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By

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Abstract : Dependency of interparticle distance in Coulomb crystal on various parameters such as plasma density, electron temperature, plasma potential and the Debye length are experimentally investigated. From the investigation, it is found that the interparticle distance is proportional to the Debye length.

Key words : Coulomb crystal, interparticle distance, Debye length, dusty plasmas, probe measurement

1. Introduction

Dusty plasmas are a mixture of plasma and dust particles. The dusty plasma research originally began in a field of astrophysics such as interstellar molecular clouds[1], proto-planetary disks, cometary tails or planetary rings [2,3]. In 1986, a theoretical work on Coulomb crystal formation by using the dusty plasmas was published[4]. A prior theoretical work on Wigner crystal formation by using strongly coupled plasmas [5] might be a trigger of this work. In order to observe the Coulomb crystals, many experiments and additional theoretical researches [6] had been carried out in many laboratories. In 1994, the Coulomb crystals were successfully observed in several laboratories at almost the same time [7–11]. In these experiments, external electrodes, walls or grooves on electrodes were often used to trap dust particles since a mechanism of the Coulomb crystal formation was expected as repulsive force due to the theoretical research history. After the success in observation of the Coulomb crystals, many scientific applications of the dusty plasmas have been proposed, for example, critical point phenomena [12], phase transitions [13–15], phonon propagation [16–18]. In addition, the dusty plasmas will contribute to fusion plasma physics near diverter plates and colloidal physics. Although it is expected that the dusty plasma research contributes to many scientific disciplines, one essential scientific problem still exists. The problem is that mechanisms of the Coulomb crystal formation are not fully understood yet. For example, although many scientists believe that the Coulomb crystal is a repulsive system, existence of attractive force is also reported [19–22]. In order to understand the Coulomb crystal formation mechanisms based on not only repulsive force but also attractive force, it is required to investigate first what parameters dominate interparticle distance in the Coulomb crystal without any artificial potential control mechanisms. Therefore, we develop an experimental apparatus being suitable for this purpose. In order to know the performance of this apparatus, the major plasma parameters, that is, plasma density, electron temperature and plasma potential, are measured first by using a single probe. Then, the Coulomb crystal formation experiments are carried out and the averaged interparticle distance is obtained. From the major plasma parameters and the interparticle distance, dependencies of the interparticle distance on various parameters are investigated. Finally, we discuss the dominant parameter, which determines the interparticle distance.

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2. Experimental Apparatus

The configuration of the experimental apparatus is schematically shown in Fig.1. The RF power from a RF oscillator of 13.56MHz is inputted to a power divider. This divider also has a function of a phase shifter. The phase difference between the two outputs from the power divider can be selected as 0 or π . The two RF outputs from the power divider are inputted to two RF electrodes. Although the RF power is often supplied between the two electrodes in this type of electrode, the RF power is supplied to each RF electrode in this apparatus and thus the RF current flows along each electrode. This method is similar to the usage of the RF antenna in experimental apparatuses for hot plasma confinement.

The developed apparatus is shown in Fig.2. Figure2 (a) shows the outside view of whole system. In Fig.2 (a), the letter (b) can be seen. Figure2 (b) is the inside view around the RF electrode took through the window marked by the letter (b) in Fig.2 (a). In this apparatus, the shape of the RF electrode is key design. One of the most important experiments is to investigate existence of the attractive force. If dust particles are trapped and are packed forcibly by a sort of a trapping mechanism,

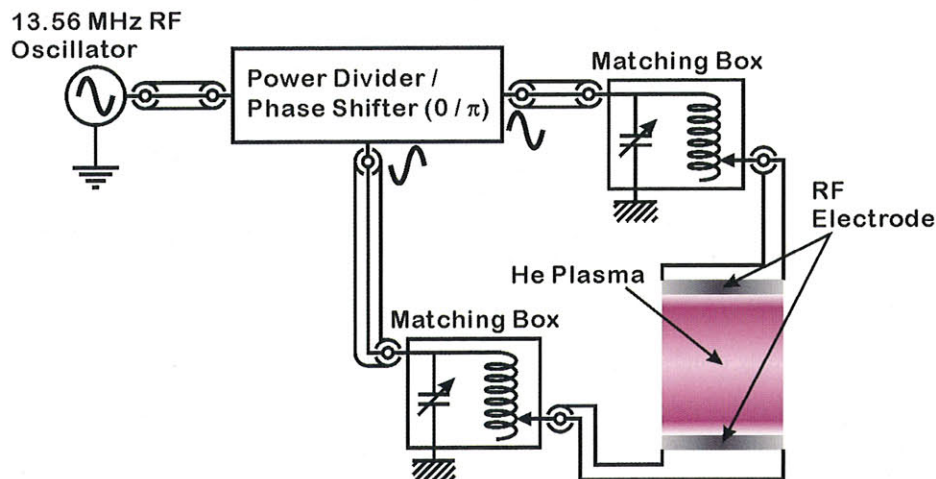


Fig.1 Schematic Diagram of Experimental Apparatus.

