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Biased-Modulation of Dust Velocity Shear Flow in RF Plasma

RFプラズマ中における微粒子速度シア流へのバイアス変調

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Dynamic behavior of a dust flow with velocity shear was investigated in RF plasmas. Here, neutral drag force was employed to drive the dust flow. The neutral gas ejected from small nozzles gave momentum to the particles to generate a directional dust flow with velocity shear. The strength of the velocity shear could be controlled over a wide range by adjusting the direction of the nozzles and the flow rate of the neutral gas. The dust shear flow was modulated by applying a sinusoidal voltage to a point electrode, which was placed just under the dust flow channel plate. The modulation gave rise to a periodic flow motion that was changed by the flow direction and flow velocity. Wave-like phenomenon was also observed in the dust shear flow.

1. Introduction

Fine particles introduced in the plasma were known to have negative charges, trapped at the sheath edge of a powered RF electrode. The property of the dust cloud in a strongly coupled state can be characterized by the Coulomb coupling parameter Γ, i.e. $\Gamma = (q_d{}^2 / 4\pi\varepsilon_0 a \kappa T_d)\exp(-a/\lambda_D)$, where q_d is dust charge, T_d is dust temperature, a is inter-particle distance and λ_D is the Debye length. It is well known that a phase transition from fluid to solid happens when $\Gamma > \Gamma_{cri} \sim 172$ in a one-component plasma (OCP). Therefore, the dust cloud behaves as a property of Coulomb fluid when $\Gamma < \Gamma_{cri}$. In this case, the dust cloud may change its shape and an collective motion will be generated, when the external forces, such as the electrostatic force, the ion drag force, the gravity, and so on, act on the dust fluid. Note that the viscosity due to the Coulomb interaction depends both on the values of Γ and a/λ_D.

In our previous experiments, we demonstrated a dynamic behavior of a dust shear flow, which was driven by neutral drag force [1]. Extremely disordered structure and convection of particles were observed experimentally. We had also observed several chaotic behaviors of the dust shear flow. The external force drove a convective vortex motion, accompanied with velocity shear flow as a result of the Coulomb interaction.

There have been many unknown subjects about physical phenomena of the shear fluid which has the viscosity caused by the Coulomb collision, which is intrinsically different from the collision between molecules in neutral fluids. We intend to investigate dynamic behavior of the dust flow that is considered as the Coulomb fluid in plasmas. Here, we investigate how the velocity shear flow evolves when the modulation bias is applied to the dust flow.

2. Experimental apparatus and method

Figure 1 shows a schematic of the experimental apparatus. Argon plasma was produced by a capacitively coupled RF discharge. We used RF power of 1 - 20 W at 13.56 MHz, and Ar pressure P_{Ar} was in a range of 20 - 60 Pa. Typical plasma density was $n_e \sim 1\times10^9$ cm^{-3} and electron temperature was T_e ~2 eV. The experiment was carried out with a use of special shape of a levitation electrode plate of 1

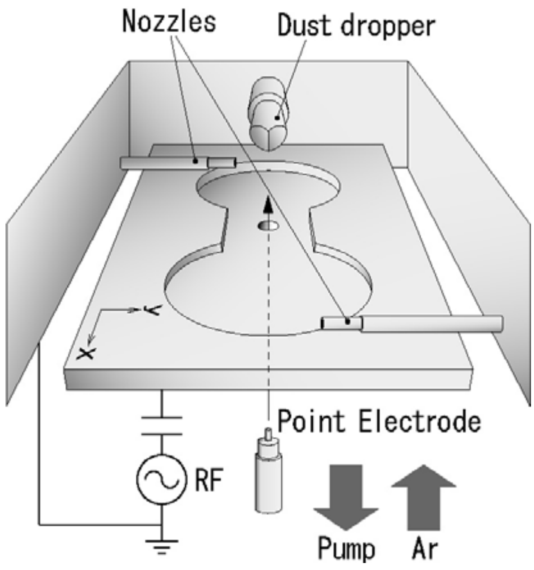

Fig. 1. Experimental apparatus.

mm in thickness, as shown in Fig. 1. The levitation plate has a hole at the center with a dumbbell shape, consisting of a straight part of 7 - 23 mm in length and 20 mm in width, combined with two circular parts of 30 mm in diameter. The straight part is used for a straight channel for counter dust streams. The dust particles of 10 μ m in diameter were introduced externally into the plasma by a dust dropper and can be trapped mainly above the circular parts. Increasing the number of the particles injected, the particles were also trapped above the straight channel region.

