Fine-Particle Clouds Controlled in a DC Discharge Plasma

Giichiro Uchida, Satoru Iizuka, and Noriyoshi Sato

Abstract—**The spatial shape of fine-particle clouds in a strongly coupled state is controlled by varying a radial potential profile provided by radially segmented electrode for particle levitation and confinement under a completely dc configuration. Fine-particle clouds change their shapes from a usual two-dimensional disk to a three-dimensional cone, and finally concave cone with an increase in the radial potential slope. These profiles are closely related to an axial variation of the radial potential profile in the ion sheath above the segmented electrode. When we apply to the segmented electrode a potential profile with peaks between the radial center and edge, fine particles are rearranged to form azimuthal rings on the horizontal plane. The radial width of the rings is controlled by changing the peak width of the radial potential profile.**

Index Terms—**Coulomb crystal, dc discharge plasma, dusty plasma, fine-particle cloud, potential control, segmented electrode, strongly coupled plasma.**

I. Introduction

FINE PARTICLES in plasmas are of current interest in various fields of plasma research and applications [1]. In plasmas, fine particle are negatively charged 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 [2]. Here, we are interested in shape control of fine-particle clouds which levitate in the presence of a vertical electric force against the gravity. Although various shapes of fine-particle clouds, such as dome [3], [4], ring [3], and funnel [5], were observed in the experiments, there has been no active shape control of fine-particle clouds in plasmas.

Our work has been carried out using a completely dc configuration to form and control fine-particle clouds which are in a liquid or solid (Coulomb lattice) state, depending on the experimental conditions [6]. 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 parameters and their spatial profiles in dc discharge plasmas in order to control fine-particle clouds. In this work, an electrode segmented radially is employed to provide an electrostatic potential profile necessary for particle levitation and confinement. Since fine particles are sensitive to the potential profile, we can control fine-particle clouds by changing a combination of potentials applied externally to the segmented parts of the electrode. Three-dimensional cone-typed and ring-typed fine-particle clouds are demonstrated to be well controlled in the experiment. These shapes are confirmed to be closely related to axial and radial potential variations provided by the segmented electrode.

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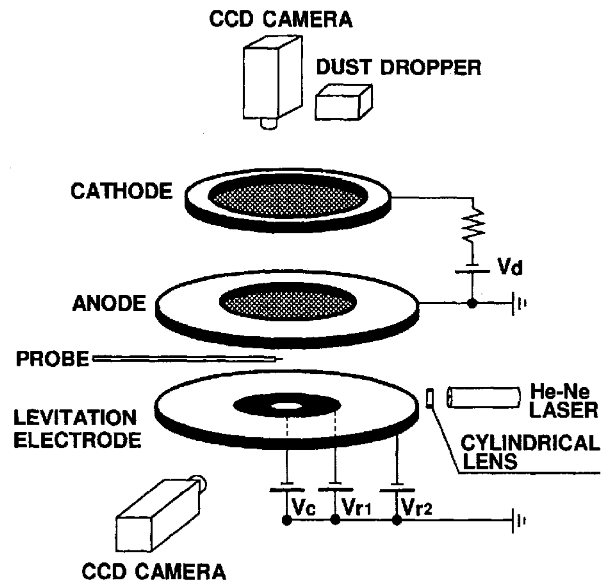

Fig. 1. Schematic of experimental apparatus. A segmented electrode (SE) is set below the mesh anode.

II. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. A dc argon discharge plasma is produced at a pressure of 220 mtorr by applying a negative dc potential of $-270 \sim -320$ V to an upper mesh cathode with respect to a middle mesh anode, which is grounded together to the metal vacuum chamber. The diameters of the mesh cathode and the mesh anode are 14 cm, and these electrodes are placed with a separation of 2.0 cm. The mesh size is 50 mesh/in for both of the cathode and anode. The plasma produced diffuses downward through the mesh anode. At a distance of 2.0 cm below the anode, a segmented electrode (SE), consisting of three electrodes, is set for particle levitation and confinement. A center electrode of the SE is a disc of 0.5 cm in diameter. Two ring electrodes are set around the center electrode. An inner ring electrode (ring electrode 1) of 0.6 and 1.5 cm in inner and outer diameters, respectively, is set in the same horizontal plane as the center electrode. An outer ring electrode (ring electrode 2) of 1.6 and 19 cm in inner and outer diameters, respectively, is set at 3 mm above the horizontal plane of the center and inner ring electrodes. Different dc potentials V_c, V_{r1}, and V_{r2} are externally applied to these electrodes in order to control a radial potential profile in the particle levitation

