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Control of Rotational Motion of Fine-Particle Cloud Confined in a Weakly-Magnetized DC Discharge Plasma

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Abstract

A rotation of strongly-coupled fine-particle cloud, levitating above a negatively biased electrode, is observed in a weakly ionized argon dc discharge plasma by applying axial magnetic field in vertical direction. When the magnetic field is applied, fine-particle cloud, constituting multilayers like the Coulomb lattice in vertical direction, start to rotate in azimuthal direction with keeping the interparticle distance almost constant. The rotation direction of fine-particle cloud is controlled by changing radial plasma density profile. In case of peaked-type density profile, the rotation direction is paramagnetic of negatively-charged fine particles. Conversely, in case of hollow-type density profile, the rotation direction is diamagnetic. A mechanism of the rotation is explained by an effect of ion motion colliding with fine particles in the presence of vertical magnetic field.

Keywords:

dc discharge plasma, dusty plasma, strongly-coupled fine particles, magnetic field, rotation, plasma density profile, ion drag force

1. Introduction

Fine particles in plasmas are of current interest in various fields of plasma researches and applications. In plasmas, fine particle are negatively charged up to form so-called "Coulomb lattice" under the strong Coulomb interaction among the particles. There have been many experiments on fine particles, which have clarified various interesting features of fine-particles in plasmas [1]. Particularly, we are interested in the fine-particle motion in weakly magnetized plasma [2-3]. Several experiments were carried out on the dusty plasma in magnetic field and various interesting motions of fine particles have been reported [4-6].

Our work has been carried out using a completely dc configuration [7]. Being different from rf discharge plasmas which have been used in most of the experiments on fine particles, it is easy to modify the plasma spatial profiles in dc discharge plasmas in order to analyze the fine-particle motion in weakly-magnetized plasma. In this work, we have introduced dc cathode, which is coaxially segmented into two parts to produce inner and outer plasmas, independently, by the effect of weak axial magnetic field. This situation enables to control the radial density profile by changing the dc discharge power. Particle levitation electrode, which is radially segmented, is also employed to provide potential profile necessary for particle levitation and confinement.

In this paper, we have observed the rotation of strongly-coupled fine-particle cloud when axial magnetic field is applied and the relation between plasma density profile and the rotation of fine-particle cloud is analyzed.

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2. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. A dc argon discharge plasma is produced at pressure of 190 mTorr by applying negative dc potential to upper cathode with respect to a middle mesh anode with the diameter of 70 mm, which is grounded as well as the metal vacuum chamber. The cathode is coaxially segmented into two parts to produce inner and outer plasmas. The diameter of inner mesh-cathode is 20 mm. The inner and outer diameters of the outer ring-cathode are 20 mm and 60 mm, respectively. Plasma density profile in radial direction is controlled by the discharge currents I_{k1} and I_{k2} by applying dc negative voltages V_{k1} and V_{k2} to respective cathode. The distance between the cathode and anode is 20 mm. The mesh size is 20 mesh/inch for both of the inner mesh-cathode and anode. Inner and outer plasmas produced diffuse downward through the mesh anode. At a distance of 20 mm below the anode, a segmented electrode (SE), consisting of two electrodes, is set for particle levitation and confinement. A center electrode of the SE is a disc of 20 mm in diameter. The ring electrode of 20 mm and 95 mm in inner and outer diameters, respectively, is set at 3mm above the horizontal plane of the center electrode. Different dc potentials V_c and V_r are externally applied to these electrodes in order to control radial potential profile in the particle levitation region. An axial magnetic field B of 566 G is applied in vertical direction perpendicular to the electrodes. A small movable Langmuir disk probe is used to measure plasma parameters. Typical electron density and electron temperature below the anode are $n_e \simeq 1 \times 10^8/\mathrm{cm}^3$ and $T_e \simeq 2$ eV, respectively. A movable single wire probe of 0.45 mm in diameter and 1 mm long is used to measure ion saturation current in the region above the SE. Fine particles used are 10 μm-diameter ($\pm$1.0 μm size distribution) spherical mono-disperse methyl methacrylate-polymer of 1.17–1.20 g/cm^3. They are supplied from a sieve (dust dropper) into the plasma through the mesh cathode and anode, and are negatively charged up in the plasma. They are observed by the Mie-scattering of He-Ne laser sheet with a breath of 5 mm injected in horizontal direction. To investigate fine-particle behaviors, CCD cameras are used as detectors of the light signals from the side and top view ports.

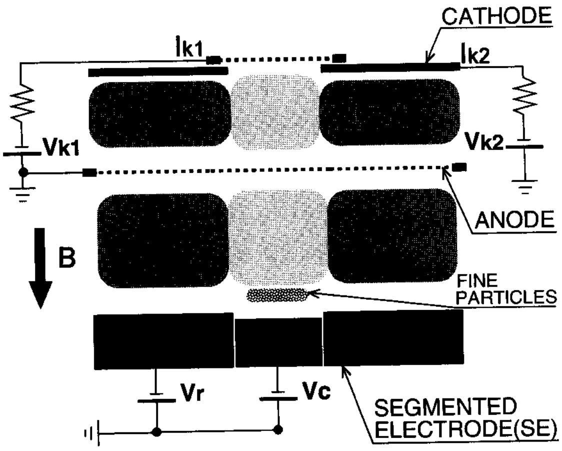

Fig. 1 Schematic of experimental apparatus.