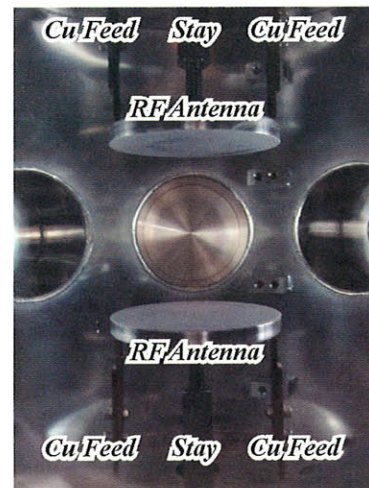
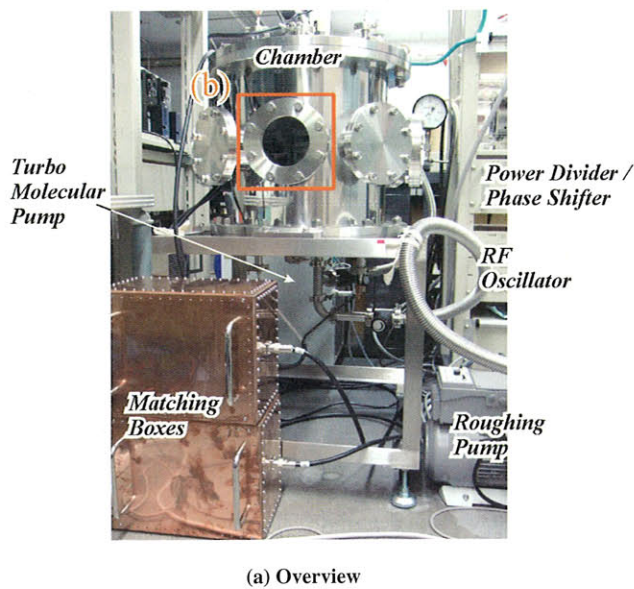


Fig.2 Experimental Apparatus

it should be difficult to investigate existence of attractive force. Therefore, we designed the experimental apparatus so as to eliminate artificial potential control as much as possible. The shape of the RF electrode is the typical example of the elimination of the artificial potential control since there are no walls and no grooves on the electrode surface, that is, flat and disk-shaped electrodes. In addition, the apparatus has no auxiliary electrodes except for the two RF electrodes. Since wave length of 13.56 MHz is about 15 m while the diameter of the RF electrode is 10 cm, the voltage change on the electrode is about 4 percents of the peak-to-peak voltage at maximum. The distance between the upper electrode and the lower electrode is set to be 10 cm at present.

The inner diameter of the vacuum chamber is 16 inches. This means that the electrode edge is 15 cm apart from the chamber wall. We expect this distance is far enough from the wall to reduce the wall potential effect sufficiently since the distance is three time longer than the radius of the electrode. This expectation can be confirmed from the result of the experimentally obtained plasma potential profile, which is described later in detail.

3. Single Probe Measurement

In order to know the performance of the apparatus, the major plasma parameters, that is, plasma density, electron temperature and plasma potential, are measured first by using a single probe. The schematics of the single probe is shown in Fig.3. A probe tip is made of tungsten and is 1 mm in diameter and 10 mm in length. The signal is acquired from the BNC-R connector. The probe pipe is isolated from the ground line of the BNC-R connector so that the potential of the probe pipe maintains the floating potential. This probe is set at the middle between the two electrodes. This location is defined as $z = 0$ as shown in Fig.4. By using this probe, the electron current dependency on the probe voltage is measured. The typical result of the probe characteristics at $r = 0$ is shown in Fig.5. In Fig.5 (a), the vertical axis is linear scale, while that is logarithmic scale in Fig.5 (b). From Fig.5 (a), the floating potential ϕ_f of 12 V is obtained. In addition, from Fig.5 (b), the electron saturation current $I_{e^{sat}}$ of 0.28 mA, the plasma potential ϕ_p of 19.3 V and the electron temperature T_e of 2.0 eV are obtained. Figure 6 shows radial profiles of the major plasma parameters in this apparatus. Figure 6 (a), (b) and (c) represent the density, the electron temperature and the plasma potential, respectively. Each profile is uniform enough even though outside the elec-

