Dust Dynamics in Wake Channel

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Abstract

Dynamics of dust particles in an rf discharge plasma is studied. The plasma is produced in a glass tube of 16 mm in diameter and 680 mm in length. Dust particles are introduced into the plasma from the top of the glass tube. A sheath is formed near the bottom of the glass tube. A dust particle charged negatively in the plasma moves downward into the sheath and is observed to move upward against gravity, while two dust particles injected into the sheath interact each other and are observed to form a vertical pair along the ion stream. The lower dust particle is trapped in the wake potential formed by the upper dust particle in the ion flow. A pair of dust particles is observed to move upward together against gravity in the wake channel.

1. Introduction

Dust particles in plasmas are studied extensively in laboratory as well as in space [1]. Plasmas with dust particles are now called as a complex plasma because of the nature of interaction between charged dust particles and a background plasma. Dust particles in a plasma are negatively charged due to the difference of mobility of electrons and ions. Among many unique features in a complex plasma, a wake potential is known to produce a pair of dust particles both charged negatively [2,3,4]. Near a boundary of any kind, a plasma loses its charge neutrality and the region is called a sheath. The wake potential is formed behind a dust particle along the ion stream in the sheath. The formation of a dust pair is considered as a result of phonon exchange between two dust particles as a Cooper pair in the superconductivity [5]. A presheath is a transition region between a plasma and a sheath and is characterized by a subsonic ion flow with $M < 1$, where M is a Mach number. In a sheath toward the boundary, there is a region of supersonic ion flow with $M > 1$ and M becomes larger toward the boundary. Dust particles have been used to study the characteristics of the sheath as a tool of diagnostics [6-11]. In the present study we report dynamics of a pair of dust particles in the sheath especially in supersonic region under the gravity.

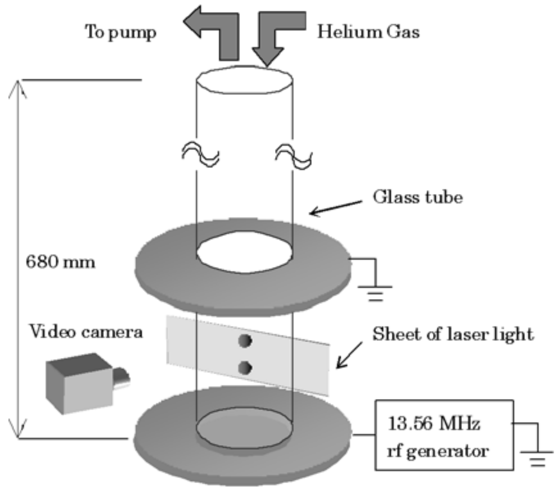

Fig. 1 Schematic diagram of experimental setup

2. Experimental setup

Fig. 1 shows an experimental setup with a glass tube of 16 mm in inner diameter with 680 mm in length. The upper part of the glass tube is connected to a vacuum system. A helium gas is introduced and is evacuated from the upper part of the glass tube. A pressure gauge at the top of the glass tube monitors the helium pressure as about 25 Pa. A capacitively coupled plasma is produced by radio-frequency (rf) discharge applied between two

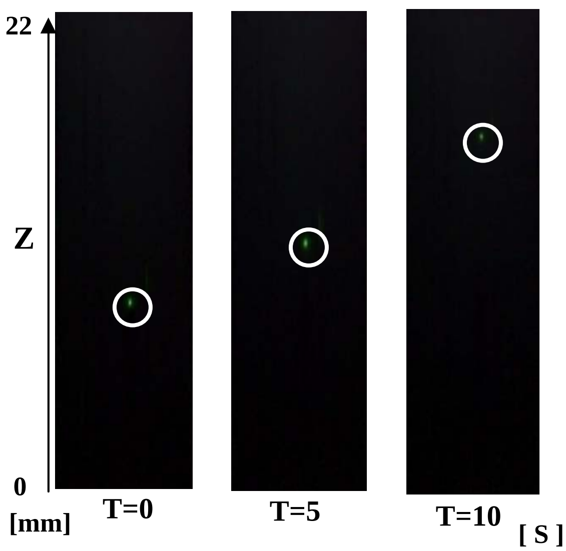

Fig. 2 A single dust motion in the sheath. The dust particle injected from the dust dropper moves deep into the glass tube and reaches a position of z= 8.5 mm. The dust particle moves upward until z=17 mm.

