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Coulomb Cluster in a Plasma under Cryogenic Environment

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Coulomb cluster of dust particles in an RF helium plasma under cryogenic environment is observed experimentally. Background neutral temperature is controlled by cryogenic liquid such as liquid helium or liquid nitrogen. Dust dynamics in a sheath is studied. A dust injected into a sheath moves toward an equilibrium position where the sheath electric force balances with the gravitational force. Dust charge determined by oscillatory motion around the equilibrium position is found to decrease with decreasing ion temperature. A Coulomb cluster is formed in a horizontal plane and the temperature dependence of the interparticle distance in the cluster is studied.

Keywords: complex plasma, cryogenic plasma, dust, Coulomb cluster, charge, sheath, liquid helium

1. Introduction

A complex plasma includes micron size dust particles in a background plasma of electrons, ions and neutral particles. Dust charge is determined by the flux balance of electrons and ions at the dust surface and is usually negative because electrons move much faster than ions. Charged dust particles are confined in a plasma to keep charge neutrality [1]. The confined dust particles form Coulomb cluster and its state is characterized by a Coulomb coupling parameter defined by a ratio between Coulomb potential energy and kinetic energy of dust particles. Although a plasma is characterized by the coupling parameter much less than 1, the complex plasma is characterized by the coupling parameter larger than 1 because of large charge of dust particles. It is known that the state of the Coulomb cluster is affected by dust-neutral collisions since dust particles lose their kinetic energy through dust-neutral collisions [2]. The temperature of dust particles may be cooled down when neutral particles are kept at cryogenic temperature. With low dust temperature and high charge of dusts, the coupling parameter is expected to be further enhanced, suggesting the possibility of a strongly coupled state. Since the temperature of dust particles is easily controlled by background neutral temperature, a complex plasma with cold neutrals may be a good tool to investigate strongly coupled states or structural transition of dust particles.

Dust structure in an RF plasma cooled by liquid nitrogen was observed [3] and dust motion in the temperature range of 4.2 K to 300 K was investigated in our earlier experiments [4]. On the other hand, a DC discharge plasma under cryogenic condition was produced and the interparticle distance between dust particles was reported to decrease with decreasing temperature [5]. Theoretical study on a cryogenic complex plasma suggested that dust particles could form Coulomb crystal on the surface of liquid helium [6]. In this paper we report dynamics of dust particles in an RF discharge helium plasma under cryogenic condition and temperature dependence of the interparticle distance in the Coulomb cluster.

2. Experimental setup

Experimental setup is shown in Fig. 1. A glass tube of 70 cm in length consists of a thin part of 60 cm in length with 1.6 cm in diameter and a thick part of 10 cm in length with 5 cm in diameter. The tube is connected to an external stainless steel pipe at the flange. The glass tube is kept at room temperature or cooled by liquid helium (LHe) or liquid nitrogen (LN_2) in a Dewar bottle. An RF helium plasma is produced near the bottom of the tube in the thick part between two round plate electrodes of 8 cm in diameter with a 2 cm hole at the center mounted outside of the glass tube as shown in Fig. 1. The RF power of 1~7 W with 13.56 MHz is applied to

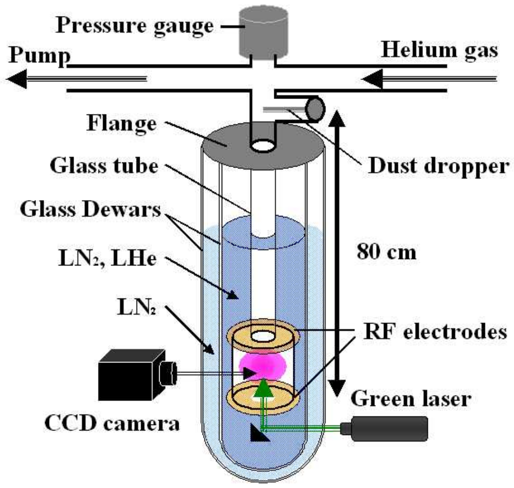

Fig. 1 Schematic of experimental setup.