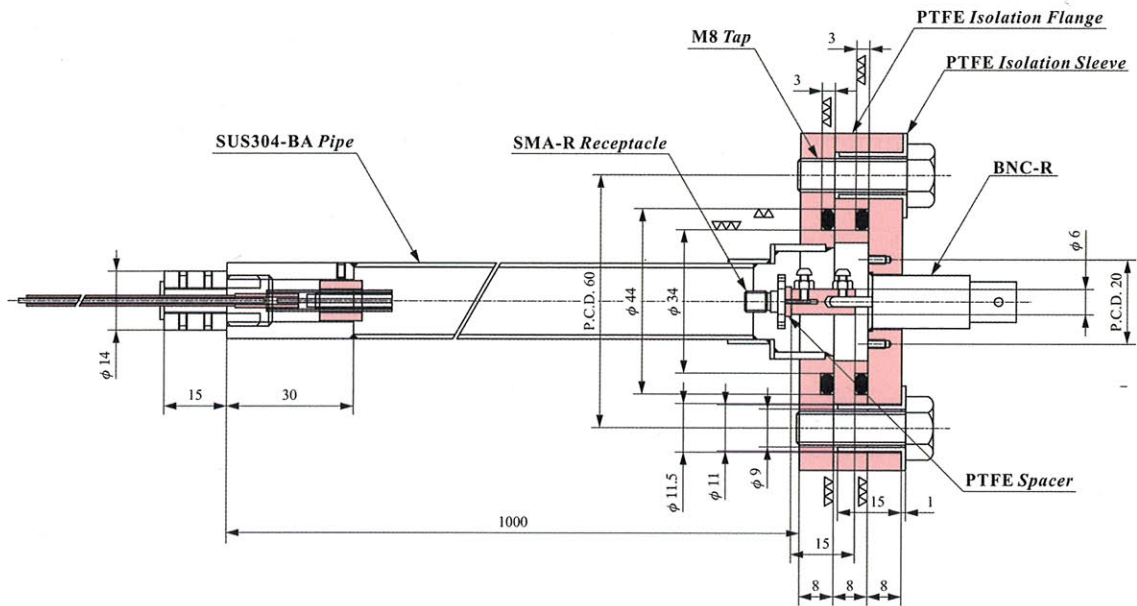


Fig.3 Schematics of Single Probe

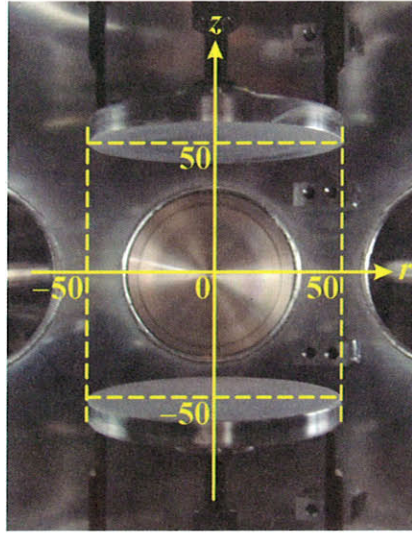
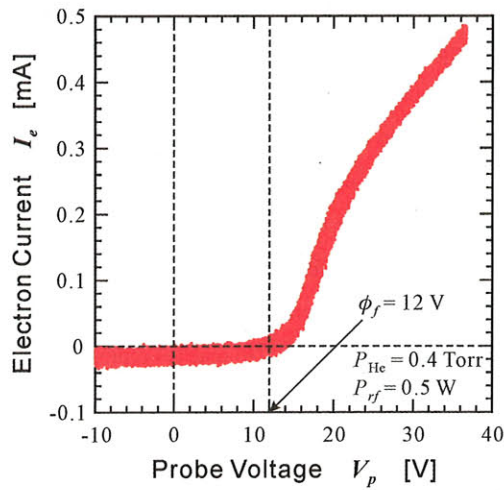
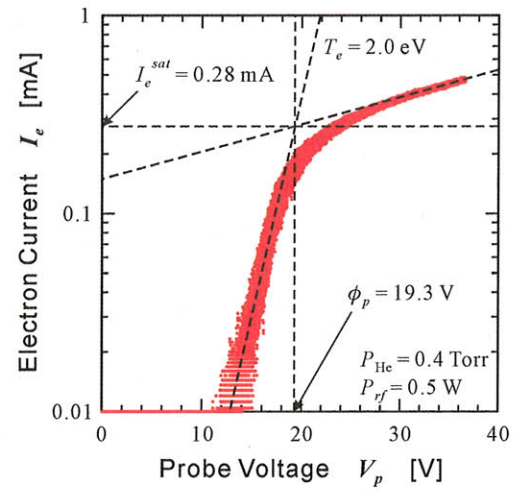