ring electrodes with 13.56 MHz and power 25 W. An upper ring electrode is 60 mm away from a lower ring electrode which is mounted at the bottom of the glass tube. The upper ring electrode is grounded and the lower ring electrode is connected to an rf generator. Acrylic particles of 10 μm in diameter are dropped into the plasma from the dust dropper situated nearly top of the glass tube under gravity. Because of the long vertical length dust particles travel in the glass tube, and the gravitational potential energy is transformed into a kinetic energy of a dust particle. The charged dust particle with enough kinetic energy will be moving into the plasma. Dust particles will be negatively charged once enter the plasma. Negatively charged dust particles will penetrate into the plasma and could dive well inside the sheath. Dust particles in the sheath are illuminated by a thin sheet of green laser light. Images of dust particles are filmed by a video camera at a frame rate of 30 s^{-1} from a side of the glass tube and analyzed by PTV (Particle Tracking Velocimetry) system.

3. Experimental results

3-1 Single dust particle

Fig. 2 shows a dust particle in the sheath at T= 0, 5 and 10 seconds, where T= 0 is the time when the dust particle reaches the lowest position in the glass tube. The dust particle injected from the dust dropper moves deep into the glass tube and reaches a position of *z*= 8.5 mm, where *z* is in a vertical direction measured from the bottom of the glass tube. Once the dust particle reached the lowest position, the dust particle was observed to move upward till $z \approx 17$mm. Trajectory of the dust particle is obtained by using PTV system from images of moving the dust particle as shown in **Fig. 3**. The upward movement of the dust particle against the gravity may be understood from the energy consideration along the z direction. The part of the gravitational potential energy is transformed into a kinetic energy of a dust particle. The charged dust particle with enough kinetic energy will be moving into the sheath where the sheath electric field pushes the dust particle upward. Thus the total energy of the dust particle at a position in the sheath is given by [7,8]

$$E(z) = U_g + U_e, \qquad (1)$$

where U_g is the gravitational potential energy given by mgz, and U_e is the electric potential energy given by $QV(z)$ with Q (< 0) a charge of a dust particle and $V(z)$ the space potential. A single dust particle can be used to study the structure of the total energy by analyzing trajectory of the dust particle [6]. The equation of motion for a single dust particle with mass *m* is given by

$$m\frac{d^2z}{dt^2} = -b\frac{dz}{dt} - \frac{dE}{dz}, \qquad (2)$$

where *b* is the drag constant due to neutral gas friction

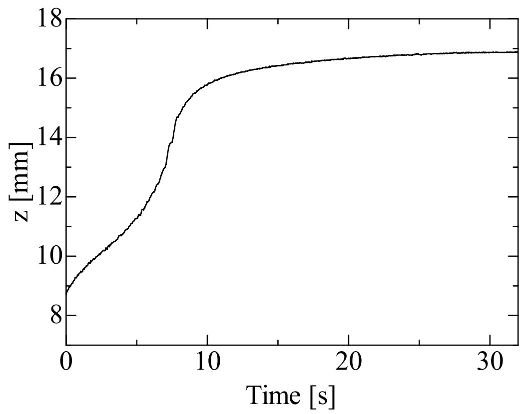

Fig. 3 Trajectory of a single dust particle in the sheath. The single particle moves upward till $z \approx 16.5$ mm.

