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Production of low-density plasma by coaxially segmented rf discharge for void-free dusty cloud in microgravity experiments

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A technique is presented for producing a low density plasma by introducing a coaxially segmented parallel-plate radio-frequency discharge for void-free dusty-cloud formation. Main plasma for the dusty plasma experiment is produced in a central core part of the parallel-plate discharge, while a plasma for igniting the core plasma discharge is produced in the periphery region surrounding the core plasma. The core plasma density can be markedly decreased to reduce the ion drag force, which is important for a formation of void-free dusty cloud under microgravity. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2187500]

Dusty plasmas have been known to form Coulomb crystals[1] in strongly coupled states since the dust particles in the plasmas are charged strongly to provide the condition that the dust Coulomb energy well surpasses their thermal energy. Usually, the polarity of the charges is negative, because the electron mobility is much larger than that of ions. On the earth, the mass of the dust cannot be neglected. In order to levitate such particles, we need a strong electric field directing upward in the sheath region,[2,3] which may influence particle alignment in vertical direction. Therefore, it is quite difficult to investigate ideally isotropic structures of fine particles.

In order to reduce such a gravity effect, the experiments under microgravity condition have been proposed.[4,5] Even under the microgravity, however, since the plasma potential becomes maximum at the center, the ions are accelerated toward plasma periphery. This ion flow gives an ion drag force to the particles, then the particles are pushed away from the plasma center toward plasma periphery. Therefore, the space, called a void, which does not contain the particles, is created in the plasma core region.[6–8] Owing to the void formation, it is difficult to produce an isotropic Coulomb crystal. Here, we note that the strength of ion drag forces depends on the ion density. Therefore, it has been a subject how the background ion density can be decreased without switching off the plasma discharge. In this letter, we propose a technique for the production of low density plasma to provide void-free dust cloud under microgravity.

In order to produce low-density plasma in central region, we separate the discharge coaxially into two parts by coaxially segmented radio-frequency (rf) electrodes. Two parallel rf electrodes, 60 mm in diameter, are placed with a spacing of 4 cm as shown in Fig. 1(a). On each rf electrode, a dielectric cylinder of 40 mm in diameter and 10 mm in height is attached at the center. Although the spacing in outer region A is larger than that in inner region B, the electric field in region A becomes large, because in region B the electric field is reduced by the dielectric cylinder. Therefore, when we increase rf power P_{RF}, the discharge starts first in outer region A at $P_{RF}=c$ as shown in Fig. 1(b). But, the plasma density in region A suddenly increases up to the value a, as shown in Fig. 1(b). Usually, the density a is too much compared with the upper limit density b for the void-free dusty cloud formation. On the other hand, in central region B, the discharge can be ignited at $P_{RF}=d$, owing to the primary electrons supplied from region A. Since the discharge starts smoothly, there appears to be no significant density jump in region B and the plasma density increases almost in proportional to P_{RF}. Thus the plasma density in the center region can be set less than b. P_{RF} can be adjusted in range from d to e as shown in Fig. 1(b) to get weak density less than b. In this way, we can control the plasma density more precisely in center region B in the lower density regime.

The experiment is carried out inside a vacuum chamber of 11.6 cm width, 15 cm height, and 11.6 cm length. P_{RF} at frequency 13.56 MHz is applied to both electrodes simultaneously by a rf power splitter, which can be varied in the range 1–10 W. The argon pressure is fixed at 100 mTorr. Fine particles, made from 10-μm-diameter acrylic balls, are supplied by a particle dispenser. The particles are observed by illumination them by laser sheet beam

Radial profiles of ion saturation current I_{is} of the plasma are shown in Fig. 2(a) with P_{RF} as a parameter. With increasing P_{RF}, the discharge starts first in region A at $P_{RF}=1$ W. The I_{is} becomes minimumal in region B. This result indicates that the discharge is triggered only in the periphery of the rf electrode. When $P_{RF}=3$ W, though the density hump at $y \cong \pm 30$ mm grows further, the plasma density is still zero in center region ($y=0$). When $P_{RF}=5$ W, however, we can observe an increase of I_{is} in the center region B. A small hump is detected at $y=0$, which indicates that a weak discharge

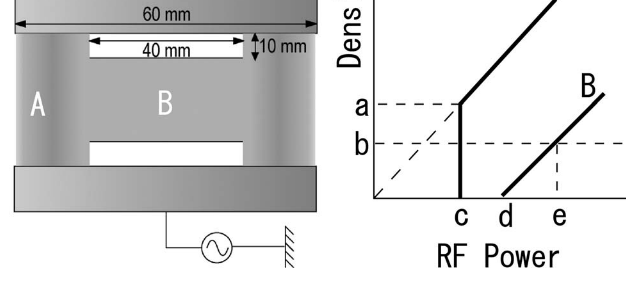

FIG. 1. (a) Experimental apparatus. (b) Density vs rf power in regions A and B.