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the electrodes to produce a plasma with density ~10^9 cm^{-3} and the electron temperature of a few eV. Acrylic particles of 0.4 μm in radius are dropped from dust dropper situated about 10 cm high from the flange. Neutral pressure is controlled in the range of 0.1 ~ 100 Pa and is measured by pressure gauge placed above the glass tube. The dust particles are illuminated by a green laser and are observed by a high-speed CCD camera through a mirror placed outside of the tube. Motion of a dust particle in the plasma dropped from dust dropper is observed and the dust charge is determined from oscillatory motion of the particle around an equilibrium position. The injected dust particle is suspended at the sheath edge by the balance of gravitational force and a sheath electric force. Acrylic particles with larger radii tend to fall onto the bottom of the tube and the size of particles is chosen to be able to levitate particles in a tube. Vertical motion of the dust particle is recorded by the CCD camera from the side. The z axis is in the upward vertical direction and z=0 is defined as the bottom of the glass tube. Next, more dust particles are introduced into the plasma and levitated as a Coulomb cluster at around an equilibrium position. The Coulomb cluster is viewed from the side as well as from the bottom. To observe a Coulomb cluster in a horizontal plane dust particles are illuminated from the side and are recorded by the CCD camera from the bottom of the glass tube through the mirror.

3. Dust dynamics in the sheath

Typical trajectories of dust particles in cryogenic environment are shown in Fig. 2. The time when a dust particle reaches the lowest position is set as T=0 and the time when the particle rises to the highest position is set as T=$\mathrm{T_s}$. The trajectories are characterized by the oscillatory motion around equilibrium positions, $z_1 \cong 8.5$ mm (4.2 K) and $z_2 \cong 30$ mm (77 K), where the sheath electric force balances with the gravitational force. A dust particle, dropped from the dropper located at 80 cm high from the bottom of the tube and gained kinetic energy in the gravitational field, reaches the plasma and gets a charge by absorption of electrons and ions. The charged dust particle with enough kinetic energy passes well over the equilibrium position and falls into the deep sheath reaching the lowest position $z_1 \cong 2.5$ mm (4.2 K) and $z_2 \cong 5$ mm (77 K). While the dust particle stays around the lowest position for a few seconds with some oscillatory motion, the dust particle starts to move up rather quickly and then oscillates around the equilibrium position with damping. Similar oscillation around the equilibrium position is also observed at room temperature.

It is noted that the dust charge Q_d varies in the sheath as it moves down because of the presence of ion flow and reduction of electron density. The electric field is stronger toward the bottom of the tube. Thus there are two positions where the sheath electric force $Q_\mathrm{d}E$ on a dust particle balances with the gravitational force $m_\mathrm{d}g$ (m_d is a dust mass) [7,8]. The lower balancing position is unstable in a sense that a particle moves away from the equilibrium position when perturbation occurs.

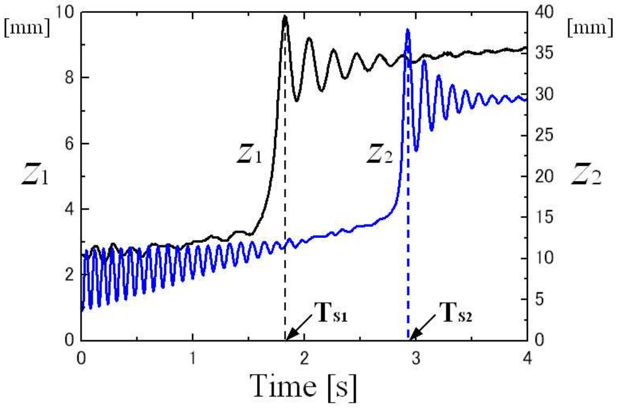

Fig. 2 Dust position as a function of time. Injected dust particles move upward to the equilibrium position. z_1 for 4.2 K, 0.6 Pa and z_2 for 77 K, 2.0 Pa.

Our observation of the dust trajectory in the deep sheath may shed a light on the nature of charge variation in the supersonic ion flow [9]. The presheath region is characterized by the slow ion flow, while the deep sheath is characterized by the supersonic ion flow with the Mach number M>>1 ($M = v_\mathrm{f} / \sqrt{k_\mathrm{B} T_\mathrm{e} / m_\mathrm{i}}$, v_f = ion flow velocity). Dust charge in the supersonic ion flow is determined by the flux balance of ions and electrons at the surface of the dust particle as [1]

$$\exp(-z_\mathrm{d}) = \sqrt{\frac{\pi m_\mathrm{e}}{8 m_\mathrm{i}}} \left[M + \left(4 z_\mathrm{d} + \frac{2T_\mathrm{i}}{T_\mathrm{e}} \right) \frac{1}{M} \right], \quad (1)$$

