating the PDSs in magnetic field are described by Vasil'ev *et al.* [8]. These experiments involved the use of a single-section superconducting solenoid with a field intensity of up to 2500 G (the field intensity in this solenoid can reach 30 000 G, but discharge contraction is not observed in the field up to 2500 G) and a warm bore in the center of the solenoid with the diameter of 15 cm. A sophisticated optical system for observing the PDS motion in a discharge tube in the central part of the solenoid was placed in the magnetic field. The experimental procedure differed from that described by Karasev *et al.* [7], where the PDSs were observed in nonuniform magnetic field in the 9 cm gap between the solenoid coils. Unfortunately, this study [8] does not elaborate on further experimental details important for this discussion (for example, the length of the solenoid and the method of stabilizing the strata by locally narrowing the discharge gap).

The motion of PDSs in a magnetic field described by Vasil'ev *et al.* [8] qualitatively agrees with the results of Karasev *et al.* [7]. In weak magnetic fields, the PDSs rotate counterclockwise relative to the direction $\mathbf{B}$. Such rotation may be explained by the effect of ion drag forces, as well as by the moment of the Ampere force at the anode end of the solenoid. With increasing field intensity, the rotation ceased at $\mathbf{B}$ of about 500 G. At high values of $\mathbf{B}$, rotation in the opposite direction is observed. Vasil'ev *et al.* [8] associate this rotation with the ion drag forces, while assuming the change of sign is caused by the radial electric field in the vicinity of the axis (where the PDSs are located) and by the radial motion of ions. The change of sign by the radial component would cause the development of eddy current in the nonuniform longitudinal electric field existing in the strata. The cessation of rotation observed in [8] may correspond to equilibrium between the ion drag forces and the entrainment of PDSs by moving gas. In our opinion, the reversal of the sign of rotation speaks in favor of the concept of rotation of gas presented above. According to the estimates given in [8], an angular velocity of rotation of the order of 1 rad/s corresponds to the velocity of PDS motion under the effect of ion drag forces (relative to stationary gas). This velocity of gas rotation is sufficient for the rotation of PDS to cease.

VI. CONCLUSIONS

We argue here that, in addition to the effect of ion drag forces on PDSs, the observed rotation of PDSs in magnetic fields is associated with the rotation of gas caused by various nonuniformities of the magnetic field and of the density and temperature of plasma. The rotation of gas in longitudinal magnetic field is affected by factors such as the narrowing of the current channel, nonuniformities of magnetic field at the solenoid ends, and the circulation of additional electric current in the strata. For example, the experimental findings by Karasev *et al.* [7] on the rotation of PDSs may be associated with their entrainment by the motion of gas under the effect of the moment of Ampère force.

It was demonstrated in Sec. II that the azimuthal and longitudinal directions do not physically differ, i.e., the friction forces from ions and electrons acting on gas are mutually balanced in both cases. It would seem that the ion drag forces acting on the PDSs in the azimuthal direction will show up along the discharge as well and provide for the velocities of motion which are two orders of magnitude higher than the observed velocities of PDSs rotation. These forces under certain conditions might have balanced out the gravitation acting on the dust particles if the discharge current were directed vertically upward. The effect of ion drag forces on the variation of longitudinal velocity of PDSs may be evaluated by varying the direction of the discharge current. In experiments aimed at comparing the real ion drag forces to their theoretically obtained values, the motion of gas must be taken into account.

Under conditions where the discharge current does not develop a torque, sign-variable rotation of gas and plasma arises in the strata under the effect of eddy electric current. However, the internal forces do not develop rotation of the medium as a single whole. The effect of ion drag forces and gas rotation may be studied in more detail by observing the motion of PDSs in plasma and eliminating both end effects by turns or simultaneously. In order to eliminate the rotation of gas in the vicinity of the anode end face of solenoid, the anode may be placed in a uniform magnetic field, or a hollow anode may be used on tube walls, where the walls are crossed by the field lines. A method of eliminating the impact of focusing at the cathode end has been proposed in [18,19]. The kinetic two-dimensional effects in strata must be taken into account in theoretical studies of motion of gas in discharges in magnetic fields at low currents [25].

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