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Levitation of positively charged fine particles in a cross-field sheath between magnetized double plasmas

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Trapping of positively charged fine particles of micron size has been successfully achieved in a cross-field sheath between magnetized double plasmas with different potentials separated vertically by the horizontal magnetic field. In the sheath the charges on the particles become positive, because ion current flowing from a lower high-potential plasma surpasses electron current coming across the magnetic field from an upper low-potential plasma. Variation of particle levitation positions can be explained by the change of the electron current absorbed by the particles under an almost constant ion current. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1649991]

Fine particles of micron size introduced into weakly ionized plasmas are usually charged negatively due to the mobility difference between ions and electrons. The potential ϕ_d of the particles is lowered, against the local space potential, to suppress incoming electron current to make it equal to the ion current flowing into the particles. Consequently, the polarity of particle charge Q_d becomes negative. Under such circumstances, various characteristic phenomena concerned with a strongly coupled state of dusty plasmas,[1,2] such as the formations of Coulomb crystals, dynamic motions of Coulomb fluids, and various wave phenomena, have been reported.[3–7] By employing a completely dc-discharge plasma, it becomes possible to control the behavior of fine particles more systematically. The effects of vertical magnetic field on the fine-particle behaviors were also investigated and a rotational motion of fine-particle cloud has been observed.[8–10] Recently, in order to eliminate the effect of the gravity acting on the particles, microgravity experiments employing a parabolic fight of aircraft and/or a space station have been proposed, and characteristic features of fine particle behaviors have been discovered.[11,12] Under the microgravity condition using a parabolic flight experiment we have observed formations of a fine-particle cloud with a spherical void inside and a spherical fine-particle cloud with no void inside in a parallel plate and a spherical grid-cage rf discharges, respectively.[13]

For the formation of positively charged particles, there exist several methods such as ionization by high-energy electrons, secondary electron emission by an impact of high-energy ions, and photo ionization by ultraviolet irradiation.[14,15] However, the emitted electrons from the particles have a possibility to attach to the particles again, therefore consequently negatively charged particles will be produced simultaneously with some probability. Another way is to irradiate slow positive beam ions to the particles. The positive ions with large ionization potential subtract electrons from the neutral particles to create positively charged particles, and as a result the positive beam ions turn to neutral.

Concerning the confinement of positively charged particles, it is quite difficult to trap them in the conventional ion sheath. In order to sustain those particles, upward electric force is required at least to balance with the gravity. However, in the sheath formed below a ceiling wall surrounding the plasma, since the electric field strength gradually increases in the upward direction, the particles have to choose either being accelerated further toward the upper wall or falling down into the plasma. That is, the balance position satisfying the condition $F_G = F_E$ is quite unstable. Here, F_G and F_E are the gravity and upward electric forces, respectively. Therefore, we require an upward electric field diminishing gradually in the upward direction. In order to create such vertical electric field distribution, first we place another plasma source with low potential instead of the ceiling wall. Second, we apply magnetic field in the horizontal direction for the electron magnetization to suppress electron flow across the magnetic field toward the lower high-potential plasma.

Figure 1 shows a schematic of the experimental apparatus. Double plasmas (upper and lower plasmas) are produced independently along the horizontal magnetic field by dc discharges with different anode potentials and separated in the vertical direction by a cross-field sheath. The cathode–anode distance in both plasmas is 4 cm. The anode potential of the upper plasma is grounded, while dc bias voltage V_A can be applied to the anode of the lower plasma. When $V_A > 0$, we can produce electric field directed upward in the cross-field sheath region. In order to avoid a mixing of both plasmas, the strength of the horizontal magnetic field is kept in the range $B = 0.9–1.4$ kG. Therefore, we can fix the upper plasma potential almost grounded even when positive $V_A = 10–60$ V is applied to the anode of the lower plasma. In the cross-field sheath we set two parallel side walls of 1 cm high and 6.5 cm long at the both ends of the sheath perpendicular to the magnetic field. The distance between side walls is 2 cm. By applying positive dc voltage V_W to the side walls, the electrons entering into the sheath across the magnetic field can be immediately accelerated along the mag-

