Experiments on Fine- Particle Plasmas for Observation of Critical Phenomena

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Abstract

The particle-motion temperature in a two-dimensional structure was estimated from the time evolution of the speed of a fine particle to be around 0.1 eV with an accuracy of less than 0.1 eV. It was observed that fine particles were isotropically arranged in a planar magnetron plasma, which diffused upward, in three dimensions, without the formation of a void.

1. Introduction

Phase transition and critical phenomena are key topics in physical research. Critical phenomena are observed in various physical systems that exhibit universality. A well-known critical point is observed in a gas-liquid system. The critical pressure, volume, and temperature are determined by an analysis of the van der Waals equation, which takes into account the van der Waals attractive force between molecules. A fine-particle plasma can be treated as a macroscopic molecular system. Therefore, critical phenomena can be observed in such a plasma if an attractive force exists between fine particles or a coagulation force exists among them along with their Coulomb repulsive force. Recently, the possibility of observing critical phenomena has been theoretically predicted by two analyses. One of them is based on the existence of an attractive force between fine particles [1]. The other is based on the model of one-component plasma [2], which consists of negatively charged fine particles and a neutralizing background. Thus far, many studies have been conducted to experimentally verify the existence of a critical point in a fine-particle plasma. Further, it is known that critical phenomena are significantly affected by gravity. Hence, microgravity conditions play an important role in experiments concerning the observation of critical phenomena.

Our working group, which is organized in the Japan Aerospace Exploration Agency (JAXA), has been planning new research projects that involve the use of fine-particle plasmas. Our first project is aimed at observing critical phenomena under microgravity. The advantage of using a fine-particle plasma is that individual particles can be observed with a CCD video camera. **Fig. 1** shows the expected arrangement of fine particles in the supercritical state. The observable correlation length, ξ, in a fine-particle plasma is in the order of inter-particle distance. Therefore, critical phenomena could even be observed at a temperature far from the critical temperature. This possibility simplifies the search for critical point conditions. By a simple calculation based on the mean field theory, it is found that the temperature accuracy required for the observation of critical phenomena in fine-particle plasmas is in the order of 0.1 eV, which is a million times larger than that required for the observation of critical phenomena in molecular systems.

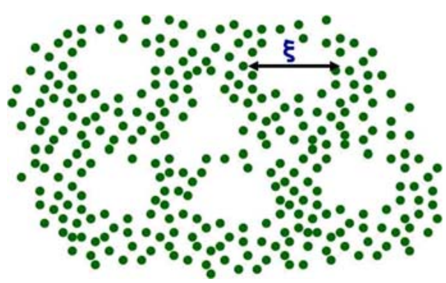

Fig.1 Expected arrangement of fine particles in the supercritical state.

Theoretical analyses by Totsuji [2] have revealed that the background plasma pressure, Coulomb coupling parameter, and ratio of the inter-particle radius to the Debye length are the key parameters for controlling and observing the critical point.

We have conducted experiments to estimate the particle-motion temperature, perform plasma diagnoses by using the experimental model for ISS experiments, and control a fine-particle plasma to observe critical phenomena. This paper presents the results of the temperature estimation of fine particles in a two-dimensional (2D) structure and the control of the behavior of these particles by using a magnetron plasma for the formation of a three-dimensional (3D) structure under gravity.

2. Estimation of particle-motion temperature in 2D structure

By using a small system for experiments under microgravity conditions [3–4], the particle-motion temperature was estimated. Monodisperse divinylbenzene spheres with a diameter of 6.5 μm were injected upward into a plasma from the bottom of a hollow formed in an rf electrode by using a piezoelectric oscillator. Such a particle injector can control the density of fine particles. A grounded ring electrode was set 14 mm above the rf electrode, and a transparent plastic cylinder was placed between the two electrodes. The fine particles were confined to the plastic cylinder. Helium gas was supplied at a pressure of 1 Torr. Vertical strings of suspended particles, comprising a 2D structure, were formed above the rf electrode. Such a 2D structure was also formed by fine particles with a diameter of 2.27 μm. The behavior of one of the particles in the top layer of a group was recorded by an upper CCD camera by laser light scattering. The time evolution of the 2D speed of the particle was analyzed by using commercial software.

