# DUST VORTEX IN A DC DISCHARGE PLASMA UNDER A WEAK MAGNETIC FIELD

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**Abstract**

A vortex flow of strongly coupled dust particles levitating above a negatively biased electrode in a horizontal plane is observed in a weakly ionized argon dc plasma by applying an axial magnetic field in the vertical direction. When the magnetic field is applied, the particles, constituting multilayers like the Coulomb lattice in the vertical direction, start to move in the azimuthal direction with keeping the interparticle distance almost constant. The angular frequency is not recognized to vary in the radial direction. However, the particles in the upper layer rotate faster than those in the bottom layer, forming a velocity shear in the vertical direction. The velocity is increased by increasing the magnetic field and/or the electron density.

## 1. Introduction

Dust particles charged negatively in plasmas are known to form the Coulomb lattices under a strong repulsive interaction, which have hexagonal, body-centered cubic and face-centered cubic crystal structures [1-4]. Recently, the studies of dust particle behavior have attracted strong attentions not only for plasma physics but also for material processing because of their important roles as a contamination source. Collective behavior of the dust particles, especially in strong-coupled state, is very complicated, because the various forces, for example, electrostatic force, ion drag force, electromagnetic force, and friction force with neutral gas act on these particles. Up to now, however, a few experiments have been reported on the particle motion in the magnetic field [5,6]. Usually, dust particles have been studied in unmagnetized rf plasmas, where the sheath moves temporally, therefore the analysis of particle motion is complicated. In our experiment, we inject particles into a dc plasma [7]. In order to control the potential structure in the particle levitation region, a segmented particle levitation electrode is set up. Therefore, the system is quite simple to analyze the motion of dust particles, wave phenomena in dusty plasmas, and other collective behaviors of dust particles in a dc sheath potential [8-10].

In this paper, we have observed a vortex flow of strongly coupled particles when an axial magnetic field is applied [8]. This motion is affected by the magnetic field, the electric field in the dc sheath, and the electron density.

## 2. Experimental apparatus and methods

A schematic diagram of the experimental apparatus is shown in Fig.1. A dc argon discharge plasma is produced at 220 mTorr by applying a negative dc potential of about 300 V to the upper cathode electrode with respect to the middle grounded ring anode. The cathode is a stainless mesh of 8.5 cm in diameter. The inner and outer diameters of the anode are 8 cm and 9.5 cm, respectively. These electrodes are placed with a separation of 0.5 cm. The discharge current is in the range 0.2 mA $\sim$ 1.5 mA. The electron density $n_e$ and temperature $T_e$ are $10^7 \sim 10^8$ cm$^{-3}$ and a few eV, respectively. Below the anode, a segmented particle levitation electrode (SPLE) is set up, consisting of two electrodes; one is a center disc of 2.0 cm in diameter, and the other is a ring with inner and outer diameters of 2.0 cm and 9.5 cm, respectively. Different dc potentials can be applied to the two electrodes independently in order to control potential structure in the particle levitation region. The particles used are mono-disperse methyl methacrylate-polymer spheres of 1.17-1.20 g/cm$^3$ and diameter of 10($\pm$1.0) $\mu$m. They are injected from a sieve into the glow region of the plasma through the mesh cathode. An axial magnetic field $B$ of 0 - 400 G is applied in the vertical direction perpendicular to the electrodes. The particles are observed by the Mie-scattering of He-Ne laser light, with a breadth of 5 mm in the horizontal direction. To investigate the particle behaviors, a CCD camera is used as a detector of the light signal which is recorded on video tape and processed by a personal computer. The plasma parameters are measured by a disc probe movable in the radial $r$ and axial $z$ directions.