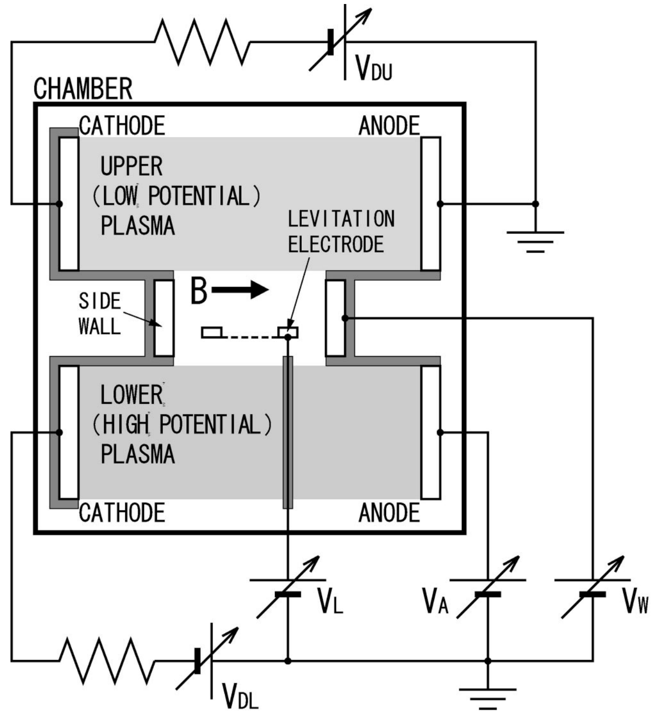

FIG. 1. Schematic of experimental apparatus.

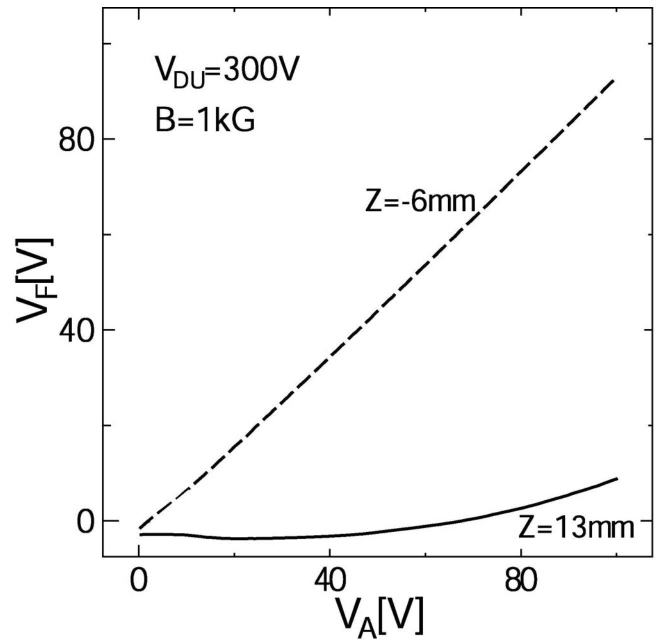

FIG. 2. Dependency of floating potential V_F in the upper ($z=13$ mm) and lower ($z=-6$ mm) plasmas on the anode voltage V_A of the lower plasma.

netic field and absorbed by the side walls. Therefore, we can constitute the sheath, where ion flux from the lower plasma dominates the electron flux from the upper plasma. Fine spherical particles of 1.5 μm in diameter, made of acrylic ball, are supplied into the upper plasma by a particle dispenser inserted into the upper plasma. Although first the particles are charged negatively in the upper plasma, the polarity turns to positive within about 1 ms when they are falling through the sheath. In order to confine the particles in the horizontal direction a levitation electrode of 9.7 mm in diameter and 0.8 mm thick with a hole of 4.6 mm in diameter at the center is placed in the sheath. Metal mesh of 100 lines per inch is spot welded on the backside of the levitation electrode to fix the potential in the central hole. We can apply positive dc voltage V_L to the levitation electrode.

We choose the argon pressure P_{Ar} and magnetic field B to meet the conditions $\rho_e \ll L \ll \rho_i$ and $\omega_{ci}\tau_{in} \ll 1 \ll \omega_{ce}\tau_{en}$ to extract ions from the lower plasma and to suppress electrons from the upper plasma. Here, ρ_j, ω_{cj}, and τ_{jn} are gyroradius, cyclotron frequency, and collision time with neutral atoms of electrons ($j=e$) and ions ($j=i$), respectively. We also choose the bias voltages to meet the condition $0 < V_L < V_W < V_A$. Therefore, the ions from the lower high-potential plasma can pass through the central hole of the levitation electrode placed in the sheath region. Henceforth, the gravitational force acting on the positively charged particles are balanced with the upward electric force that diminishes in the upward direction. In this way, positively charged particles can be stably sustained and confined above the levitation electrode.

