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Interaction between dust particles charged in a plasma and electrons on liquid helium surface
プラズマ中で帯電した微粒子と液体ヘリウム表面上の電子との相互作用

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Micron-sized particles with negative charge and larger mass density than liquid helium (LHe) are dropped onto the LHe surface charged with electrons emitted from a hot filament. When a plasma is produced a few cm above the surface, abrupt incease in LHe temperature makes floating particle observation difficult. In the presence of electrons emitted from a hot filament on the surface, particles negatively charged are observed floating and drifting on a horizontal plane a few mm below LHe surface. Interparticle distance is identified to be on the order of the wavelength of surface waves. Our analytical study suggests that dust particles float as a result of the interaction with the charged LHe surface .

1. Introduction

A two dimensional structure of micron-sized charged dust particles in a plasma is studied for the purpose of observing dust waves and modeling low-dimensional material properties. Since LHe provides an ideal flat surface and has strong surface tension enough to sustain dust particles, we have tried to charge up dust particles in plasmas generated in LHe vapor and drop the particles on LHe surface[1]. In this study, a new experiment is proposed to levitate charged dust particles on the charged LHe surface.

2. Particles and LHe surface with electrons

When electrons approach to LHe surface, they are trapped on the surface via image force[1], so an electron sheet appears on the surface. Under the existence of the vertical electric field E_0 at the surface, the electric forces and the restoring forces for a flat surface (surface tension and gravity) produce surface waves with the dispersion relation[2,3]:

$$\rho\omega^2 = \rho g k + \gamma k^3 - 2\varepsilon_0 E_0^2 k^2 \qquad (1)$$

where ρ expresses the mass density of the liquid, g the gravitational acceleration, γ the surface tension and E_0 the applied external electric field. Equation (1) indicates that instability appears at a critical field $E_c=[4\rho g\gamma/\varepsilon_0^2]^{1/4}$ and the wave vector where the instability develops is $k_c=[\rho g/\gamma]^{1/2}$. The surface waves with $k=k_c$ become unstable when $E \geq E_c$, and a new equilibrium state in the charge distribution develops, resulting in dimple formation. Typically, a dimple contains 5×10^6 electrons and has depth of a few tenths of a mm and a width of $\sim k_c^{-1}$, a few mm. The charged surface wave and dimples on the charged LHe surface are expected to interact with charged particles near the surface.

2. Experimental apparatus

The experimental setup is shown in Fig. 1. Liquid helium is transferred into a glass Dewar bottle, and its temperature is lowered by evacuation cooling to 1~2K. Inside the Dewar, a set of four electrodes are placed as described in Fig. 1(b), which is movable vertically such that LHe surface is placed inside acrylic tube with the inner diameter of 40mm. Electrons are emitted from 1% thoriated tungsten filament of 0.05mm in radius which is heated with the direct current of about 1A and biased by V_f=-6V. Heating of the filament brings slight increase in LHe temperature. The emitted electrons are extracted through the hole with stainless mesh (100mesh/inch) with the diameter of 10mm at the bottom of the chamber by the accelerating electrode biased by V_a=10~20V toward LHe surface. The electron density on LHe surface is controlled by filament current, V_f and V_a. The upward electric field is yielded between the bottom and the ground electrode by applying dc voltage V_b. Acrylic particles with 3 μm in diameter and 1.16 g/cm^3 in mass density are dropped from the top. They obtain negative charge in the electron source chamber and fall onto LHe surface. A green laser (532nm) irradiates the horizontal plane along the surface and particles are recorded by CCD camera.

An RF plasma (10kHz or 13.56MHz) is produced in the electron source chamber, but it causes abrupt temperature increase which results in the perturbation on the surface. Thus, we could not observe any floating particles during plasma production in the present study. The suppression of the perturbation on the surface is now under consideration.