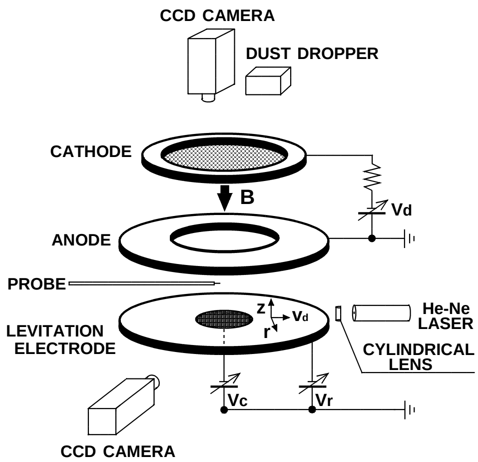


**Figure 1.** Schematic diagram of experimental apparatus

## 3. Experimental results

The potentials of the center and ring electrodes of the SPLE, $V_c$ and $V_r$, are fixed at $0 > V_c > V_r$, to form a potential hill for confining the negatively charged particles above the center electrode, then axisymmetrical dust structure is formed in the dc ion sheath region. The dust cloud distributes like a plane disc in the horizontal direction as shown in Fig. 2(a). Decreasing $V_r$ from $-16$ V to $-30$ V, the dust cloud is pressed toward the center, because the ion sheath region formed by the ring electrode moves toward the center. By this compression, the interparticle distance decreases from about 500 $\mu$m to 350 $\mu$m, and the particles are pushed up in the vertical direction, resulting in an increase of the number of the layers. Total width of the layers is changed from about 0.5 mm to 2.5 mm. It should be noted that the cloud structure is changed from a two-dimensional plane disc to a three-dimensional cone [11] as shown in Fig. 2(b). This change of the particle cloud structure is due to the vertical change of the radial potential profile which becomes broad in the upward direction. In the cone, the interparticle distance of the upper layer is smaller than that of the bottom layer.

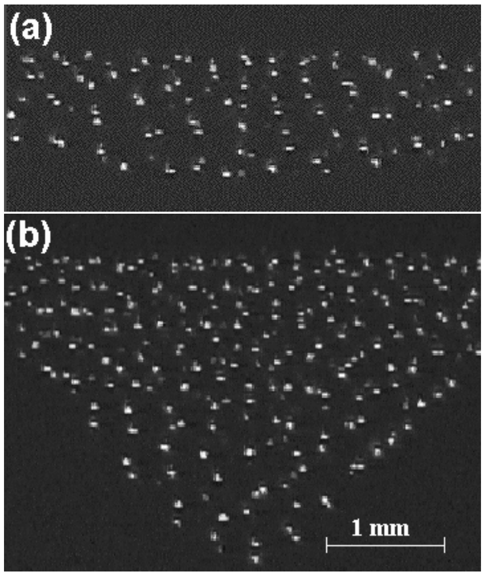


**Figure 2.** Images of dust cloud (side view). (a) $V_c$ = −15 V, $V_r$ = −20 V, (b) $V_c$ = −15 V, $V_r$ = −30 V

Before applying a vertical magnetic field, the particles are distributed around the stable positions, with a small fluctuation. When the magnetic field $B$ is applied, the particles start to rotate in the azimuthal direction above the center electrode, with almost keeping lattice structures as shown in Fig. 3. It should be noted that the particle velocity in the upper layer is faster than that in the bottom layer, and a shear motion is observed in the vertical direction as shown in Fig. 4. The azimuthal velocity $v_d$ of the particles near periphery is faster than inside. However, the angular frequency $\omega$(= $v_d$/r) is almost constant in the radial direction (see Figs. 5 and 6). Assuming that the charge of the dust-particles with diameter of 10 $\mu$m is of the order of $10^4$e, the dust-particle cyclotron frequency $\omega_{cd}$ is $10^{-4} \sim 10^{-5}$ rad/sec under the magnetic field of 120 G. On the other hand, the observed angular frequency $\omega$ is of the order of 0.1 rad/sec, much larger than the dust-particle cyclotron frequency $\omega_{cd}$. Figs. 5 and 6 show that $\omega$ increases with an increase in $B$ and/or $n_e$.