Dependency of the floating potentials V_F on V_A is measured in the lower ($z=-6$ mm) and upper ($z=13$ mm) plasmas by a vertically movable probe of 0.45 mm in diameter and 4 mm long, which points to y direction. Here, vertical position z is counted from the lower edge of the side walls, x axis points to the anode, and y axis is perpendicular to both x and z. The cross-field sheath region is $0<z<L=10$ mm, and typically $B=1$ kG and $P_{\mathrm{Ar}}=20$ Pa. In the lower plasma the floating potential V_F increases almost linearly with V_A as shown in Fig. 2. However, in the upper plasma the potential V_F is almost fixed at about $-(2-3)$ V in the range $0<V_A<60$ V, and starts to be pulled up gradually by the lower plasma potential for 60 $V<V_A$. From these results we find that upward electric field E is generated in the sheath. Figure 3 shows a photo of the fine particle clouds levitated above the levitation electrode, where we find a few particles trapped, forming a Coulomb crystal with a spacing of $\sim$0.3 mm. Here, $V_A=40$ V, $V_W=20$ V, and $V_L=10$ V. The plasma densities in the upper and lower plasmas are $4.2\times10^7/\mathrm{cm}^3$ and $1.4\times10^8/\mathrm{cm}^3$, respectively. The average electron temperature in the both plasmas is $\sim$2.6 eV.

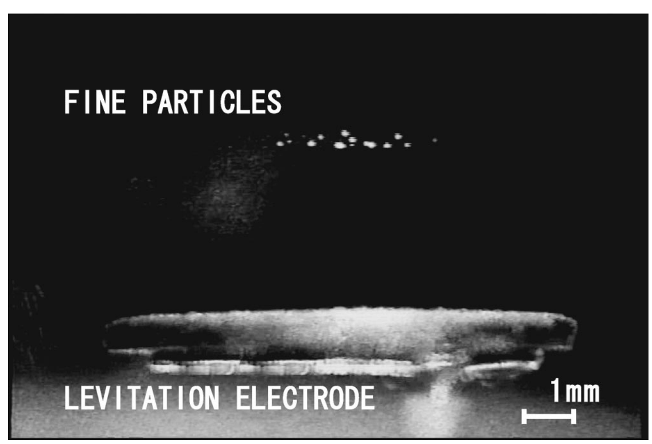

FIG. 3. Photograph of fine particles trapped above the levitation electrode.

