Dust Charge in Collisional Plasma in Liquid Helium Vapor

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A plasma was produced stably in liquid helium vapor and dust particles were introduced into the plasma. Some dust particles were trapped in the plasma and rotated around discharge electrode. Charge state of dust particles ejected from a plasma and deflected in dc electric field was estimated as $Q \sim -10^2$e through PTV analysis. The dust particles are found to lose their charge exponentially in position as they move away from the plasma toward the surface of the liquid helium. The reduction of the charge results from the lower ion temperature in liquid helium vapor.

Keywords: dust plasma, complex plasma, dust charge, liquid helium, collisional plasma, PTV analysis, decharging

1. Introduction

Most of dust plasma experiments in laboratories have been carried out at room temperature (300K), where plasmas are characterized by electrons with temperature of a few eV and ions with temperature of about 0.03eV. In such a plasma, micron-sized dust particles have large negative charges as a result of interaction with ambient plasma[1]. For example, in a typical laboratory plasma, a dust charge $Q = 4\pi\varepsilon_0 a\phi \sim -10^5$e where a=5μm and dust surface potential ϕ= -20V. With such a great amount of charge, electrostatic energy often exceeds thermal energy of dust particles, forming structures known as Coulomb crystals. In a gravitational field, sheet-like Coulomb crystals, two-dimensional (2D) structures, are observed at the sheath edge facing the electrode.

It has been shown that an ideal 2D crystals are formed by electrons on the liquid helium surface, called electron dimple lattice[2]. Each dimple contains about 10^5 electrons[3], which are equivalent with surface charge on a dust particle. In hope of forming 2D structures of micron-sized charged dust particles on liquid helium surface, we have conducted an experiment on dust plasma production in liquid helium vapor[4]. In the vapor, neutral gas temperature is quite low, and the ion temperature may be also lowered, resulting in the reduction of charge and weakening of electrostatic coupling among dust particles.

In our preliminary experiments, heat from large volume plasma caused abrupt temperature increase and then evaporation of liquid helium. So we had to generate plasma a several centimeters away from the liquid helium surface, causing a new problem of maintaining charge as dusts move toward the surface of the liquid helium. This is a reasonable question because of extremely high density of neutral atoms in liquid helium vapor. When neutral density is quite high like 10^{25} m^{-3}, surface charge of a dust particle will be decreased[5], and plasmas will localize around the electrode. Therefore, to measure a dust charge in the area of neutral background between plasma and liquid helium surface is an essential issue to understand physics of a dust plasma in cryogenic environment, toward the realization of 2D structure of dust particles on the liquid helium surface.

In this paper, we present the experimental results of a dust charge measurement using PTV (Particle Tracking Velocimetry) analysis in collisional liquid helium vapor. The PTV method is explained in Sec. 2. In Sec. 3, observed trajectories and estimated dust charge is explained. The variation of charge is discussed in Sec. 4. The charge reduction is compared with that in 1 atm helium gas at the room temperature in Sec. 5.

2. PTV analysis and models

In this section, a PTV analysis is briefly described. A micron-sized charged particle moves downward in gravitational field and the particle is deflected in the presence of horizontal electric field. The trajectory of the dust particles with charge Q and mass M_d in horizontal dc electric field E is described by

$$\upsilon_x = \frac{\Delta x}{\Delta t}, \upsilon_y = \frac{\Delta y}{\Delta t},$$
$$M_d \frac{\Delta \upsilon_x}{\Delta t} = QE - k\upsilon_x \quad (y \geq 0), \qquad (1)$$
$$M_d \frac{\Delta \upsilon_y}{\Delta t} = M_d g - k\upsilon_y,$$

where the coordinate x and y are set such that x is toward the same direction as horizontal electric field and y as the gravitational force. Here, k is the friction coefficient due to collisions between dust particles and neutral helium atoms, which is determined experimentally. In Sec. 5, we will use Stokes formula $k = 6\pi\eta a$ (η : viscosity coefficient of helium gas($\sim 1.96\times10^{-6}$ Pa·s), a : radius of a dust particle) and compare it with k obtained from the particle motion in y direction.