where $z_\mathrm{d} = |Q_\mathrm{d}| e / 4\pi\varepsilon_0 a k_\mathrm{B} T_\mathrm{e}$ is a normalized dust charge, a is a dust radius, $T_{\mathrm{e(i)}}$ is electron (ion) temperature, and $m_{\mathrm{e(i)}}$ is an electron (ion) mass. On the other hand, the dust charge is determined by the integration of Gauss law as $Q_\mathrm{d}(z) = 4\pi\varepsilon_0 a [\phi_\mathrm{d}(z) - \phi(z)]$, where $Q_\mathrm{d}(z)$ is the dust charge at a position z, $\phi_\mathrm{d}(z)$ is the dust surface potential and $\phi(z)$ is the sheath potential near the dust particle. The sheath potential satisfies the differential equation [10]

$$\frac{\partial^2}{\partial z^2} \left(\nabla^2 - \lambda_\mathrm{De}^{-2} \right) \phi + M^{-2} \lambda_\mathrm{De}^{-2} \nabla^2 \phi = 0, \quad (2)$$

where λ_De is the electron Debye length. The dust particle reaching the deep sheath well beyond the equilibrium position is trapped in x-y plane in the potential, where the sheath electric force balances with a gravitational force in z direction. The dust particle trapped in such a metastable state then starts to move upward to the stable equilibrium position.

The damping in the dust oscillation is caused by the neutral drag. The study of the decay time reveals the role of neutral particles in the dust dynamics, where a dust particle at a position z receives a drag force given by $-\gamma\dot{z}$ with a drag constant γ. The drag constant, defined by $\gamma=2m_d/\tau$ where τ is a decay time constant, may be approximated by the Epstein's drag constant as $\gamma \sim n_n m_n a^2 v_{th}$ [11], where n_n is neutral density, m_n is a neutral mass and v_{th} is the neutral thermal velocity. Figure 3 shows the inverse decay time constant τ^{-1} as a function of neutral pressure. The empirical formula from the straight lines in Fig. 3 is given by $\tau^{-1}/P=C_{Tn}$, where P is neutral pressure and C_{Tn} is a coefficient for a certain neutral temperature. We obtain $C_{4.2} \cong 6.0$, $C_{77} \cong 1.6$, $C_{300} \cong 0.8$ in the unit of m·s/kg, which guarantees the relation $C_{Tn} \propto T_n^{-1/2}$. This result confirms that neutral temperature in the glass tube is well controlled by the surrounding liquid. Although the electron temperature may remain hot in a discharge plasma, ions may be cooled through the interaction with neutral particles. The ion-neutral cross section for helium ions σ is $\sim 3\times10^{-19}\,\mathrm{m}^2$, while ion mean free path l_i in our experimental pressure range is l_i ~0.2 mm at 4.2K and l_i~1 mm in the range 77K to 300K. Since our plasma is much larger than the ion mean free path, the ion temperature is expected to be $T_i \sim T_n$ through the ion-neutral collisions.

4. Dust charge

The charge of a dust particle at the equilibrium position can be determined by the method established for the room temperature plasma sheath [12]. Figures 4 and 5 show the vertical dust positions around the equilibrium position where the time is measured from the time the dust reaches the highest position in the oscillatory motion. Figure 4 shows the damped oscillation with frequency lowered with decreasing temperature, while the equilibrium positions are lowered with decreasing temperature. Figure 5 shows dust trajectories at various pressures at 77 K. When the pressure is lowered, the equilibrium position becomes higher in z direction and oscillation becomes higher in frequency with smaller damping constant.

Dust charge is determined as [12]

$$Q_d(z_{eq}) = \frac{(m_d g)^2}{2k[\phi(z_{eq}) - \phi_0]}, \qquad (3)$$

where z_{eq} is the equilibrium position, k is the spring constant in the harmonic oscillation model, $\phi(z_{eq})$ is the sheath potential at the equilibrium position and ϕ_0 is the extreme value of the harmonic electric potential in a parabolic sheath potential model. In the observed dust oscillation with damping, the angular frequency is given by $\omega = \sqrt{(k/m_d) - \tau^{-2}}$ and the spring constant $k = m_d(\omega^2 + \tau^{-2}) = Q_d(z_{eq})[(d^2\phi/dz^2)_{zeq}]$. Dust charge is then determined as

$$|Q_d| = \sqrt{2\pi\varepsilon_0 a m_d(\omega^2 + \tau^{-2})z_0^2}, \qquad (4)$$

where $z_0 = z_{eq} + m_d g/k$. Dust charge, obtained by Eq. (4), is shown as a function of pressure in Fig. 6. Absolute value of the dust charge decreases with decreasing ion temperature in the range of 4.2 K to 300 K, as is expected by a collisional model [13], while charges remain nearly constant at a certain temperature for a change of pressure.

