Behaviors of Fine Particles in a Planar Magnetron Plasma

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The rotation of fine particles to the direction that agrees with that of E×B drift of charged particles was observed in a planar magnetron plasma. The speed of the rotation was measured to be 1.3×10^{-2} m/s at the pressure of 100 Pa. A velocity was calculated under the effect of drag forces of E×B drift ions and neutral molecules on the rotation of fine particles to be 4.2×10^{-1} m/s. The drive to the direction of E×B drift by the streams of slightly magnetized ions should affect the rotation of fine particles.

Keywords: fine particles, dusty plasma, magnetron plasma, E×B drift , ion drag force, Coulomb crystal

1. Introduction

Fine particles in a glow discharge plasma show many interesting behaviors, because they act as large negative particles in it. Owing to the visibility of each particle by laser light scattering, new discoveries on physical phenomena are expected in a plasma containing fine particles. The ordering of fine particles in crystal structures was one of the novel discoveries [1]. However, the methods of behavior control of fine particles in a plasma have not well been developed. We made a system of planar magnetron plasma for the observation and control of behavior of fine particles [2]. Using the system under higher pressure (100 Pa) and lower discharge power (less than 100 mW), we observed fine particles to arrange in isotropic three-dimensional structures on the two-dimensional structure formed by particle strings, and found that the upper fine particles were driven by the diffusible plasma [2]. On the other hand, the behaviors of each particle in a magnetically confined plasma have not well been understood generally. In this paper, the effect of E×B drift on a fine particle in a planar magnetron plasma is analyzed.

2. Experimental

Figure 1 shows the system of fine particle plasma. A planar magnetron plasma was generated in a cylindrical vacuum chamber of 30 cm in diameter and 23 cm in height. The system contains an rf (radio frequency) electrode of a square, 20 cm on a side, put in the lower position. An upper flange of the chamber, which was set at a distance of 15 cm from the rf electrode, acted as a grounded counter electrode. Strong permanent magnets, whose residual magnetic flux density is 1.4 T, were put in the rf electrode to form a square loop of magnetic field parallel to the rf electrode. A high density plasma is generated due to the confinement of electrons by the E×B drift on the surface of the electrode. The magnetron plasma that forms a loop diffuses toward the center and then upward. It is expected that fine particles are pushed toward center and upward by the diffusible plasma, leading to being suspended under the force balance with the gravity without the formation of a void.

Fine particles were observed through a side or the upper viewing windows by the laser light scattering of 532 nm in wavelength. The incident laser light was expanded in the vertical or horizontal direction with the use of a cylindrical lens. The arrangement of fine particles was recorded by a CCD video camera attached with a convex lens.

The experimental conditions were as follows: discharge gas, helium; rf discharge power, less than 100 mW to 2 W; gas pressure, 60 to 120 Pa; and fine particles, divinylbenzene spheres of 2.27 microns or 6.5 microns in diameter.

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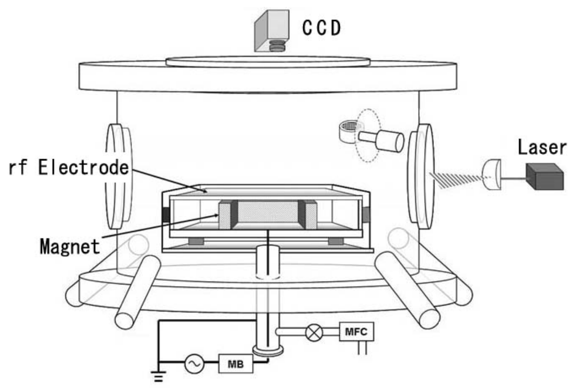

Fig.1 Schematic diagram of the planar magnetron plasma system.

3. Results and Discussion

3.1 Using smaller fine particles

A side view of fine particles of 2.27 microns in diameter suspended above the position of the center of the planar magnetron plasma under a pressure of 100 Pa and rf power of less than 100 mW is shown in Fig.2. It is seen that fine particles are divided into two groups. The upper one shows randomly or three-dimensionally ordered fine particles, while the lower one shows the vertically aligned fine particles. The boundary between the two groups is clearly observed. According to the wake-filed theory [3], the boundary also shows the boundary between a plasma and the sheath. Using smaller ones and the upward-flowing plasma that were derived from the diffusion of the loop of planar magnetron plasma [2], fine particles were suspended not only in the sheath but in the region of plasma owing to smaller gravity and upward force. The rotation of fine particles by the effect of E×B drift of charged particles was hardly observed. This result should be due to the lower velocity of charged particles at a lower electric field in the sheath because small fine particles are suspended at the position of the force balance between the gravity and electrostatic force in the sheath.

