Measurement of Ion Density and Electron Temperature by Double-Probe Method to Study Critical Phenomena in Dusty Plasmas

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Abstract: A dusty plasma research was performed to investigate critical phenomena in JAXA, participating in missions of a joint Russian/German Scientific project with cooperation of the PK-3 plus flight module on the International Space Station. In the research, it was necessary to obtain plasma parameters such as densities and temperatures of electron and ion for analyzing a state of dusty plasmas expressed by parameters in a phase diagram of Coulomb coupling parameter and ratio of inter-particle distance to Debye length. This work was dedicated to obtain ion density and electron temperature by using a double-probe method. The ion density was measured to be in the order of 10^8–10^9 cm^{-3}. The electron temperature was observed to be enhanced by injecting dust particles to the plasmas.

Keywords: Dusty Plasma, Fine Particle Plasma, Complex Plasma, PK-3 Plus, Microgravity, ISS

1. Introduction

This research was motivated in the experiments on the International Space Station (ISS) of dusty (complex or fine particle) plasmas, which had been going on with collaboration between Max-Planck-Institute for Extraterrestrial Physics (MPE, Germany) and Joint Institute for High Temperatures (JIHT, Russia) for several years.

Plasmas including dust particles (typically, micrometer-sized), so-called dusty plasmas, have attracted considerable scientific interest in recent decades. The dust particles are charged by fluxes of electron and ion in the plasmas. The charge of dust particles can be in the order of a few thousands of elementary charge in typical laboratory plasmas. The charged dust particles are regarded as a strongly coupled Coulomb system. In the system, one can observe many physical phenomena found in solid or liquid state, such as crystallization, phase transition, wave propagation, and so on.

Complex plasma experiments have been done in microgravity conditions with apparatuses boarding on parabolic flight, sounding rocket and the ISS for recent years. Several physical phenomena, e.g., wave propagation and so on, have been reported by MPE and JIHT in the experiments on the ISS. The utility for dusty plasmas on the ISS was replaced an improved apparatus denoted by PK-3 plus set in the Russian module at the end of 2005 [1].

Several scientists in Japan have joined to the mission of PK-3 plus since July 2009, for demonstrating a critical phenomenon in dusty plasmas predicted in calculation by one of the authors [2]. Plasmas of high density were required to approach to the critical point. Referring a previous work for diagnostics in PK-3 plus, high power and high pressure conditions were employed to obtain the plasmas of high density [3]. In the previous diagnostics, electron densities were measured by the hairpin resonator, which was relatively large antenna compared with size of chamber and possibly affected the plasmas. In the present research, a double-probe method was used for measuring ion density and electron temperature to reduce disturbance in the plasmas and examined the results from the hairpin resonator.

2. Diagnostics in Dusty Plasmas

2.1 Measurement of electron density by hairpin resonator

The previous work was done for measurements of electron density with a hairpin resonator in the PK-3 plus apparatus, equipped with parallel plate electrodes

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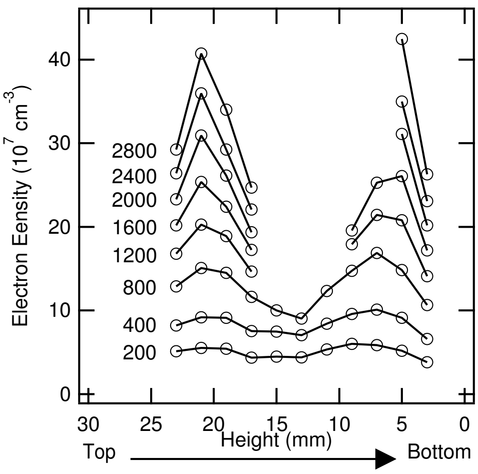

Fig. 1 The spatial distribution profiles of electron density between top and bottom electrodes at 40 Pa, measured with changing rf power from 200 to 2800 mW.