In our experiment, particle motion is recorded with a high-speed CCD camera ((c)Library, Himawari-SP200

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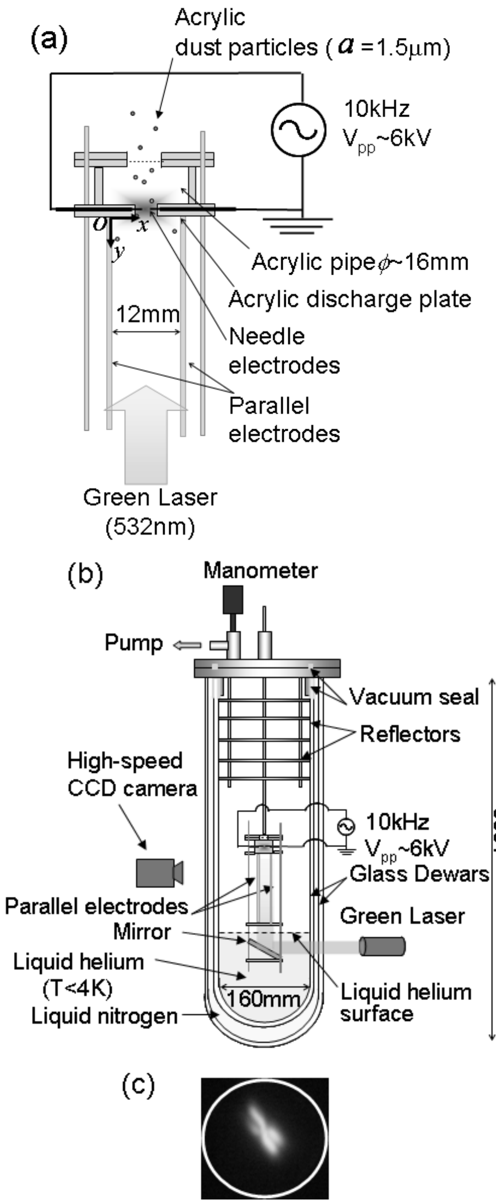

Fig. 1 (a) Schematic diagram of the measurement system. (b) Cryogenic glass Dewar system to impound liquid helium with temperature less than 4K. Green laser and camera are set in front of 20mm-wide optical slits. (c) Snapshot of plasma in liquid helium vapor.

system with 400fps) and particle positions on each frame are traced by image analysis system ((c)Library, Cosmos system, Software:Move-tr/2D). We use displacement of particle positions Δx and Δy and time Δt ~(1/400)sec between successive frames.

3. Experimental set up

Our measurement system is shown in Fig. 1(a), which is inserted in liquid helium vapor as shown in Fig. 1(b).

To make a discharge, AC voltage (10kHz, V_{pp}~6kV) was applied between needle electrodes separated by 2mm whose sizes were 0.5mm and 5mm in diameter and length. The needle electrodes were placed in a hole with 11mm in diameter on the discharge plate. Plasma was generated above the surface of liquid helium inside a Dewar bottle, where the liquid helium temperature and the vapor pressure was lowered by evacuation cooling to 1~4K and 300~1000Pa, respectively. The discharge region was found to localize around the needles from CCD image as shown in Fig. 1(c), since neutral particle density in liquid helium vapor was around 10^{25} m^{-3}. The bright discharge region had thickness of about 1mm, which is narrowly longer than the electron Debye length λ_{De} ~0.5mm with the plasma density and temperature on the order of $10^{15}m^{-3}$ and 5eV, respectively. Acrylic dust particles with the radius a~1.5μm are injected through stainless mesh and charged in the plasma. They move down in 12mm gap of parallel electrodes which are placed just below the acrylic discharge plate. Particles were irradiated by green sheet laser (532nm) which was reflected at right angles by small mirror. Particle trajectories between parallel electrodes with dc voltage applied were recorded by high-speed CCD camera through 20mm-wide optical slits on the Dewar.