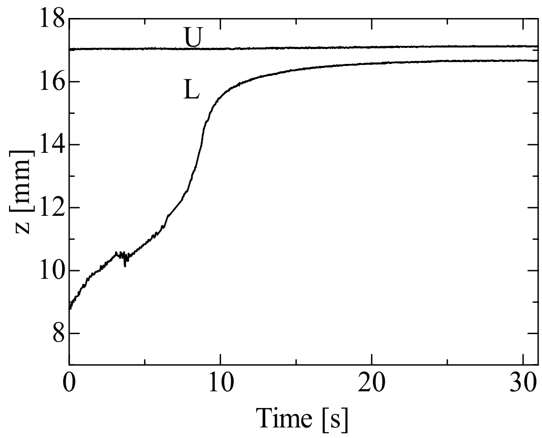

Fig. 4 Trajectory of two dust particles in the sheath. The upper particle (U) stays at $z \approx 17$ mm, while the lower particle (L) moves upward till $z \approx 16.5$ mm.

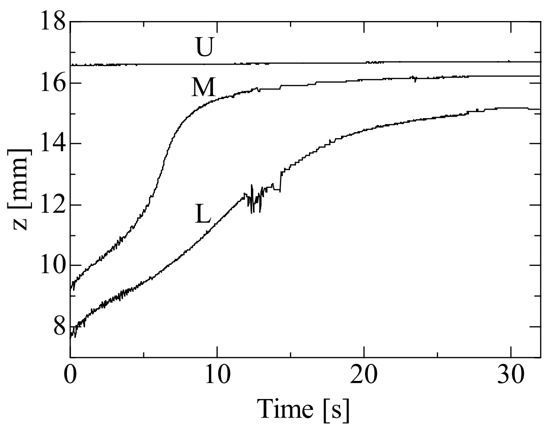

Fig. 5 Trajectory of three dust particles in the sheath. The upper particle (U) stays at 16.8 mm, while the middle particle (M) and the lower particle (L) move upward till $z \approx 16.2$ mm and $z \approx 15.2$ mm, respectively.

[12]. The total energy can be calculated from the trajectory of a single dust particle as

$$E(z) = E(0) - \frac{1}{2}m\left(\frac{dz}{dt}\right)^2 - b\int_{z_A}^{z}\left(\frac{dz}{dt}\right)dz, \quad (3)$$

where $E(0)$ is a potential energy at $z = 0$ and z_A is a position of a dust particle at T = 0.

3-2 Two and three dust particles

Fig. 4 shows trajectory of two dust particles observed in the sheath. A dust particle injected from the dust dropper settles at $z \approx 17$ mm. The second dust particle injected from the dust dropper moves deep into the glass tube and reaches a position of $z \approx 8.5$ mm. Two dust particles are nearly in the same vertical line. The lower dust particle moves upward toward the upper dust particle. In Fig. 4, trajectory of the lower particle is similar to the trajectory of the particle in Fig. 3, confirming that the second particle moves independently of the first particle until the second particle comes close to the first one.

Fig. 5 shows trajectory of three dust particles, while **Fig. 6** shows positions of three dust particles at T=0, 10 and 20 seconds. A dust particle injected from the dust dropper settles at $z \approx 16.8$ mm in the glass tube. Next two dust particles injected from the dust dropper move deep into the glass tube, reaching a position of $z \approx 9$ mm. Three dust particles are nearly in the same vertical line. The lower two dust particles move upward toward the first dust particle. We note that trajectories of the middle particle and the lower particle are affected by the interaction each other. Here consider now various forces acting on a dust particle moving in the sheath. The forces acting on dust particles may include: gravitational force, ion drag force, neutral drag force, sheath electric force and the wake electric force and screened Coulomb force in the presence of other dust particles. We focus attention on a screened Coulomb force in the presence of other dust particles. An electric potential around a dust particle with charge Q placed in a plasma is given by

$$\phi_D = \frac{Q}{4\pi\varepsilon_0 r}e^{-r/\lambda}, \quad (4)$$

where λ is the screening length. On the other hand, when a dust particle is placed in a supersonic ion flow, an electric potential at Δz behind the dust particle is known as a wake potential and is given by [4]