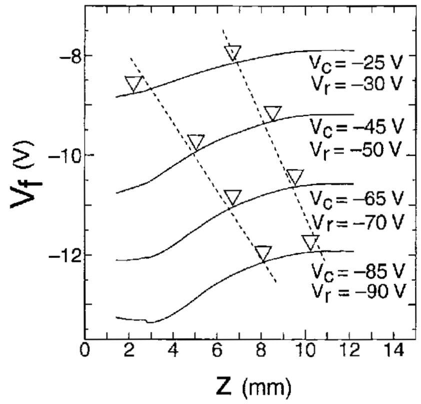

Fig. 2. Axial profiles of floating potential V_f in the dc sheath for various potentials of segmented electrodes. ▽ (open triangles) shows upper and lower positions of particle levitation. V_c is center electrode potential and V_r (= V_{r1} = V_{r2}) is ring electrode potential.

region. A small movable disk Langmuir 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 potential profiles in the region above the SE. Floating potential profiles are measured in the absence of fine particles. Fine particles used are spherical monodisperse methyl methacrylate-polymer of 1.17–1.20 g/cm^3, and of 10 μm in diameter ($\pm$1.0 μm size distribution). They are supplied from a sieve (dust dropper) into the plasma through the mesh cathode and anode, and are observed by the Mie-scattering of He–Ne laser sheet with a breath of 5 mm injected in the horizontal direction. To investigate fine-particle behaviors, charge coupled devices (CCD) cameras are used as detectors of the light signals from the side and top view ports. The signals detected are recorded on videotape and processed by a personal computer.

III. Experimental Results

A. Control of Axial Potential Profile

When the potentials applied to the center and ring electrodes, V_c and V_r (= V_{r1} = V_{r2}), respectively, are changed under a fixed condition of $V_c - V_r = 5$ V, axial profiles of floating potentials V_f are measured in the ion sheath region, as plotted in Fig. 2. With a decrease in V_c (and V_r), the potential profiles are observed to shift toward the upper region above the electrode for particle levitation. This result is due to the increase of the ion sheath width. Open triangles indicate upper and lower boundaries of fine-particle clouds. In our experiment, the ion drag force acting on a 10-μm-diameter particle is smaller by one order of magnitude than the gravitational force. Therefore, fine particles levitate at the point satisfying the condition of $Q(\partial V_s(z_0)/\partial z) \simeq M_d g$. Here, V_s is the space potential which is assumed to be proportional to V_f. This result shows that the axial position of particle levitation is controlled by changing the dc potentials applied to the electrode for particle levitation.

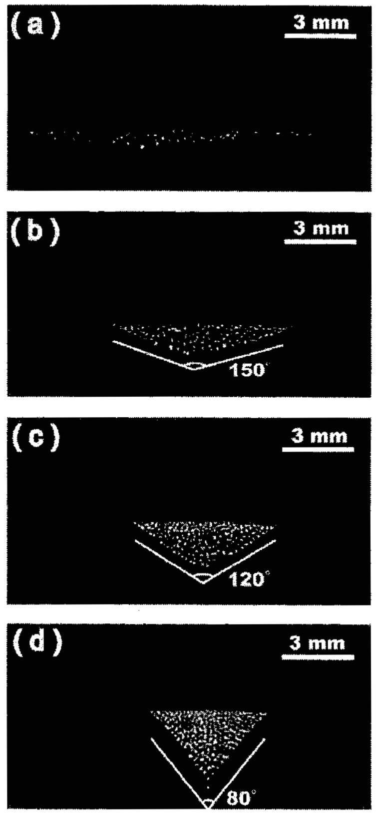

Fig. 3. CCD images of fine-particle clouds with different ring electrode potential V_{r2}. Center electrode and inner electrode potentials are $V_c = V_{r1} = -15$ V. (a) $V_{r2} = -10$ V (flat-disk shape), (b) $V_{r2} = -18$ V (convex-cone shape), (c) $V_{r2} = -27$ V (convex-cone shape) and (d) $V_{r2} = -37$ V (concave-cone shape).