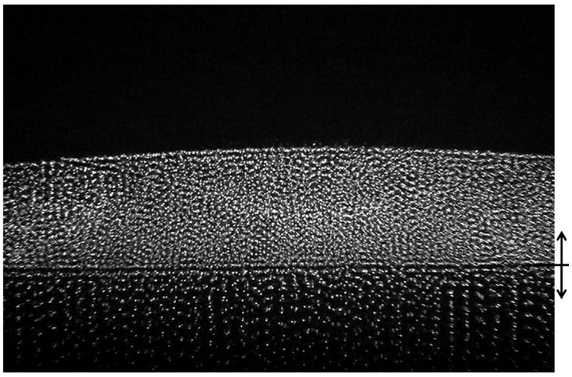

Fig.2 Side view of 2.27-micron fine particles suspended above the center of planar magnetron plasma under the pressure of 100 Pa and rf power less than 100mW.

3.2 Using larger fine particles

Divinylbenzene fine particles of 6.5 microns in diameter were injected in a helium plasma under a pressure of 60 to 120 Pa and rf power of 2 W. Owing to the larger gravity, they all sank in the sheath. Fine particles were observed to rotate horizontally with the visible speed forming particle strings in the vertical direction in the sheath. A top view of the rotation under a pressure of 100 Pa is shown in Fig.3. The vertical position and width of laser light was 5 mm above the rf electrode and about 1 mm, respectively. The uppermost fine particles of the strings are observed in Fig.2. Fine particles in the lower part rotated following the uppermost ones with the same horizontal positions [4]. Because video frames for 0.1 second were piled up, the trajectories that verify the rotation of fine particles are indicated in the figure. It is seen that fine particles were rotating around the center of planar magnetron plasma. The direction of the rotation was counter-clockwise and agrees with that of E×B drift of charged particles.

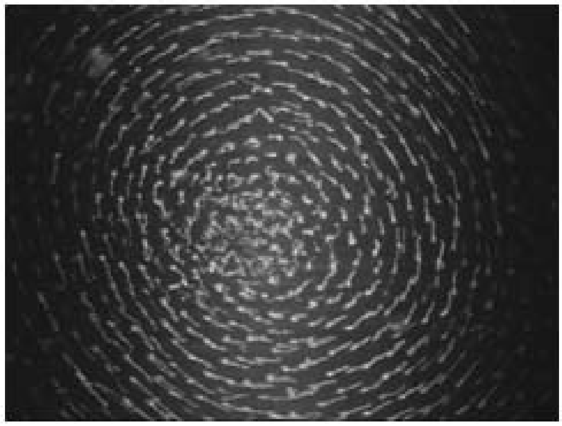

Fig.3 Top view of rotation of 6.5-micron fine particles by E×B drift under the pressure of 100 Pa and rf power of 2 W.

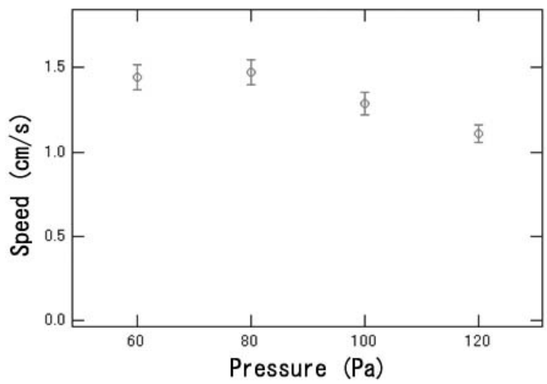

Fig.4 Plot of rotation speed of fine particles against pressure.

The speed of the rotation was evaluated through the obtained video images. Figure 4 shows the dependence of the speed of rotation of fine particles on the pressure at the radial position of 3 cm from the center. The speed decreases from 1.5 cm/s to 1.1 cm/s with the increase of pressure. The result suggests that the speed of fine particles was affected by the neutral-gas drag force.