Fig. 2(a) shows the time evolution of the speed of a fine particle in a plasma. The fine particle was almost stationary; therefore, the state of the fine particles was considered to be similar to the solid state. In order to estimate the particle-motion temperature, the distribution of the maximum speeds of the particle was determined, as shown in Fig. 2(b), and fitted to a Maxwellian distribution function under the ergodic hypothesis. **Fig. 3** shows the dependence of the particle-motion temperature on the rf power. It is observed that the temperature increases from 0.1 to 0.15 eV with the rf power. This indicates that the fine particles were heated by the rf power. **Fig. 4** shows the dependence of the temperature on the particle density. The temperature increases from 0.05 to 0.2 eV with the particle density. The reason for this increase in temperature has not yet been clarified. However, it is speculated that at high densities, fine particles repel each other due to Coulomb interaction, and consequently, their temperature increases. The increase in the particle-motion temperature corresponds to a decrease in the value of the Coulomb coupling parameter. It should be noted that other physical parameters such as Coulomb energy and inter-particle distance also change simultaneously and may decrease or increase the value of the Coulomb coupling parameter. Therefore, in the future, each physical parameter of the fine-particle plasma should be analyzed in detail in order to clearly determine the reason for the change in the particle-motion temperature. From the results shown in Figs. 3 and 4, it is reasonable to conclude that the temperature is controllable with accuracy less than 0.1 eV.

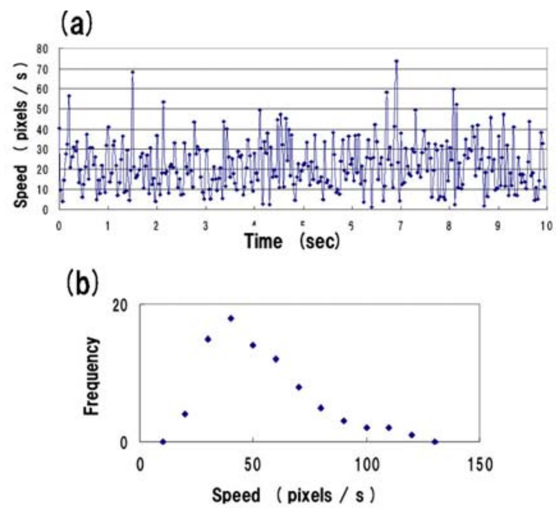

Fig. 2 (a) Time evolution of the speed of a fine particle and (b) distribution of maximum speeds.

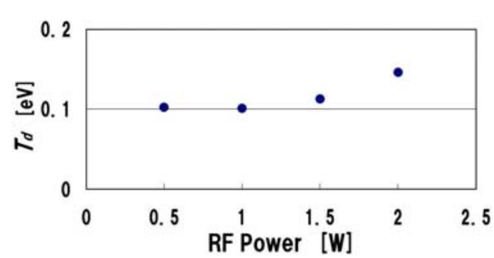

Fig.3 Plot of particle-motion temperature against rf power.

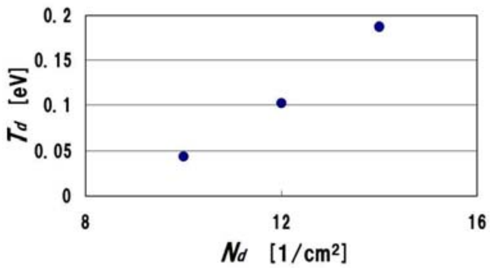

Fig.4 Plot of particle-motion temperature against particle density.

The particle-motion temperature was estimated to be around 0.1 eV, which is considerably less than the electron temperature, but close to the ion or gas temperature. This result indicates that fine particles are almost in thermal equilibrium at an ion or gas temperature.

According to the mean field theory, ξ is proportional to *Tc*/(*Tc* – *T*)–1/2, where *Tc* and *T* are the critical temperature and measurement temperature, respectively. Here, the critical phenomena of fine-particle plasmas are compared with those of real molecular systems: the lower limit of correlation length detected by an optical method in molecular systems is in the order of 103 molecular particles, while it is several particles in fine particle plasmas. Therefore, by using the mean field theory, the temperature accuracy required to observe critical phenomena in fine-particle plasmas is estimated to be 106 times that required to observe these phenomena in molecular systems. This means that the temperature accuracy required in fine-particle plasmas is in the order of 0.1 eV. Thus, it is possible to observe critical phenomena in fine-particle plasmas.

3. Control of behavior of fine particles by planar magnetron plasma

3.1 Experimental

A planar magnetron plasma was produced in a large chamber system. A square rf electrode with a side length of 20 cm was set in the lower position of the system. The upper flange of the chamber, which was at a distance of 15 cm from the rf electrode, served as a grounded counter electrode. Strong permanent magnets were attached to the rf electrode in order to generate a magnetic field parallel to the electrode in the form of a square with a side length of 5.5 cm. A high density plasma was produced due to the confinement of electrons by $E \times B$ drift on the surface of the electrode, as shown in **Fig. 5**. The

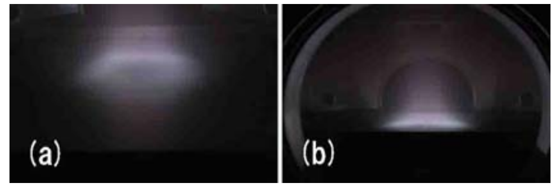

Fig.5 Images of planar magnetron plasma: (a) oblique view and (b) side view.

magnetron plasma formed a loop, diffused toward the center, and then diffused upward. It is considered that, when fine particles are injected into the plasma, they are pushed toward the center and then upward by the diffusible plasma; therefore, the particles are suspended under a force balance with gravity and no void is formed.