B. Control of Radial Potential Profile

1) Formation of concave-cone clouds: The radial potential profile is controlled by the segmented electrodes. The potentials of the center and inner ring electrodes of the SE, V_c and V_{r1}, respectively, are fixed at $V_c = V_{r1} = -15$ V, while the outer ring electrode potential V_{r2} is varied from -10 V to -37 V to form a potential hill for confining fine particles above the center electrode. In case of $V_{r2} = -10$ V, as shown in Fig. 3(a), fine particles have a few particle layers and distributes two-dimensionally like a flat disc on the horizontal plane. By decreasing V_{r2} from -10 V to -18 V, the cloud is pressed toward the center. By this radial compression, the interparticle distance decreases from about 500 μm to 350 μm, and fine particles are pushed up in the vertical direction, resulting in an increase of the number of layers. A total width of the layers is changed from about 0.5 mm to 2.5 mm. It should be noted that the cloud shape is changed from a two-dimensional flat disc to a three-dimensional (3-D) cone as found in Fig. 3(b). The edge angle of the cone is about 150°. With a further decrease in the ring electrode potential, the cloud is more pressed toward the center. Then, a dome-like convex cone is formed at $V_{r2} = -27$ V, changing into a concave cone at $V_{r2} = -37$ V, as found in Fig. 3(c) and (d), respectively. When $V_{r2} = -37$ V, we clearly observe a concave cone with only one fine particle at the apex.

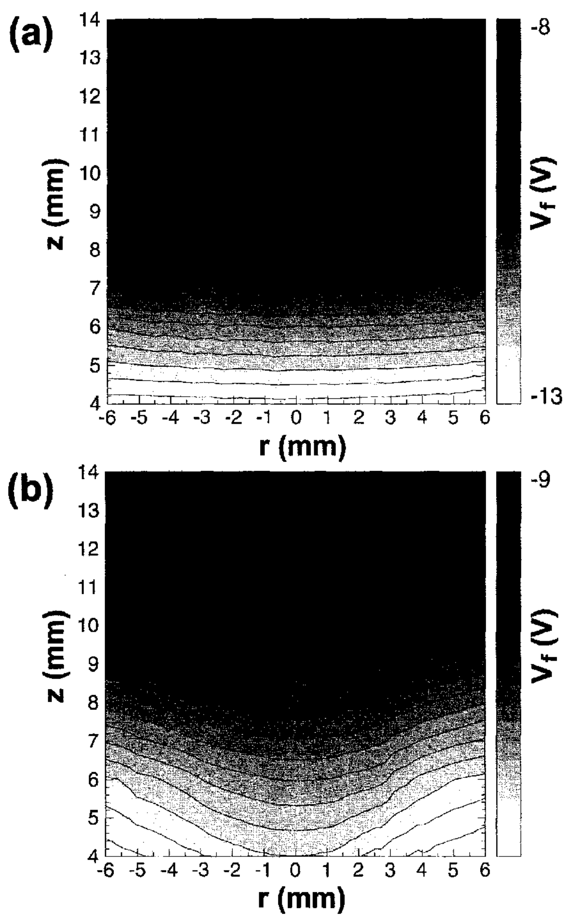

Fig. 4. Contour plots of floating potential V_f in the dc sheath. $V_c = V_{r1} = -15$ V. (a) $V_{r2} = -10$ V and (b) $V_{r2} = -37$ V.

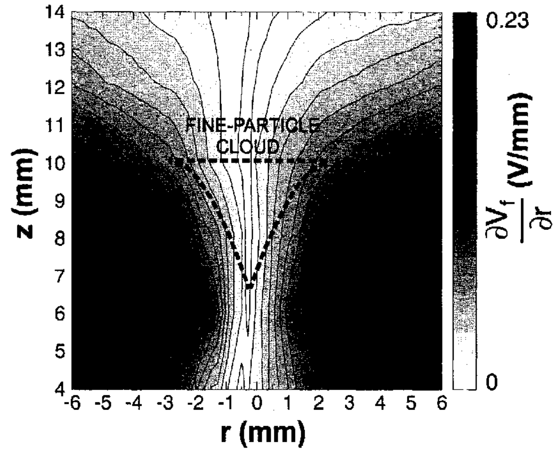

Fig. 5. Contour plots of floating potential gradient $\partial V_f/\partial r$ in the radial direction. $\partial V_f/\partial r$ is in the radial direction. $V_c = V_{r1} = -15$ V and $V_{r2} = -37$ V. Dotted area shows particle levitation region.