4. Results

Typical trajectories are plotted in Fig. 2 when 30~90V are applied between parallel electrodes. Particles fell down almost in a straight line in y<0, and changed their trajectories at the vicinity of the plasma (-5<y<0 mm), although the trajectories in the discharge plate could not be clearly observed. Particles crossed the hole on the discharge plate with the thickness of 5mm for about 0.01sec, which was sufficiently longer than charging time

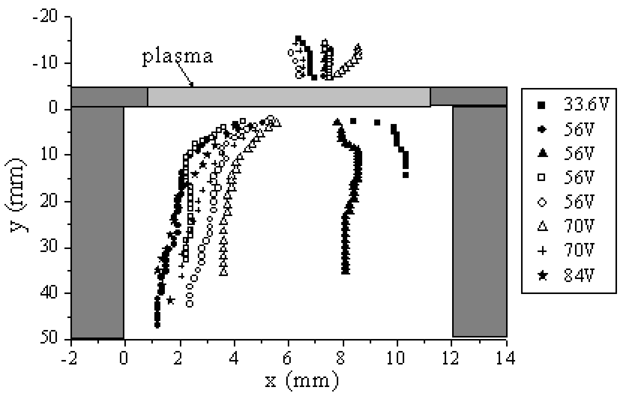

Fig. 2 Dust particle trajectories in liquid helium vapor, when 30~90V was applied between the parallel electrodes (The right-hand side electrode was grounded). The radius of particles is 1.5μm. Liquid helium surface is at y~100mm.

10^{-9}sec with plasma density on the order $10^{15}m^{-3}$. Depending on the initial velocity just after passing the plasma, some particles (~10%) were observed toward the grounded electrode against the electric field but they thereafter followed the electric field.

PTV analysis yielded dust charge $Q=Z_d e$ as a function of the vertical position y, and $|Z_d|$ is plotted in Fig. 3. Here, the friction coefficient k in eq.(1) was estimated k~10^{-13}kg/sec from the particle motion in y direction. We observed k was nearly constant with or without electric field. Particles lost their charges exponentially, in other words, decharging[6] occurred as particles moved away

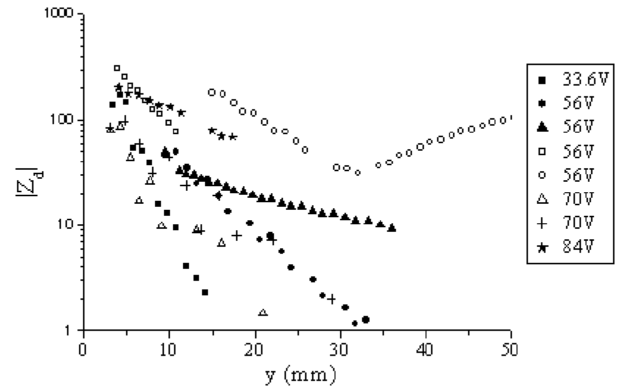

Fig. 3 Estimated dust charge from trajectories plotted with closed squares in Fig. 2 as a function of vertical position *y.*

from the plasma. The reduction of charge number was approximated by $|Z_d|=|Z_{d0}(4K)|\exp(-y/y_0)$, with the charge at the plasma $|Z_{d0}(4K)|$~10^2 and the charge reduction length y_0~9mm. Although the charge of particle moving against the electric field was positive (Q>0) in our model, a numerical calculation showed that particles with high positive velocity in x direction when ejected from plasma reproduce the observed trajectory even with the same $|Z_{d0}(4K)|$.

In the experiments, some particles were seemed to be trapped in plasma. However, the device configuration in Fig. 1(a) concealed particle trajectories near discharge region for CCD camera observation. Here, discharge system was modified such that particle trajectories near discharge region can be observed clearly; the discharge needle electrodes are plunged into a transparent rectangular parallelepiped tube with 30mm on side and 40mm on height. The gap between needle electrodes was 2mm, and AC voltage of 10kHz and V_{pp}~6kV was applied. The generated plasma region covers AC electrode like scabbard. Acrylic particles with the radius a=1.5μm are dropped from the center of ceiling of transparent rectangular parallelepiped tube The gap between parallel electrodes was set at 20mm.