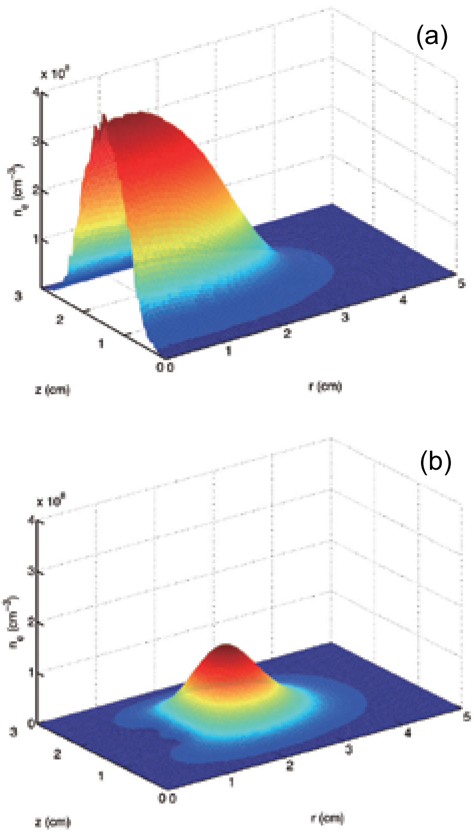

Fig. 2 The spatial distribution profiles of electron density in a Ne plasma calculated by a PIC/MCC code, (a) a pristine plasma, and (b) the plasma with the antenna of hairpin.

surrounded by grounded guard rings in a chamber[3]. The electrodes at top and bottom sides were separated 30 mm. The diameter of the electrodes was 60 mm. Figure 1 shows spatial distribution profiles of electron density between the top and bottom electrodes in Ar plasmas at 40 Pa, measured with changing rf power from 200 to 2800 mW. Two peaks are found in the profiles of electron density at distance of 8 mm from each electrode. Conversely, the profile was simulated for a Ne plasma by a particle-in-cell Monte Carlo code (PIC/MCC)[4]. The electron density is the highest at the axial and radial center in the pristine plasma without an antenna of the hairpin resonator (Fig. 2 (a)). Introducing the hairpin resonator to the center of the chamber, electrons are missed around the hairpin resonator, and the density of electron is reduced all over the chamber (Fig. 2 (b)). The plasma is affected by the hairpin resonator and electrons are lost on its surface. Therefore it is reasonable to think that the profile of electron density obtained by the hairpin resonator misses the highest around the center of the plasma and the electron density is estimated under that of the pristine plasma.

2.2 Measurement of ion density and electron temperature by double-probe method

Hindering loss of electron on an equipment for diagnostic, a traditional double-probe method was employed, which did not take electrons and ions as currents in an electrical circuit for the method[5,6]. Ion density and electron temperature were measured with the tips of 0.35 mm in diameter, 8 mm in length and separated 7 mm each other, which were made of tungsten wire (Fig. 3).

The tips were connected to a voltage source with floating on the ground of plasmas. Figure 4 shows pictures of the tips introducing to a dust cloud illuminated by a laser. Here dust particles of 2.6 μm in diameter were injected with extremely high density, and instability and wave were excited in the dust cloud. The tips were set at 8 mm high from the bottom electrode and surrounded by the sheath, where corresponds to a dust-free region[7,8]. In the figure, the right tip is initially applied -30 V negative to the left one. The voltage was swept to +30 V with sampling current in an electrical circuit insulated from that for generating plasmas. When the tip has negative potential to the other, a sheath of corrected ions around the tip expands to thickness determined by the Bohm criterion. The dust particles reach to an equilibrium position near

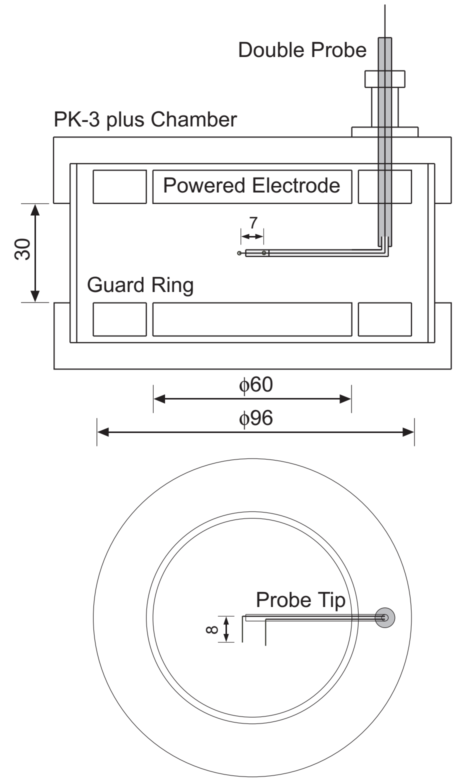

Fig. 3 Schematics of the PK-3 plus chamber and the tips for the double-probe method.