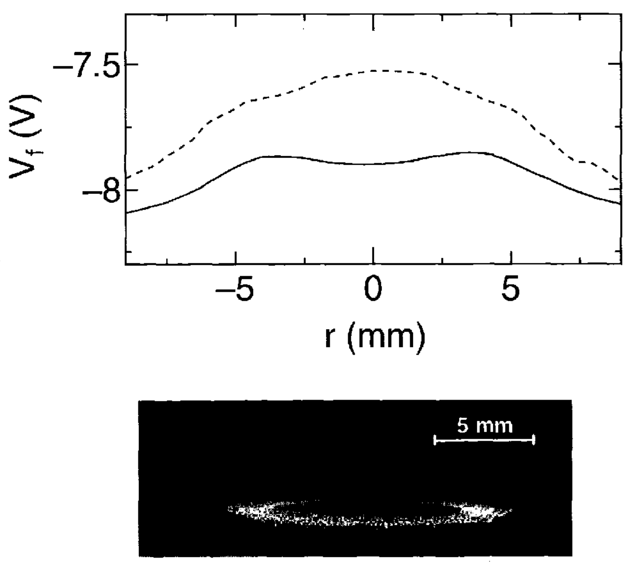

Fig. 6. (a) Radial profiles of floating potential V_f. Dotted curve corresponds to $V_c = V_{r1} = -20$ V and $V_{r2} = -50$ V. Solid curve corresponds to $V_c = V_{r2} = -50$ V and $V_{r1} = -20$ V. (b) CCD image of a ring-typed fine-particle cloud.

Contour plots of floating potential are shown in Fig. 4, where darkness is proportional to the potential. When $V_c = -15$ V and $V_{r2} = -10$ V, a potential hill confining fine particles above the center electrode is very gentle, as found in Fig. 4(a). On the other hand, a potential hill becomes very steep at $V_{r2} = -37$ V, as found in Fig. 4(b). The contour plots of radial potential gradient in this case are demonstrated in Fig. 5, where darkness corresponds to the strength of radial electric field. The potential gradient in the lower region is much larger than that of the upper region. Under this situation, a fine-particle cloud forms a concave cone. The levitation region of fine particles is indicated by a dotted curve in Fig. 5. Fine particles are almost confined along the equip-potential gradient contour. Therefore, the formation of a concave cone has a close relation to the axial variation of the radial potential profile.

2) Formation of ring-shaped clouds: Fig. 6(a) presents radial profiles of floating potentials at 7 mm above the SE. When the potentials of the center and two ring electrodes of the SE are fixed at $V_c = V_{r1} = -20 \text{ V} > V_{r2} = -50$ V, a potential hill with a peak at the radial center is formed as shown by a dotted curve in Fig. 6(a). When V_c is decreased from -20 V to -50 V, the potential profile changes to have a peak between the radial center and edge as shown by a solid curve in Fig. 6(a). Fine particles levitating in the central region are forced to move outward in the radial direction by a radial repulsive electric field in the central region, and a ring-typed fine-particle cloud is formed at a radial position of about 5 mm, as presented in Fig. 6(b). Fig. 7 shows a closeup photograph of the ring-shaped cloud from the top in case of small number of particles. In this case, only a few particles are confined in the radial direction of the ring, forming a narrow ring structure. By decreasing the particle number, it is possible to form as an azimuthal string of particles.

IV. Discussion

In case of $V_c = V_{r1} = V_{r2} = -15$ V, a drastic decrease in the electron density is observed at a distance of about 10 mm above the center electrode. Therefore, the ion sheath of about 10 mm in

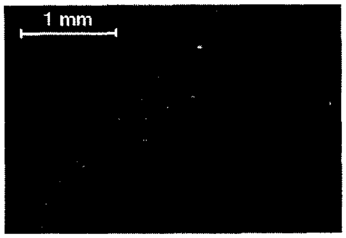

Fig. 7. CCD top-view image of a ring-typed fine-particle cloud. A few particles are confined in the radial direction of the ring.

width is considered to be formed above the center electrode. In our experiment, at a argon pressure of 220 mTorr, the mean free paths of ions and electrons are 0.2 mm and 1.2 mm, respectively. Therefore, the ion sheath formed is collisional. A space potential V_s decreasing toward the electrode is given by the following equation in the collisional ion sheath [7],

$$V_s(z) = -\frac{3}{5}\left(\frac{3}{2\varepsilon_o}\right)^{2/3} \frac{(en_s u_s)^{2/3}}{(2e\lambda_i/\pi m_i)^{1/3}}(z - L_s)^{5/3} \quad (1)$$

where

- e elementary charge;
- ε_o permittivity of free space;
- λ_i mean free path for ion momentum transfer;
- n_s ion density at the plasma-sheath boundary;
- v_s velocity at the plasma-sheath boundary;
- m_i ion mass;
- m_e electron mass;
- L_s is ion sheath width.