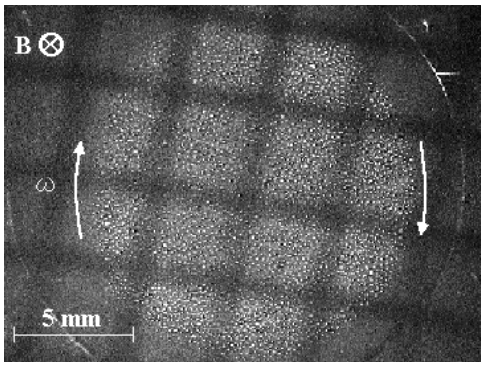


**Figure 3.** Image of rotational motion of dust particles observed through a mesh cathode from the top

The rotation direction is in the same direction as the electron gyration, that is, in the electron-diamagnetic direction. It must be remarked that the appearance of the rotational motion depends on the dust-particle density. When the density is extremely low, there appears no particle rotation in the azimuthal direction. The rotational motion appears when the interparticle distance is reduced to the order of those of the Coulomb lattices. This means that this rotational motion is generated as a result of the collective phenomena of dust particles in the magnetic field.

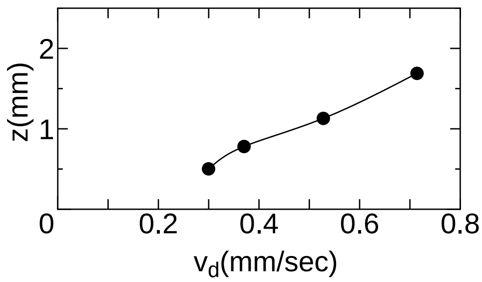


**Figure 4.** Axial profile of particle rotation velocity $v_d$

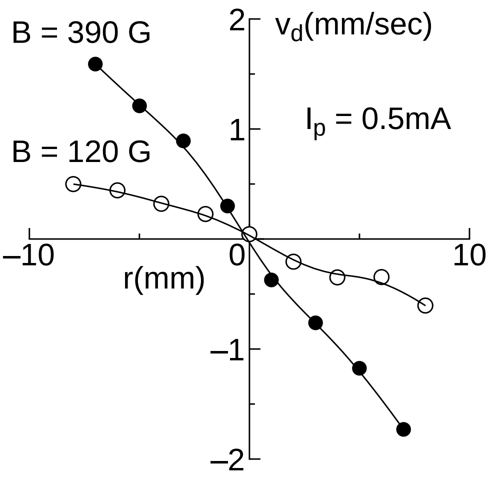


**Figure 5.** Radial profiles of particle rotation velocity $v_d$ under magnetic fields of $B$ = 120 G (○) and 390 G (●)

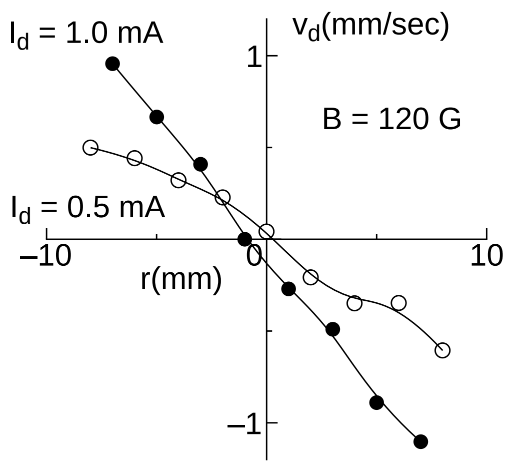


**Figure 6.** Radial profiles of particle rotation velocity $v_d$ for discharge currents of $I_d$ = 0.5 mA (○) and 1.0 mA (●)

## 4. Conclusions

A vortex flow of strongly coupled particles has been observed in a weakly ionized argon dc plasma by applying axial magnetic field. In a strongly coupled state, the angular frequency of the rotational motion is almost constant in the radial direction. In the vertical direction, however, the velocity shear is observed, forming a three-dimensional structure with a velocity shear. The rotational velocity increases with an increase in the magnetic field and/or the electron density.

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