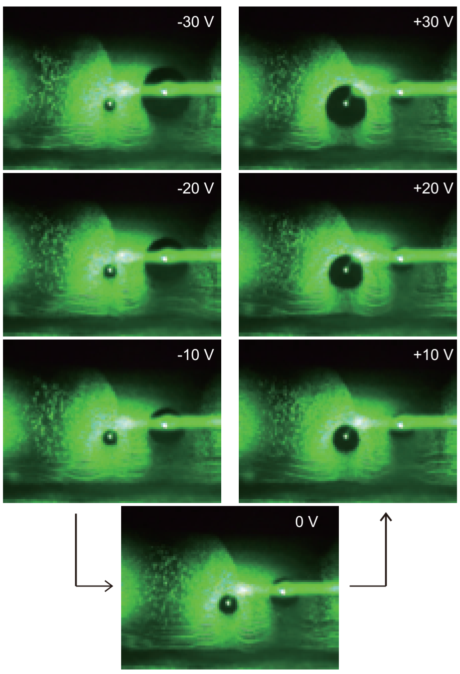

Fig. 4 Pictures of the tips for the double-probe method introduced to the dust cloud in the plasma. The tips were set at 8 mm high from the bottom electrode. The dust particles were illuminated by a laser and observed to distribute from 2.5 to 13 mm high. The right tip was negatively biased at -30 V to the left one, initially. The bias voltage was changed to positive side and reached to +30 V.

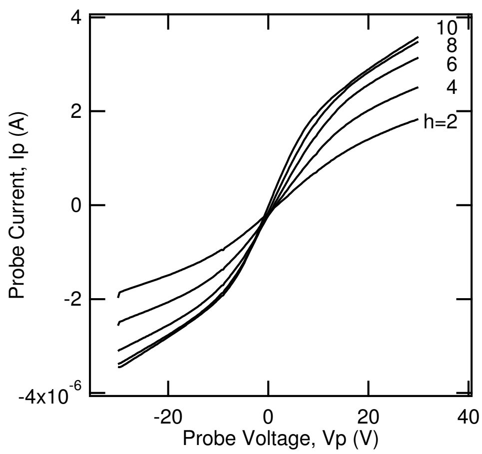

Fig. 5 Electric characteristics in the double-probe method. The probe currents (I_p) were plotted as functions of voltage applied between the tips (V_p). The curves were obtained with changing height of the tips, denoted by "h", from 2 to 10 mm.

the sheath edge[9]. Therefore spatial distribution of the dust cloud would be a rough standard to show the sheath. Each tip was surrounded by each sheath separated through the plasma and dust cloud, which was clearly shown in the pictures. Here the tips were regarded to work for measuring ion density and electron temperature in the dusty plasma.

Figure 5 shows electric characteristics of the circuit for the double-probe method, probe current (I_p) plotted as a function of probe voltage (V_p), with variation of tip height from the bottom electrode in a plasma generated at 40 Pa of Ar and 400 mW of rf power. Ion currents linearly increasing with biasing were observed in regimes of highly negative and positive voltage, denoted by I_{i-} and I_{i+}, respectively. The lines of ion current define parameters of slops, S_{i-} and S_{i+}, and cross-sections on $V_p = 0$, I_{isat-} and I_{isat+} as ion saturation currents. The ion saturation currents tended to increase with tip closing to center of the plasma. The slop of ion current is redefined to be $S \approx S_{i-} \approx S_{i+}$. The linear part around $V_p = 0$ indicates a current from the tip mainly correcting electrons, whose slope, $\left.\frac{dI_p}{dV_p}\right|_{V_p=0}$, is integrated by an electron energy distribution function in a plasma. It is noted that the slope is enhanced by that of ion current coming from the sheath expanding with biasing tips. Hence electron temperature, T_e is expressed by the formula with following the manner