Here we analyze the rotation of fine particles to the direction of E×B drift. The E×B drift speed of a charged particle, V_d, is related to the equation as

$$V_d = E/B, \tag{1}$$

where E and B are the sheath electric field and magnetic field parallel to the rf electrode, respectively. The magnetic field, B, at the radial position of 3 cm from the center and at the vertical position of 0.5 cm from the rf electrode, where the highest fine particles of the strings exist was measures to be 0.1 T. The sheath electrostatic field, E, was determined by the force balance between the gravity and a upward electrostatic force. The gravity, mg, where m and g are the mass of a fine particle and the gravitational constant, respectively, is 1.5×10^{-12} N. The upward electrostatic force is obtained by QE, where Q is the charge of a fine particle. The value of Q was determined to be 2.1×10^{4} e for measured plasma parameters by a Langmuir probe, the plasma density of 1.1×10^{9} cm^{-3} and the electron temperature of 5.3 eV at the pressure of 100 Pa, and an estimated plasma parameter, the ion temperature of 0.1 eV. Consequently, the sheath electrostatic field, E=450 V/m. Then the E×B drift speed is calculate from the Eq.(1),

$$V_d = 4500 \text{ [m/s]}. \tag{2}$$

The calculated speed is extraordinarily larger than the measured speed of fine particles, 1.1×10^{-2} to 1.5×10^{-2} m/s. The result means that fine particles were not driven being magnetized, *i. e.*, at the speed of E×B drift.

Next the effect of drag forces of E×B drift ions and neutral molecules on the rotation of fine particles is evaluated. The dynamic equation of a fine particle is expressed as

$$M\, dV_D/dt = f_{ion} - f_{gas}, \tag{3}$$

where M and V_D are the mass and the velocity of fine particles, respectively, and f_{id} and f_{gas} are ion drag-force and opposite gas-drag force, respectively, and expressed as

$$f_{ion} = n_i v_s m_i V_d \Sigma_i, \tag{4a}$$
$$f_{gas} = n_o v_o m_o V_D S_D, \tag{4b}$$

where n_i, v_s, m_i, V_d, and Σ_i are density, velocity, mass, E×B drift velocity and scattering cross section, for ions, respectively, and n_o, v_o, m_o and S_D are density, velocity, mass, scattering cross section, for neutral molecules, respectively. When the speed of fine particles is constant, the left side of Eq.(3) is zero and then the following equation holds,

$$n_i v_s m_i V_d \Sigma_i = n_o v_o m_o V_D S_D. \tag{5}$$

Consequently, the velocity of fine particles, V_D, is expresses as,

$$V_D = \frac{n_i v_s m_i \Sigma_i}{n_o v_o m_o S_D} V_d. \tag{6}$$

$n_i/n_o = 1.1\times10^{9}/2.6\times10^{16} = 4.2\times10^{-8}$ for the measured plasma density and the pressure of 100 Pa. $v_s/v_o = (4500^2+2200^2)^{1/2}/1100 = 4.6$ for the ion temperature of 0.1 eV and the gas temperature of 0.025 eV. m_i/m_o is nearly 1. $\Sigma_i / S_D = \pi\lambda_D^2/\pi r_D^2 = 71^2/(6.5/2)^2 = 4.8\times10^2$ for the plasma density and the ion temperature given above, where λ_D and r_D are the Debye length and the radius of fine particles, respectively. Thus the velocity of fine particles is calculated form Eq.(6) as,

$$V_D = (4.2\times10^{-8})\times(4.6)\times(4.8\times10^{2})\, V_d = 9.3\times10^{-5}\, V_d. \tag{7}$$

When Eq.(2) is substituted into Eq.(7),

$$V_D = 4.2\times10^{-1} \text{ [m/s]}. \tag{8}$$

The rotation speed of fine particles measured at 100 Pa is 1.3×10^{-2} m/s as shown in Fig.4. The calculated value in Eq.(8) is 30 times larger than the measured value.

Then the Hall parameter for ions, h_i, was calculated by the equation,

$$h_i = f_{ci}/\nu_{in}, \tag{9}$$

where f_{ci} and ν_{in} are the ion cyclotron frequency and ion-neutral collision frequency, respectively. The value of h_i was calculated to be 0.02 under the conditions given above. It is suggested that fine particles were driven to the direction of E×B drift by such streams of slightly magnetized ions.

4. Conclusions

The rotation of fine particles to the direction that agrees with that of E×B drift of charged particles was observed in a planar magnetron plasma. The speed of the rotation was measured to be 1.3×10^{-2} m/s at the pressure of 100 Pa. A velocity was calculated under the effect of drag forces of E×B drift ions and neutral molecules on the rotation of fine particles to be 4.2×10^{-1} m/s. It is suggested that the discrepancy between the measured and calculated values is due to the drive to the direction of E×B drift by the streams of slightly magnetized ions.

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