Some trajectories of particles recorded on high-speed CCD camera are presented in Fig. 4. In Fig. 4(a), the particles bend its trajectory near the plasma and ejected against the electric field. The trajectory in Fig. 4(b) indicates the particle lost its kinetic energy and traced

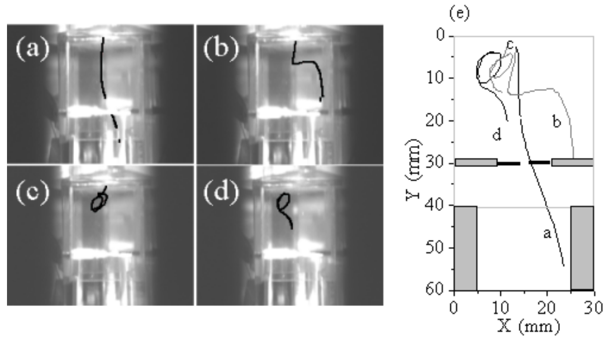

Fig. 4 (a)-(d): Photographs with particle trajectories in liquid helium vapor when 200V is applied to left-hand side of parallel electrodes while right-hand side electrode is grounded (Electric field E~7kV/m). The radius of particles is 1.5μm. (e):The trajectories were plotted with apparatus configuration of transparent rectangular parallelpiped acrylic tube.

equi-potential line near the electrically floating wall. Figures 4(c) and 4(d) clearly show swirling particles trapped in a potential near discharge region. They accumulated electric charges and rotated with repeated acceleration and deceleration, and was finally accelerated and expelled from closed orbit. Trajectories of these particles in and beyond the plasma were not observed in the present measurement system, but they would go against the electric field depending on incident angles to discharge region.

5. Discussion

The observed trajectories shown in Fig. 4 show that some particles were trapped above the plasma while others passed the plasma. The gravitational force for a particle is $F_g=2\times10^{-14}$N, while the electrostatic forces in the plasma is estimated to be F_E~10^{-14}N (Q~-10^2e) and F_E~10^{-13}N (Q~-10^3e) with the assumption of electrostatic potential drop 6V/cm (In Fig. 4, the particles moved in circles whose diameter was about 8mm.).When $F_E>F_g$, particles go up, while particles move down when $F_E<F_g$. In the region of dc electric field, the horizontal electrostatic force on the particles was about 5×10^{-14}N, so the particle trajectory was deflected. We consider the accumulated charge was different from the positions where particles come across the plasma. Thus, it is important to estimate plasma potential distribution near discharge region so as to estimate the charge variation of particles, which is our future work.

To study the effect of the cryogenic temperature, we performed a similar experiment in plasma in 1atm helium gas at 300K with the same neutral background density as in liquid helium vapor. The same system as Fig. 1(a), but with the gap between parallel electrodes expanded to 50mm, was placed in the stainless steel chamber filled with 1atm

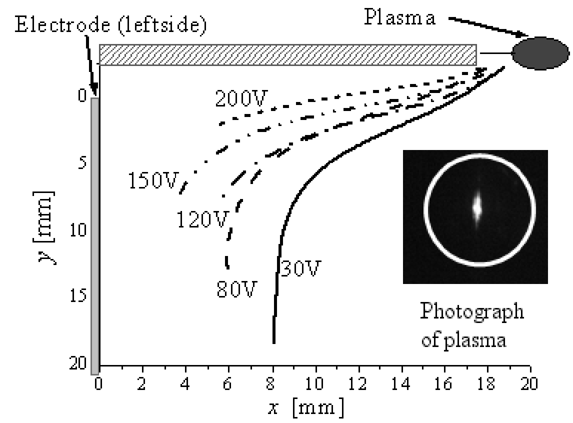

Fig. 5 Typical trajectories of dust particles with radius of 5μm in atmospheric-pressure helium plasma at 300K. The number labeled to each trajectory represent the applied voltage to the left-hand side electrode while right-hand side electrode is grounded.