$$\phi_w = \frac{1}{1-M^{-2}}\frac{Q}{2\pi\varepsilon_0\Delta z}\cos\left(\frac{\Delta z}{\lambda\sqrt{M^2-1}}\right), \quad (5)$$

where M is the Mach number defined by v_i/C_s, v_i is velocity of ion flow, C_s is ion acoustic velocity defined by $\sqrt{k_B T_e/m_i}$, m_i is ion mass and T_e is the electron temperature. **Fig. 7** shows potentials behind the upper dust particle without ion flow and with ion flow. The potential without ion flow is characterized by the screening length. On the other hand, the wake potential is characterized by the length $\lambda\sqrt{M^2-1}$. In a sheath toward the bottom of the glass tube, there is a region of supersonic ion flow with $M > 1$ and M becomes larger toward the bottom of the glass tube. In case of three dust particles as shown in Fig. 5, interparticle distance between the upper particle and the middle particle at equilibrium height is 0.6 mm while interparticle distance between the middle particle and the lower particle at equilibrium height is 1.0 mm. Assuming the screening length is 0.2 mm at all positions in the sheath, Mach numbers at $z \approx 16.2$ mm and at $z \approx 15.2$ mm are 1.4 and 2.0, respectively. Thus change of trajectory of the lower particle can be understood by the presence of wake potential formed behind a particle.

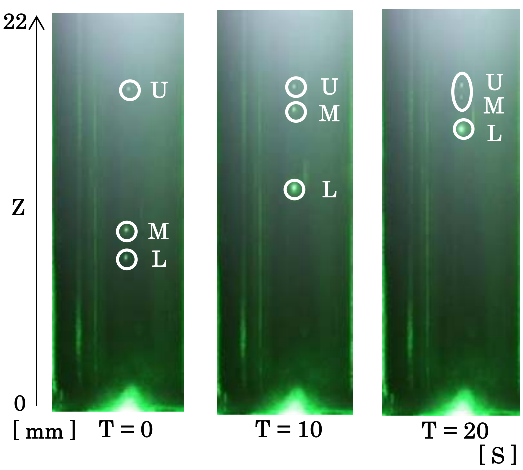

Fig. 6 Three dust particles in the sheath. The upper particle stays at 16.8 mm, while the middle particle and the lower particle move upward till $z \approx 16.2$ mm and $z \approx 15.2$ mm, respectively.

4. Discussion and Conclusion

Dynamics of dust particles in the sheath is studied in an rf discharge plasma. A dust particle charged

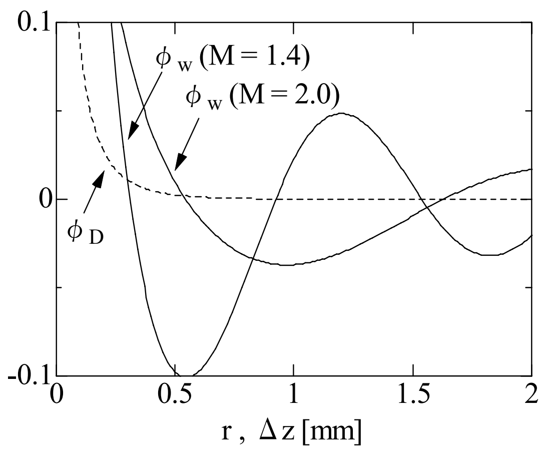

Fig. 7 Potentials behind the upper dust particle without ion flow ϕ_D (broken line) and with ion flow ϕ_w (solid lines).

negatively in a plasma moves downward into a sheath, and then is observed to move upward against gravity. The single dust particle can be used to study the potential structure by analyzing trajectory of the dust particle. Two dust particles injected into a sheath interact each other and are observed to form a pair vertically along the ion stream. The lower dust particle is trapped in the wake potential formed by the upper dust particle in the ion flow. A pair of dust particles is observed to move upward together against gravity in the wake channel.

Acknowledgments

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