The dust shear flow was modulated by giving a sinusoidal voltage to a point electrode that was placed just under the dust flow channel plate.

3. Experimental results and discussion

Figure 2(b) shows the streamline of the dust shear flow, when the modulation bias is turned off. The point electrode was situated at the center of the dust flow channel as schematically shown in Fig. 2(a). The data was obtained by integrating 30 frames taken by a high-speed camera with 125 frames per second. In this experiment, the dust particles were driven by a neutral drag force of argon

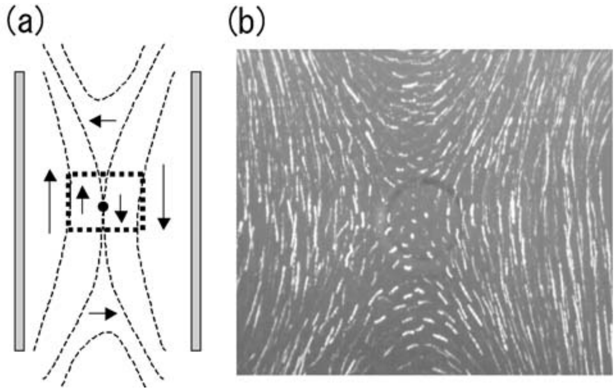

Fig. 2 (a) Schematic of dust flow channel with X-point of flow separatrix at the center. (b) Stream lines of dust shear flow without modulation.

gas ejected from two nozzles of 0.8 mm in inner diameter. Since the experimental position was far away from the nozzles placed at the outer edge of the circular parts of the levitation electrode (see Fig. 1), the flow dynamics ware considered as a result of electrostatic interaction between the dust particles in the shear flow region. The counter flows meet near the point electrode and form an X-point with separatrix in the flow pattern.

When the sinusoidal voltage was applied to the point electrode, the dust particles started to move with back and forth motions by the electrostatic potential evolved in the sheath region around the electrode. Here, although the distribution of electrostatic potential formed by the electrode potential was almost point-symmetric, the response of the dust flow was dependent on the direction of the flow. For the particles incoming toward the electrode the potential modulation seemed to act as deceleration and for the particles escaping from the point electrode region it seemed to act as acceleration.

The applied voltage could also excite a dust wave propagating in the dust shear flow. The wave propagation against the dust flow seemed to be

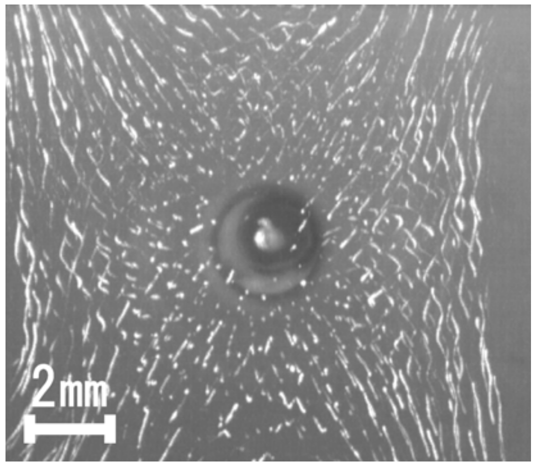

Fig. 3 Stream lines of dust shear flow with modulation

heavily damped. However, the wave propagating in the same direction of the dust flow seemed to be weakly damped.

4. Conclusion

Dynamic behavior of the dust flow with velocity shear was investigated in RF plasmas. In this study, the dust shear flow was modulated by applying a sinusoidal voltage to a point electrode placed just under the dust flow channel plate. The modulation evolved a periodic flow motion that was changed by the flow direction and flow velocity. Wave phenomenon was also excited by the modulation. The propagation properties were changed by the flow direction.

References

[1] T. Gohda et al., 14th International Conference on Plasma Physics,, Fukuoka, Japan, Sep 8-12, (2008) p. 259.