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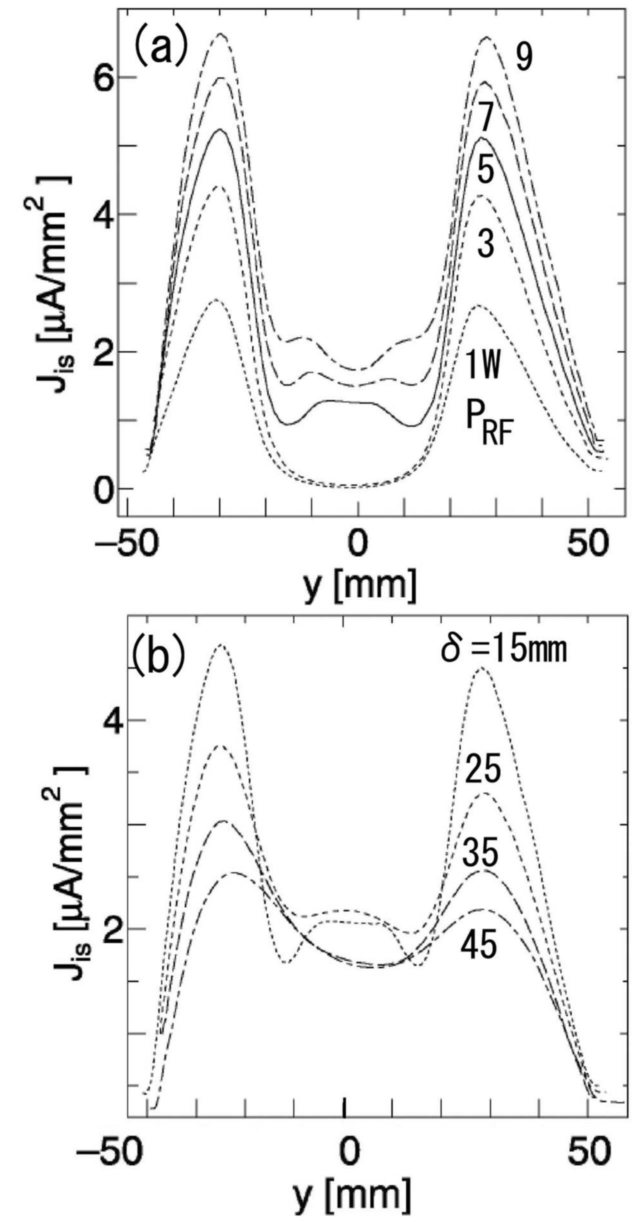

FIG. 2. Radial profiles of ion saturation current J_{is} with (a) rf power P_{RF} and (b) gap length δ as parameters: (a) δ=15 mm and (b) P_{RF}=5 W.

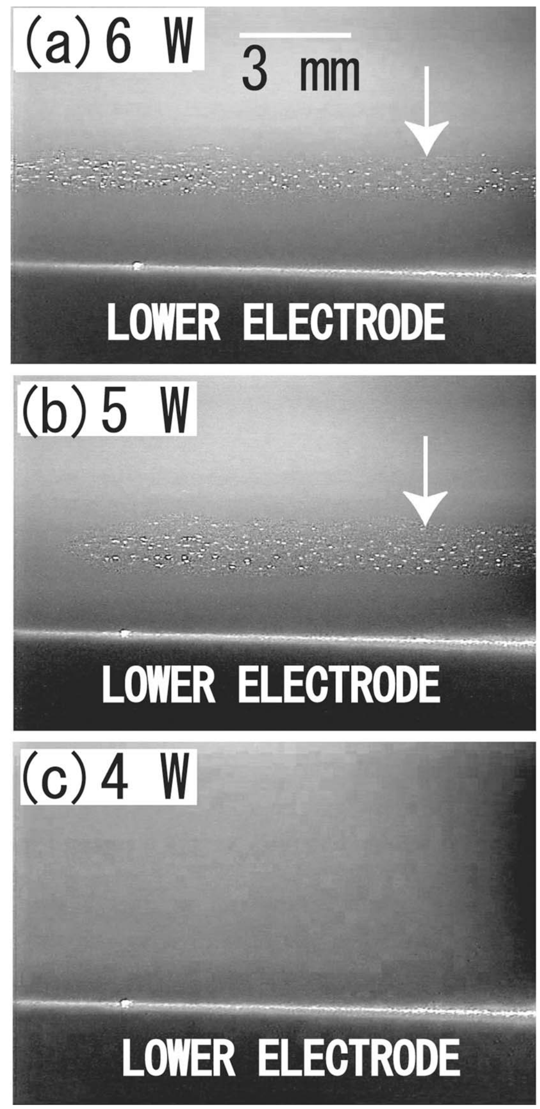

FIG. 3. Particle trapping in the ground experiment at P_{RF}=(a) 6 W and (b) 5 W as indicated by an arrow, and no trapping at (c) 4 W. δ=15 mm.