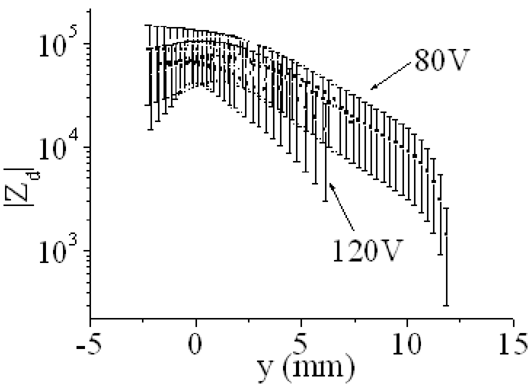

Fig. 6 Charge number $|Z_d|= |Q|/e$ as a function of the vertical position y with 80V and 120V applied between parallel electrodes.

He gas at room temperature. Typical trajectories of particles with the radius of a ~5μm are displayed in Fig. 5, indicating particles have negative charge. PTV analysis yielded $|Z_d|$, which is plotted in Fig. 6. Here, error bars stemmed from the uncertainty of friction coefficient k; k~$(2\sim4)\times10^{-9}$ kg/sec from particle motion in y direction and k~2×10^{-8} kg/sec from Stokes formula. Using Stokes formula is valid in this experiment, since the mean free path of helium atoms λ~0.2μm was sufficiently smaller than dust radius a ~5μm. Figure 6 shows that the reduction of charge number was approximated by $|Z_d|=|Z_{d0}(300\text{K})|\exp(-y/y_0)$ in $0\le y\le 6$ mm, and $|Z_{d0}(300\text{K})|=1\times10^5$ and y_0=3mm on the average.

The estimated charge at y=0 $|Z_{d0}(300\text{K})|=1\times10^5$ is reasonable, thus small $|Z_{d0}(4\text{K})|$ in liquid helium vapor was due to lowered ion temperature, apart from the difference of particle radius. Using $Q=4\pi\varepsilon_0 a\phi$ with the dust surface potential ϕ, the average charge reduction rate y_0 would indicate the electrostatic potential distribution around the plasma. It is found that even though neutral density is the same in 1atm helium gas at 300K and in liquid helium vapor, the plasma in liquid helium vapor may diffuse longer distance than in room temperature gas.

6. Summary

We succeeded in producing a plasma and measuring a dust charge in liquid helium vapor for the first time. Discharge region was localized around the electrodes due to high collisionality in ambient atmosphere. The PTV technique was used to estimate a dust charge along the trajectory. A dust charge was found to be lowered in liquid helium vapor than in 1 atm helium gas plasma at 300K. It is also found that the charge decrease exponentially, *i.e.*, decharging occurred, as leaving the localized discharge region. The decharging process is an important issue[6] in complex plasma, although the decharging process in our study is not well understood.

A few particles were confined in electric potential and exhibited rotating orbits above the discharge electrode. Some particles moved down into the region of dc electric field and changed their trajectories. In fact, when a large quantity of particles were introduced, they showed uniform rotation like vortex, which may be recognized as a kind of complex plasma.

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[1] O. Ishihara, J. Phys. D: Appl. Phys. **40**, R121(2007).
[2] H. Ikezi, R. W. Giannetta, and P. M. Platzman, Phys. Rev. B **25**, 4488 (1982); H. Ikezi, Phys. Rev. B **27**, 585 (1983).
[3] P. Leiderer, *Two-Dimensional Electron Systems*, ed. by E. Andrei, Kluwer Academic Publisher, 1997, p. 317.
[4] C. Kojima, M. Kugue, T. Maezawa, M. Shindo, Y. Nakamura, and O. Ishihara, 13th ICPP (2006, Kiev, Ukraine) E134p.
[5] S. A. Khrapak, G. E. Morfill, A. G. Khrapak, and L. G. D'yachkov, Phys. Plasmas **13**, 052114 (2006).
[6] A.V. Ivlev, M. Kretschmer, M. Zuzic, G. E. Morfill, H. Rothermel, H. M. Thomas, V. E. Fortov, V. I. Molotkov, A. P. Nefedov, A. M. Lipaev, O. F. Petrov, Yu. M. Baturin, A. I. Ivanov, and J. Goree, Phys. Rev. Lett. **90**, 055003 (2003).