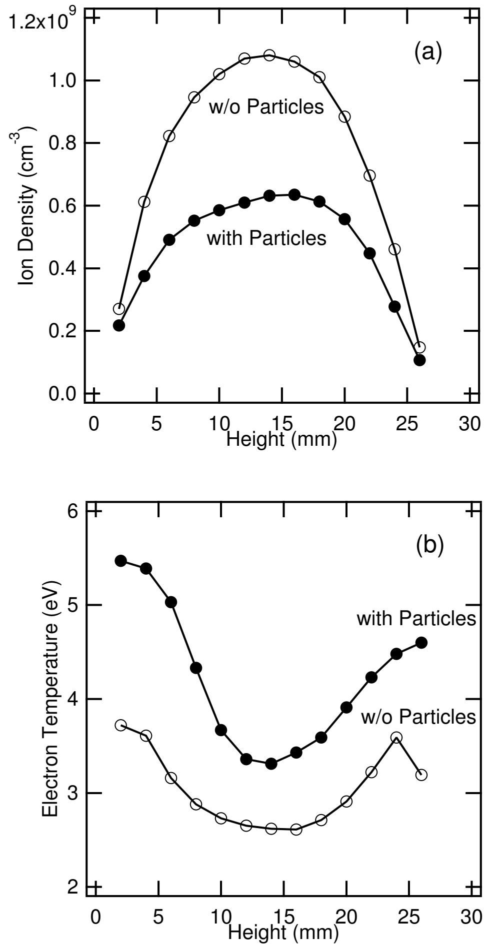

Fig. 6 Spatial distribution profiles of (a) ion density and (b) electron temperature measured by using the double-probe method in the Ar plasma at 40 Pa and 400 mW. Open and solid circles indicate parameters in case without and with the dust particles, respectively.

which suppresses the slope of ion current from that of electron current[10],

$$T_e = \frac{e}{k_B} \frac{|I_{isat-}| + |I_{isat+}|}{4\left(\left.\frac{dI_p}{dV_p}\right|_{V_p=0} - 0.82S\right)}, \quad (1)$$

where e and k_B are elementary charge and the Boltzmann constant, respectively. Ion density, n_i, is calculated from the equation,

$$|I_{isat-}| \approx |I_{isat+}| = 0.61 n_i e \sqrt{\frac{k_B T_e}{m_i}} A, \quad (2)$$

where m_i and A correspond to mass of ion and surface area of the tip, respectively.

3. State of dusty plasmas

Figures 6 (a) and (b) show ion densities and electron temperatures, respectively, measured by using the double-probe method in the Ar plasma at 40 Pa and 400 mW. The spatial distribution profile of ion density around the center should be identical to that of electron density. This profile corresponds to that of pristine plasma derived by the PIC/MCC code. The electron densities expected from the ion densities measured by the double-probe method are higher than those by the hairpin resonator. Therefore it is concluded that the hairpin resonator can affect ionization in volume of the chamber and extinguish the plasma, resulting in reducing electron density and making its spatial profile with two peaks.

In is noted that electron temperature is enhanced throughout the plasma by injecting the dust particles. Density of the dust particle was hard to be precisely measured due to the instability, however, might be reached to 10^6 cm^{-3}. The total area on surface of the dust particle in the cloud can be a few tens mm^2. The plasma should be lost on the surface by recombination between electrons and ions as seen in the measurement of the hairpin resonator. Hence ionization rate should be kept to sustain the plasma, encountering loss by the recombination. This leads to the electron temperature enhanced[11,12]. In Fig. 4, too many dust particles were injected just before extinguishing the plasma. The ion densities in case without the dust particles could not be maintained, although the electron temperature was enhanced (Fig. 6 (a)).

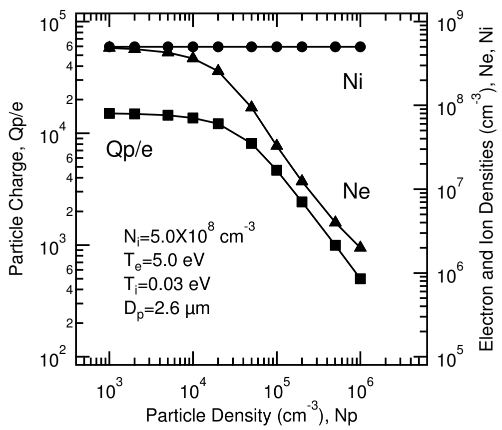

Fig. 7 Variations of electron density and charge of the dust particle calculated from the parameters obtained by the double-probe method in changing dust particle density, and plotted with ion density.

Two parameters of ion density and electron temperature enable to calculate other parameters in dusty plasmas. Electron density and charge of the dust particle are calculated in the orbit-motion-limited (OML) theory[13]. In Fig. 7, assuming the parameters of 5.0×10^8 cm^{-3} for ion density, 5.0 eV for electron temperature, and room temperature for ion temperature, one can estimate the charge of the dust particles to be 10^2–10^4 with varying density of the dust particle. The electron densities should be conserved by charge neutrality in plasmas.

4. Conclusion

The double-probe method seemed to be more appropriate for diagnostics in PK-3 plus than the hairpin resonator. The spatial distribution profiles of ion density obtained by the double-probe method was reasonable compared with the result from the PIC/MCC code. In the PK-3 plus, the electron and ion densities could reached to 10^9 cm^{-3} at several Watts of rf power. Injecting the dust particles, the electron temperature should be enhanced. This may lead to complicate prediction for critical phenomena. The double-probe method, however, gives several measures in ion density and electron temperature for analyzing the phenomena with helps of other theories, e.g., OML.

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