The axial potential profile calculated from (1) is plotted by a solid curve in Fig. 8. The result is well consistent with the measured potential profiles in Fig. 2. In the experiment, V_f is measured instead of V_s, because a variation of V_f is considered to be roughly proportional to that of V_s.

Two effects are important for the formation of concave cone-typed fine-particle clouds. The one is a spatial variation of potential structure. Just above the SE, a radial potential difference is almost equal to that of the SE ($z = 0$). However, in an unmagnetized plasma, the radial potential profile becomes flat within a quite short axial distance from the SE, as shown in Fig. 4(b). The difference of the radial potential gradients between the upper and lower layers of fine-particle clouds increases as the potential difference of the center and ring electrodes becomes larger, forming a concave cone structure as demonstrated in Figs. 3 and 5.

The other effect is the difference of the electrostatic coupling force among the particles in the upper and lower layers. The electrostatic coupling force between two particles is given by $F_E = (Q^2/4\pi\varepsilon_0 r^2)\exp(-r/\lambda_{De})$, where the Debye length λ_{De} is defined by $\lambda_{De} = ((e^2 n_e/\varepsilon_o kT_e) + (e^2 n_i/\varepsilon_o kT_i))^{-1/2}$. If the interparticle distance r is almost equal to the Debye length at each axial position, the interaction of the Coulomb force between fine particles is proportional to Q^2/λ_{De}^2. In the experiment, the width of the particle levitation region is about 3 mm in the axial direction, therefore, the charge of fine particles and the Debye length change layer by layer. The charge $Q = 4\pi a\varepsilon_o(V_f(z) - V_s(z))$ is smaller in the deeper sheath region. In case of Fig. 3(d), the charge of lower particles is estimated to be about 0.8 times that of upper particles, and the Debye length of the lower position is 1.2 times that of the upper position. Actually, the interparticle distance of the upper layer is shorter than that of the lower layer as found in Fig. 3(d). Therefore, the electrostatic interaction force between upper particles is about two times that of lower particles. Taking account of this force, upper particles tend to spread further in the radial direction than the lower particles. In Fig. 5, fine particles are almost confined along equip-potential gradient contour, but a little difference is observed between the fine-particle shape and equip-potential gradient contour. Upper particles are confined by the stronger electric field than that of lower particles. This difference of electrostatic coupling force in the upper and lower layers is considered to enhance a concave cone-typed structure of fine-particle cloud.

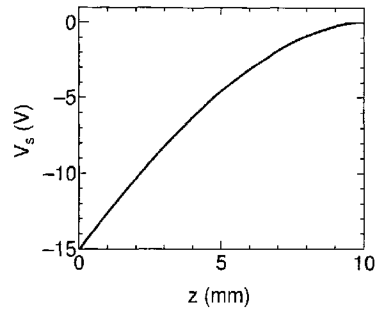

Fig. 8. Axial profiles of space potential V_s in the dc ion sheath. $T_e \simeq 2$ eV and $n_e \simeq 1 \times 10^8/\mathrm{cm}^3$.

Being concerned with the ring formation, by controlling the number of potential peaks in the radial direction, we can also form many rings in the dc ion sheath.

V. Conclusion

Fine-particle clouds of various shapes are observed by controlling the radial potential profile in the dc sheath, which is provided by a segmented electrode for particle levitation and confinement. According to the potential profile applied to the segmented electrode, fine-particle clouds have spatial shapes of disk, convex cone, concave cone, and ring. When the radial potential gradient to confine fine particles is large, fine particles form a concave cone. This is due to the fact that the radial potential profile becomes broad in the upward direction. The azimuthal rings are formed by apply to segmented electrode the potential profiles with peaks between the radial center and edge. Therefore, a segmented electrode is quite useful to control the spatial shapes of fine-particle clouds.

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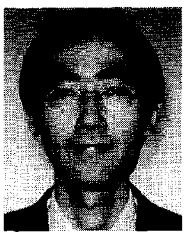

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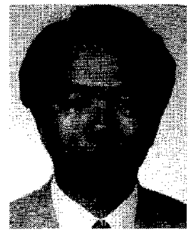

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