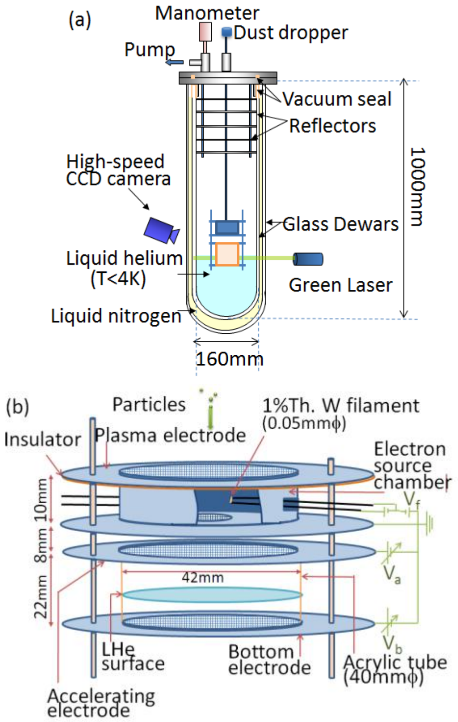

Fig.1. Schematic diagram of the measurement system: (a) Cryogenic double glass Dewar system to impound liquid helium with temperature less than 4K. Green laser and camera are set in front of 20mm-wide optical slits. (b) Electrodes with an electron source chamber immersed in LHe.

3. Results and discussion

Electrons were constantly supplied from the filament during the experiment, and thus the vapor pressure increased slowly from 240Pa to 645Pa, corresponding LHe temperature from 1.4 to 1.6K. As increasing V_b>2.5kV (corresponding E>1.1kV/cm), small ripples were observed on LHe surface, and then strong perturbations appeared followed by the surface collapse as observed earlier[4]. Since no perturbations occurred without filament emission for V_b>2.5kV, we can conclude that LHe surface is successfully charged by electrons and surface instability developed when V_b>2.5kV. In case V_b =0V with filament emission, particles penetrated the surface toward the bottom electrode. When dropping dust particles after setting filament current and electric field strength properly so as not to generate the instability, some of them were found drifting on the horizontal plane 2mm below the surface. Figure 2 shows a snapshot of dust particles drifting in one direction on the plane at a speed of 6mm/sec. The direction of the drift is indicated by the arrow in the figure. These particles disappeared when they reach the acrylic wall. Reversing the polarity of the electric field suddenly, all floating particles fell down to the bottom electrode. These experimental facts indicate that charged dust particles interact with the surface charge. The interparticle distance was about 1.8mm, which is identified to be on the order of the wave length of the surface wave given by $\lambda = 2\pi / k_c$ ~3mm obtained with the liquid properties corresponding to the present experiment; ρ =0.15g/cm^3 and γ =3.3$\times$10^{-4}N/m at the vapor pressure of 645Pa. The applied electric field was about 1kV/cm, much less than predicted E_c ~4kV/cm, but further increase of the field resulted in the strong perturbation of surface as mentioned before. Because of the weaker electric field than E_c, dimple formation was not observed in the present experiment.

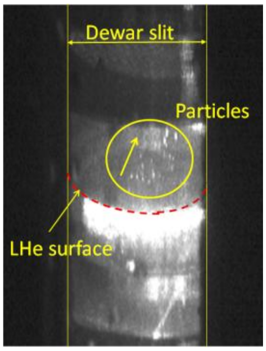

Fig.2. A snapshot of drifting dust particles irradiated by laser sheet below LHe surface. Periphery line of LHe surface and slit lines on the Dewar are included as references.

4. Summary

Floating charged dust particles 2mm below LHe surface is observed clearly. Our analysis suggests that charged particles float as a result of interaction with the charged LHe surface.

Acknowledgments

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References

[1] M. Shindo, N. Uotani and O. Ishihara: J. Plasma Fusion Res. Series **8** (2009) 294.

[2] M. W. Cole and M. H. Cohen: Phys. Rev. Lett. **23** (1969) 1238.

[3] K. Mima, H. Ikezi and A. Hasegawa: Phys. Rev. B**14** (1976) 3953.

[4] P. Leiderer: in *Two-dimensional electron systems*, ed. by Eva Y. Andrei, Kluwer Academic Publishers, 2010, pp. 317-339.