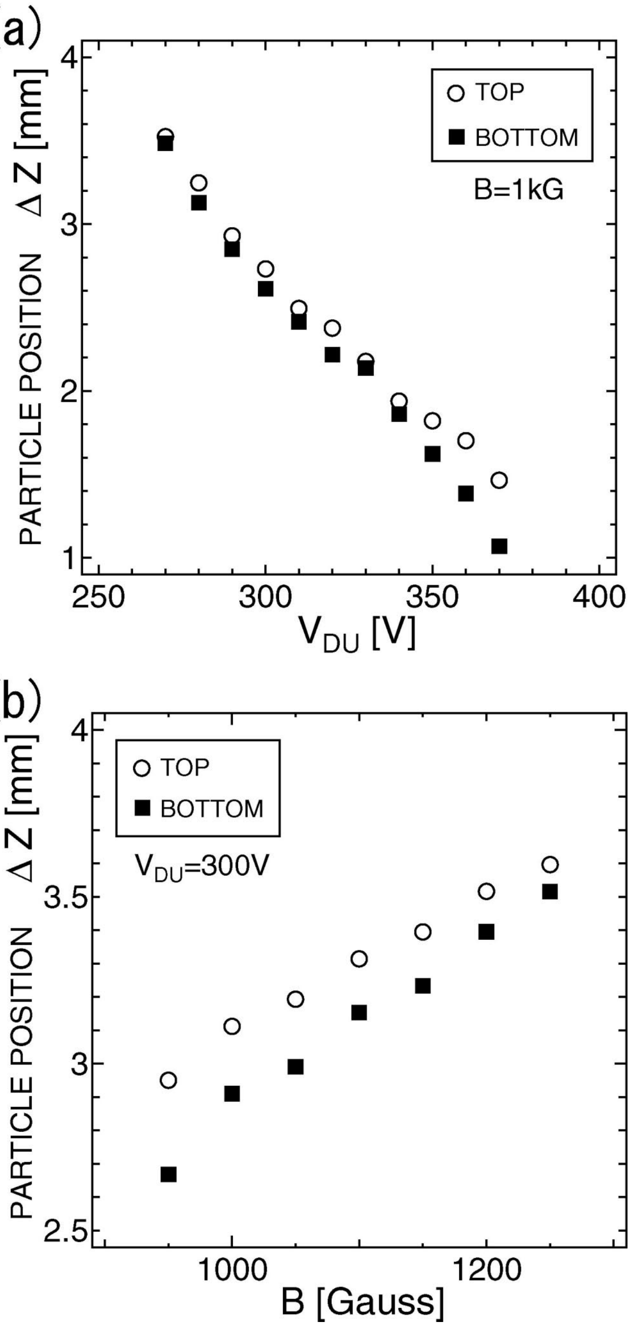

FIG. 4. Dependencies of the top and bottom particle positions Δz ($=z-z_L$) in a fine-particle cloud on (a) discharge voltage V_{DU} for the upper plasma production and (b) magnetic field strength B. The levitation electrode is set at $z_L=3$ mm.

Figure 4(a) shows the variation of the top and bottom particle positions Δz above the levitation electrode in a particle cloud as a function of the discharge voltage V_{DU} for the production of upper plasma. The position of the particles is shifted downward with an increase in the discharge voltage V_{DU}. This behavior can be explained by the following charging model. Since the collision mean free path λ_C ($\approx$0.4 mm) of ions with neutral atoms is much less than the cross-field sheath width $L(=10\text{ mm})$, the ions have to suffer many collisions during their motion across the sheath. Therefore, energy distribution function $f_i(W)$ of ions impinging on the fine particles is not a monochromatic, but has an energy spread of the order of $W_C/e \approx (\lambda_C/L)V_A$. Here, $W=(1/2)m_i v_i^2$, m_i is ion mass, and v_i is ion velocity. That is, the ions with energy $e\phi_d<W$ can overcome the particle potential ϕ_d. But, the ions with energy $0<W<e\phi_d$ are reflected by the positive particle potential ϕ_d. Therefore, the ion current that can be absorbed by the positively charged particle with surface area S_p is expressed by

$$I_i \approx \frac{e}{m_i} S_p \int_{e\phi_d}^{\infty} f_i(W)\,dW.$$

Since the particles are levitated in the sheath, the condition $I_i=I_e$ for the ion and electron currents flowing into the particles has to be satisfied in the steady state. Therefore, when I_e coming across the magnetic field from the upper plasma is increased by the increase in the discharge voltage, ϕ_d has to be decreased consequently to enhance I_i to make it equal to the increase in I_e. Then, the charge $Q_d(\approx 4\pi\varepsilon_0 a\phi_d>0)$ on the particles decreases, which shifts the particles downward direction for getting a stronger electric field E to satisfy the force balance equation $Q_d E \approx M_d g=$constant. Here, a and M_d are radius and mass of the particle, respectively. Similar dependency can be observed by increasing the strength of magnetic field B. Figure 4(b) shows the variation of particle positions as a function of B. The particles are shifted upward with an increase in B, showing that the reduction of I_e in the stronger B case leads to an increase in ϕ_d and as a result Q_d is increased, then the particles move toward a weaker electric field region in the upper direction. In the case of Fig. 3, the charge on the particles is estimated to be $Q_d/e \approx 80$ from the above force balance relation.

In summary, we have established a confinement of positively charged particles levitated in the cross-field sheath between magnetized double plasmas. Application of double plasmas and horizontal magnetic field is a key technique for producing upward directed electric field decreasing in the vertical position. In the cross-field sheath the condition that the ion current flowing into the particles exceeds the electron current is satisfied. The shift of the particle positions can be explained not only by the change of the charge but also of the plasma potential, when more electrons are leaking from the upper discharge by increasing the discharge current of the upper plasma or decreasing the strength of the magnetic field.

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