3. Experimental Results

The density profile in radial r direction is controlled by the radially segmented cathodes. The discharge current I_{k1} is fixed at 0.4 mA, while the discharge current I_{k2} is varied from 0 mA to 1.4 mA. Radial profile of ion saturation current I_{is} is measured at 13 mm above the SE, as plotted in Fig. 2. When $I_{k2} = 0 \sim 0.6$ mA, peaked-type density profiles are formed in the center plasma region, where plasma density is about 1×10^8 cm^{-3} at $r = 0$. Conversely, when $I_{k2} = 0.8 \sim 1.4$ mA, hollow-type density profiles are formed. Dot lines in Fig. 2 show the position of the edge of fine-particle cloud. From these results, it is found that the radial gradient of plasma density around fine-particle cloud is

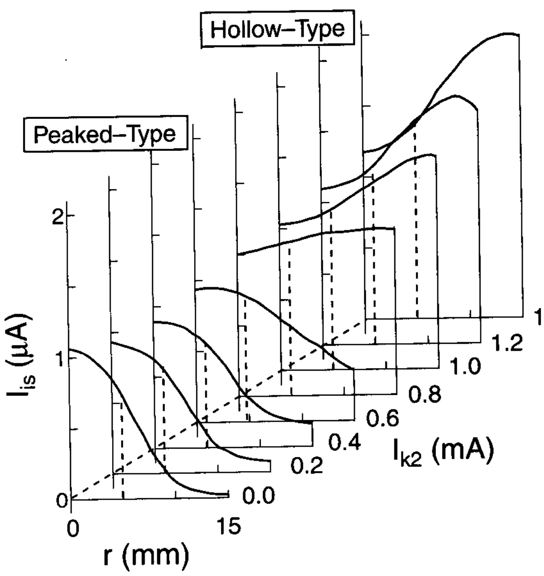

Fig. 2 Radial profiles of ion saturation current I_{is} for various I_{k2}, where I_{k1} is fixed at 0.4 mA.

controlled by changing I_{k2}.

The potentials V_c and V_r of the center and ring electrodes of the SE are fixed at $0 > V_c = -55$ V $> V_r = -65$ V, in order always to form a potential hill for confining the negatively-charged fine particles above the center electrode ($z = 0$). The dc ion sheath is formed in the region of $z = 0 \sim 20$ mm from the result that electron density suddenly decreases at $z = 20 \sim 22$ mm by the probe measurement. Therefore, axisymmetrical particle-cloud structure observed at $z = 14 \sim 17$ mm, as shown in Fig. 3, is in the dc ion sheath region. According to the potential profile applied to the segmented electrode, the spatial shape of fine-particle clouds is changed and various shapes with disk, cone, and ring are observed [8]. When the radial potential gradient to confine fine particles is large, fine particles form a cone as shown in Fig. 3. Therefore, the shape of fine-particle cloud is closely related with the radial potential profile which becomes broad in the upward (z) direction. The electric field at the fine-particle levitation position ($z = 14 \sim 17$ mm) is roughly estimated to be 1000 ~ 2000 V/m from a theoretical model of the collisional dc ion sheath formed in the region of $z = 0 \sim 20$ mm. Under our experimental conditions, fine particles have about (1–5) $\times$ 10^4e charges, that is calculated from a balance between the gravitational force and the electrostatic force in the ion sheath. Taking account of the mean interparticle distance of about 300 μm, Coulomb coupling parameter Γ is roughly estimated to be 88 ~ 2200, indicating that fine-particle cloud is in the strongly-coupled state. Here, fine-particle temperature is assumed to be electron temperature, because fine particles always fluctuate around their stable positions under the influence of perturbing space potential with the order of electron temperature. The Debye length and the charge of fine particles are assumed to be 300 μm and (1–5) $\times$ 10^4e, respectively.

When the magnetic field B is applied, the fine-particle cloud starts to rotate as a whole in azimuthal direction above the center electrode, with almost keeping lattice structures. When $I_{k2} = 0.1$ mA (peaked-type density profile), fine-particle cloud rotates in paramagnetic direction of negatively-charged fine particles, as shown in Fig. 4. The azimuthal velocity v_d of the particles near periphery is faster than inside. Since $v_d \propto r$, the angular frequency ω (= v_d/r) is almost constant 0.06 rad/s in radial direction. Therefore, strongly-coupled fine-particle cloud behaves like a rigid body. On the other hand, when $I_{k2} = 0.8$ mA (hollow-type density profile), fine-particle cloud rotates in

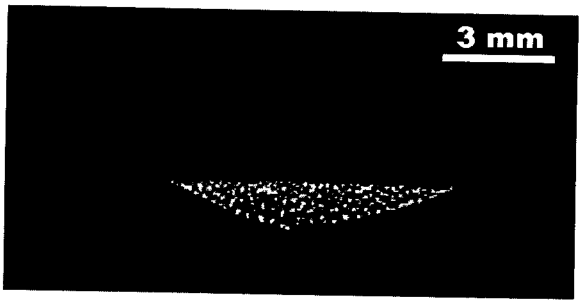

Fig. 3 Image of fine particle cloud from horizontal side.