starts even in the dielectric cylinder region. This weak discharge can be sustained from the following two reasons. First, primary electrons can be supplied from the periphery A. Second, the strength of electric field at $y \cong 0$ is also increased by an increase in the rf power.

The fact that the plasma density has a hump at the center region means that the plasma potential also has also a small positive hump around the center, because the electron density n_e and the plasma potential ϕ satisfies usually the Boltzmann relation of $n_e = n_0 \exp(e\phi/\kappa T_e)$. Here, n_0 is the maximum density at $y=0$ and T_e is electron temperature. This means that the fine particles with negative charges can be easily trapped in a small positive potential hump ϕ. However, such a hump disappears with an increase in gap distance δ as shown in Fig. 2(b). When $\delta > 35$ mm, the hump in B vanishes but only diffusion plasma from A is observed. Anyway, fine particles can be trapped in the center region whenever the density hump is produced locally in region B.

When δ=15 mm, we inject fine particles of 10 μm into the center region. When P_{rf}=4 W, no particle levitation is observed in the center region, as shown in Fig. 3(c). Fine particles injected into the center region B are immediately transported toward outer region A, because the plasma potential is higher in region A. When P_{rf}=5 W, however, we clearly observe a trapping of fine particles as shown by an arrow in Fig. 3(b). These particles are levitated above the lower dielectric cylindrical electrode. When P_{rf}=6 W, the range for particle levitation spreads in the radial direction. This is consistent with the fact that the small hump produced in region B also spreads in radial direction with an increase in rf power.

The microgravity experiment has been carried out by a parabolic flight of an aircraft.[5] After reaching the microgravity fine particles are injected between the dielectric cylinders with spacing δ=15 mm. The particles are levitated in the middle between dielectric cylindrical electrode as indicated by an arrow in Fig. 4(a). The area within dotted box in Fig. 4(a) is enlarged, as shown in Fig. 4(b). We find a disklike particle cloud of about 3 mm width, in which many particles form a Coulomb fluid with fluctuated particle density. We find no void in the particle cloud.

We think that the electrostatic force is important for the particle trapping in region B, because the particles are

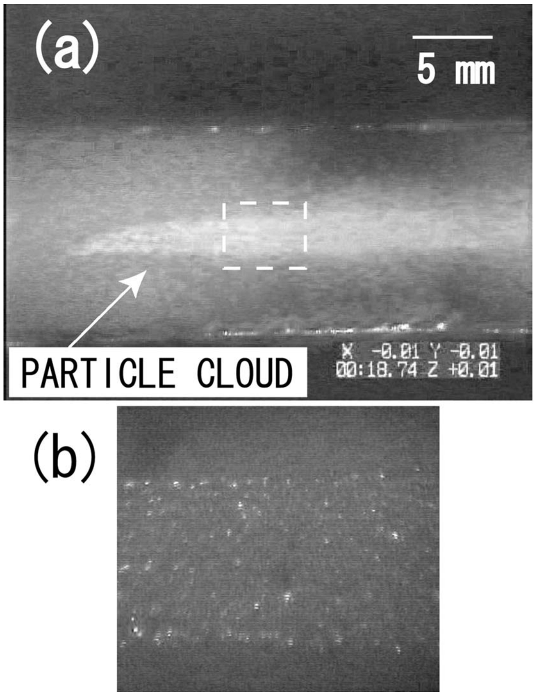

FIG. 4. (a) Trapping of void-free particle cloud under the microgravity. $P_{RF}=5$ W and $\delta=15$ mm. (b) Trimmed and enlarged area within dotted box in (a).

trapped only when weak discharge (small density hump) appears in region B. The ion drag force due to the ion flow from region A to region B may also drive the particle toward the center. However, this force is insufficient to trap the particles in region B, because no particle trapping is observed when rf power is less than 4 W as shown in Fig. 3(c), in spite of the fact that there exists ion flow from region A to region B.

In conclusion, we have demonstrated the production of low density plasma by introducing coaxially segmented rf electrodes. We have also verified that the dusty plasma can be trapped in the central region when the local discharge is triggered between the dielectric electrodes. This configuration is quite effective for producing void-free dusty cloud in a microgravity experiment.

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