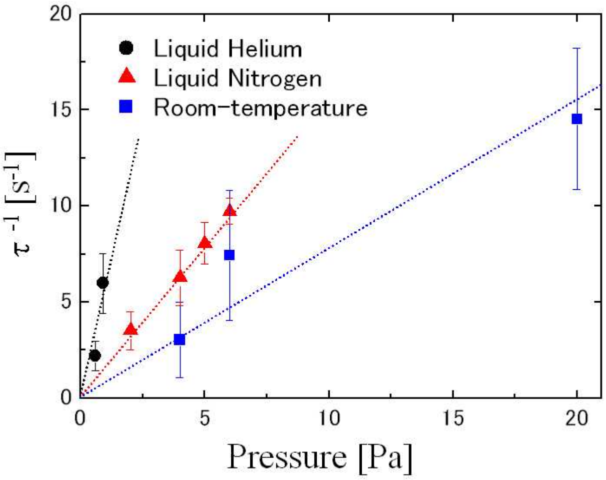

Fig. 3 Inverse decay time constant as a function of pressure for 4.2 K, 77 K and 300 K.

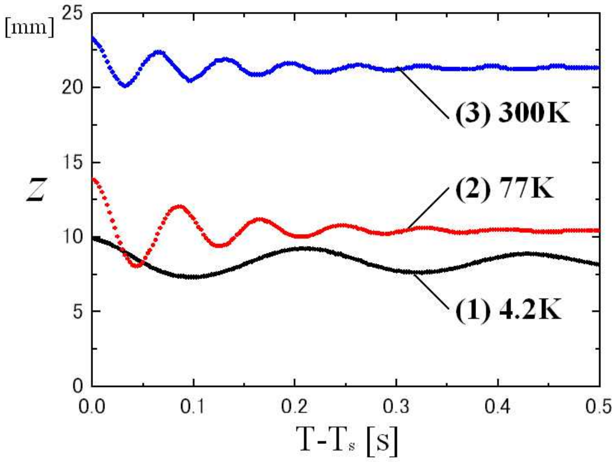

Fig. 4 Damped oscillations at equilibrium positions for (1) 4.2 K, 0.6 Pa (2) 77 K, 6.0 Pa (3) 300 K, 6.0 Pa. The equilibrium position and the oscillating frequency depend on the temperature.

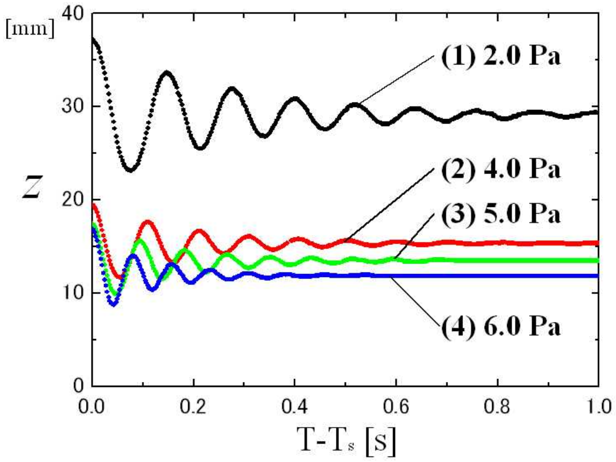

Fig. 5 Pressure dependence of equilibrium positions at 77 K for 2~6 Pa.