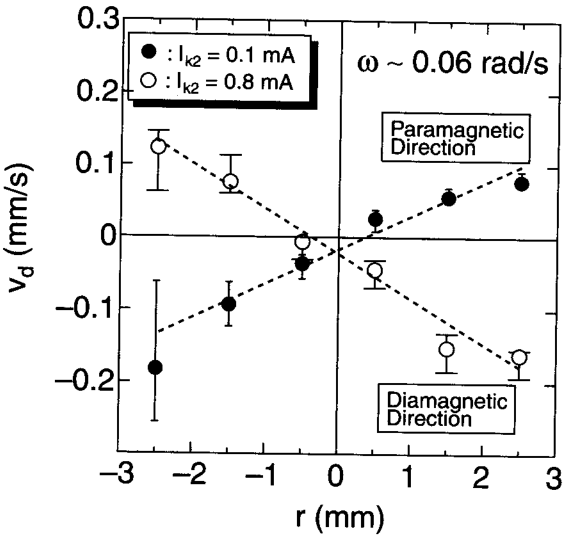

Fig. 4 Radial profiles of particle-cloud rotation velocity v_d at I_{k2} = 0.1 mA (●) and 0.8 mA (○), where I_{k1} is fixed at 0.4 mA.

diamagnetic direction of negatively-charged fine particles. The rotation direction clearly depends on the density gradient around fine-particle cloud.

4. Discussion

Gravitational force acting on the fine particle, 6.1 $\times$ 10^{-12} N, balances with axial electrostatic force in the sheath. In radial direction, negatively-charged fine particles are confined by a relatively weak external-electrostatic force of the order of 10^{-13} N. On the other hand, in azimuthal direction, the rotation-driving force F_d balances with gas friction force F_{Nd} and as a result the fine-particle cloud rotates with constant velocity v_d in azimuthal direction. For slow fine-particle speed of $v_d \ll v_{th,N}$, F_{Nd} is given by $4/3\pi a^2 m_N n_N v_{th,N} v_d$, where a is the radius of fine particle, m_N is the mass of neutral gas atom, n_N is the density of neutral gas atom, $v_{th,N}$ is thermal velocity of neutral gas atom [9]. Then, F_d is estimated from $F_{Nd} = 1.3 \times 10^{-11}\ v_d$ at argon pressure of 190 mTorr and argon temperature 300 K. Therefore, it is found that the rotation velocity observed around $v_d = 0.1$ mm/s can be driven by only $F_d \sim 10^{-15}$ N, that is much weaker than the forces balancing in axial and radial directions. The driving force F_d for azimuthal rotation could be originated from the ion drag force by taking account of ion trajectories modified by the magnetic field. The mean free path for collisions between ion and neutral gas at 190 mTorr is about 300 μm, which is much smaller than the Larmor radius 3 mm of ions at B = 566 G. The hole parameter $\omega_{ci}\tau_i$ of ions in this case is only 0.01. Although $\omega_{ci}\tau_i$ is so small, the ion trajectory is not straight but is slightly bent, which is very important to generate a difference of diamagnetic ion flux impinging on the fine particles in azimuthal direction, when the plasma parameters vary in radial direction. Then, net ion drag force appears in azimuthal direction by the effect of collisional ion cyclotron motion.

The ion drag force F_{ion}, that is due to momentum exchange between positive ions and negatively-charged fine particle, proportionally increases with ion density [10]. F_{ion} acting on fine particle with 10 μm in diameter, which has 1×10^4e charges, is of the order of 10^{-13} N, when the ion density is 1×10^8 cm^{-3} and ion drift velocity is equal to ion thermal velocity. If the ion trajectory has no velocity component in azimuthal direction, the force acting on fine-particles is balanced out perfectly. But, a small unbalance of the force of the order of 10^{-15} N, which is generated from a difference of diamagnetic ion flux on fine particle in azimuthal direction, drives the fine-particle motion in azimuthal direction. In case of the peaked-type density profile, ion flux coming from paramagnetic direction toward fine particles will surpass that coming from diamagnetic direction, because ion density at the center of fine-particle cloud is more than that at the periphery. Conversely, in case of the hollow-typed density profile, the ion flux coming from diamagnetic direction will be dominant compared with that coming from paramagnetic direction. The rotation direction of fine-particle cloud shown in Fig. 4 is consistent with the model mentioned above. During the experiment, the shape of fine-particle cloud does not much change in spite of the fact that the density profile is controlled from peaked-type to hollow-type. This result also indicates that potential profile around fine particles is kept almost constant, forming always hill type in order to confine negatively-charged fine particles in radial direction.

5. Conclusion

We clearly showed the effect of density profile on the rotation of strongly-coupled fine-particle cloud in weakly magnetized plasma. The rotation of fine-particle cloud could be explained by the balance of azimuthal ion flux generated by the density gradient in radial direction.

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