The plasma was produced by using helium as the discharge gas at a pressure of 80–130 Pa and rf power of less than 2 W.

Monodisperse divinylbenzene spheres with a diameter of 2.27 μm were dropped from a small vessel containing a piezoelectric oscillator.

The behavior of each particle was recorded by a CCD video, under the illumination of laser light vertically expanded with a cylindrical lens.

3.2 Results and discussion

Fig. 6 shows a side-view image of fine particles floating 1.0–1.5 cm above the center of the magnetron plasma loop at a pressure of 130 Pa. Several strings of particles are observed in the lower part of the group of fine particles; however, most of them are randomly oriented and float in the iffusible plasma, and no void is formed. A dense horizontal region is observed in the center of the figure. These results indicate that the fine particles float in the diffusible plasma under a balance between ion drag and gravitational forces.

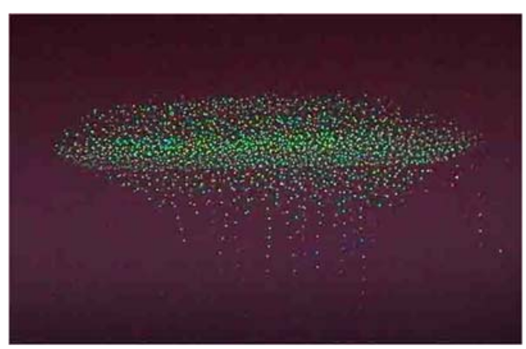

Fig.6 Side view of fine particles floating above a loop of magnetron plasma of helium at 130 Pa.

As the pressure decreases, the plasma spreads and the particles begin to disperse. **Fig. 7** shows the arrangement of particles at a pressure of 80 Pa. In Fig. 7, because the vertical expansion of laser light is not enough to illuminate whole fine particles, the lower and upper parts are separately shown. Figure 8 shows that particles in the lower part form vertical strings similar to those in the 2D structure [3–4]. However, particles in the central part do not form strings, but appear to be randomly arranged. In the upper part, it is observed that several particles are pushed in the upward direction. These results confirm that the fine particles are pushed upward by the diffusible plasma and are suspended in it under a force balance with gravity.

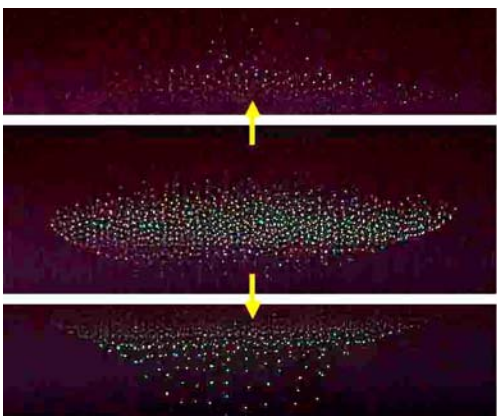

Fig. 7 Side view of fine particles floating above a loop of magnetron plasma of helium at 80 Pa.

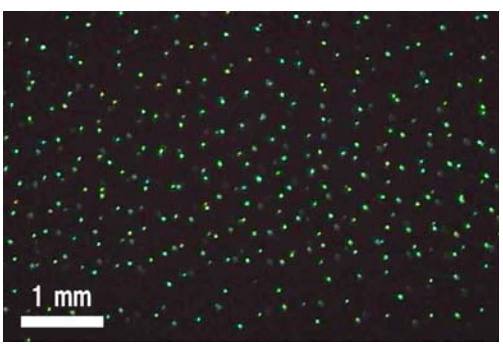

Fig. 8 Close-up view of fine particles floating above a loop of magnetron plasma of helium at 80 Pa.

A close-up image of the particles in the central part is shown in **Fig. 8**. Because of the broadening of the laser beam in the depth direction, the figure shows several layers of particles piled up in the direction. It appears that some particles were relatively ordered and formed 3D structures isotropically.

We intend to produce larger and more ordered 3D structures by using a larger magnetic loop than the present one, in order to control the state of the fine-particle plasma such that it is close to the critical point under gravity. A system consisting of multi-planar magnetron plasma sources can be used to produce a large 3D fine-particle plasma without any void under microgravity. We expect to observe critical phenomena by using such a system.

4. Conclusion

The particle-motion temperature in the 2D structure was estimated from the time evolution of the speed of a fine particle to be around 0.1 eV with an accuracy of less than 0.1 eV. It was observed that fine particles were isotropically arranged in a planar magnetron plasma, which diffused upward, in three dimensions, without the formation of a void. Such an arrangement of fine particles should facilitate the experimental study of the critical point.

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