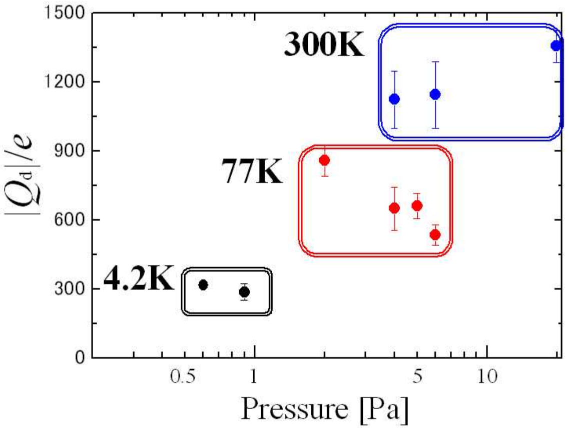

Fig. 6 Dust charge as a function of pressure for 300 K, 77 K and 4.2 K.

5. Coulomb Cluster in cryogenic environment

Typical dust trajectories at 4.2 K are shown in Fig. 7, where many dust particles are injected into the sheath region. After reaching the lowest position near the bottom of the tube, some dust particles move up in the sheath toward the equilibrium position without delay, while some dust particles stay at the lowest position for a while before moving up. Figure 8 (1) shows a snap shot of dust particles at 4.2 K from the side, revealing the presence of two groups of dust particles, one near the bottom of the tube and the other near the equilibrium position. In the steady state, dust particles form a Coulomb cluster in an equilibrium plane as shown in Figs. 8 (2) and (3). Figure 8 (2) is a top view of dust particles at 77 K, 60 Pa and Fig. 8 (3) is a top view of dust particles at 300 K, 60 Pa.

Average interparticle distance d in the cluster is $d \sim 0.5$ mm for Figs. 8 (2) and (3), which is on the order of the electron Debye length. Our finding is rather unexpected since shorter interparticle distance in cryogenic environment was reported earlier for dust particles with a=2.7 μm and was explained as a result of decreasing ion Debye length [5]. The interparticle distance is still an open issue in a complex plasma community. Generally, the screening length around a dust particle is considered to be given by an ion Debye length for a small dust particle ($a \ll \lambda_D$, where λ_D is a Debye length), while the screening length is considered to be given by an electron Debye length for a large dust particle ($a \gtrsim \lambda_D$). It may be worthwhile to note that the potential far from a dust particle scales as r^{-2} rather than the exponential decay if plasma absorption on the dust surface is properly treated in a quasineutrality condition [1].

6. Conclusions

Dust dynamics in a sheath is studied in a long glass tube, where the temperature of neutral particles is controlled in a range from 4.2 K to 300 K. Dust charge under cryogenic environment is determined by tracking dust oscillation around an equilibrium position where the sheath electric force balances with the gravitational force.

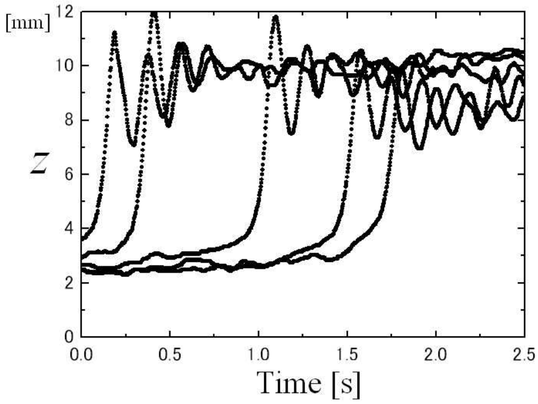

Fig. 7 Typical dust trajectories when many dust particles are injected at the same time. 4.2 K, 0.6 Pa.

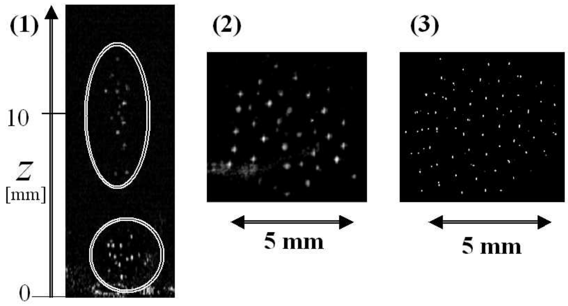

Fig. 8 (1) Side view of Coulomb clusters at 4.2 K, 0.6 Pa. (2) Top view of Coulomb cluster at 77 K, 60 Pa. (3) Top view of Coulomb cluster at 300 K, 60 Pa.

Obtained charge is found to decrease with decreasing ion temperature which is nearly equal to the neutral temperature. Coulomb cluster is observed in an equilibrium plane and the interparticle distance is nearly constant in the temperature range from 4.2 K to 300 K.

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