Fig.4 Coordinates for Probe Measurement

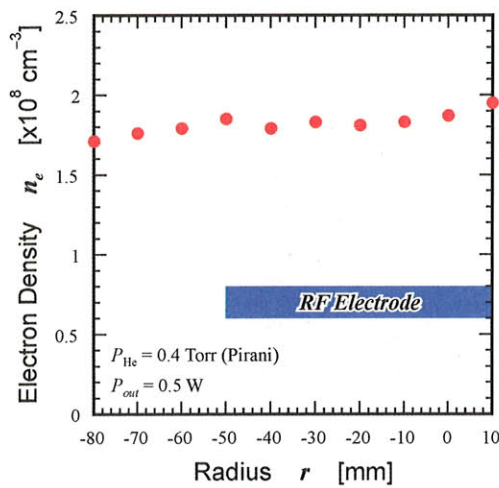


(a) Probe Characteristics

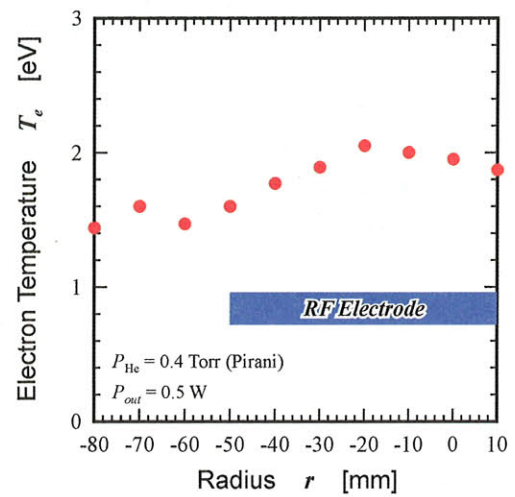


(b) Semi-logarithmic Plot of Probe Characteristics

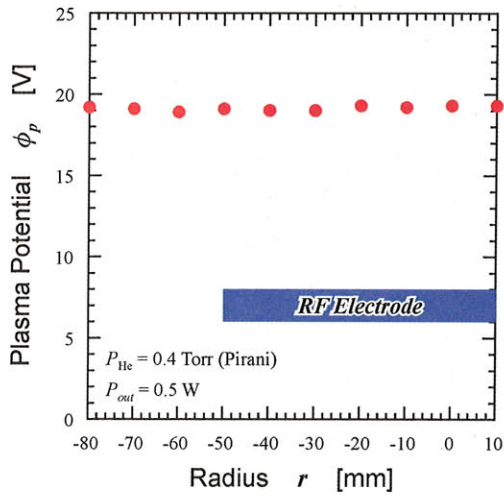
Fig.5 Electron Current Dependency on Probe Voltage



(a) Density Profile



(b) Electron Temperature Profile



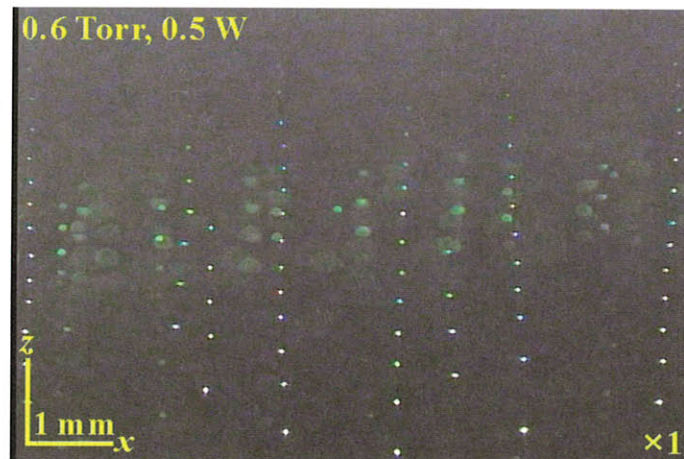
(c) Plasma Potential Profile

Fig.6 Radial Profiles of Major Plasma Parameters

trode, especially, the plasma potential profile is extremely uniform. The plasma potential profile indicates that any particle trap mechanisms do not exist as expected.

4. Interparticle Distance

If the Coulomb crystal can be formed by using this apparatus, a sort of self-organization mechanisms such as the attractive force must exist since this apparatus has no particle confinement mechanisms as shown in Fig.6 (c). The typical experimental result of the Coulomb crystal formation is shown in Fig.7. Figure7 (a) and (b) are the horizontal and vertical observation data from CCD cameras, respectively. The bright points in these figures are the dust particles of 1 mm in diameter. This result indicates that the large Coulomb crystal is successfully formed though the confinement potential does not exist. In order to clarify the mechanisms of the self-organization, it is necessary to know what parameter dominates the interparticle distance as the first step. In order to obtain the interparticle distance, the pair distribution function is very useful. To calculate the pair distribution function, the coordinates of the dust particles are obtained from the observation data. By using Eq.(1), which is the definition of the two-dimensional pair distribution function for the discrete data, and the coordinates data, the



(a) Horizontal View

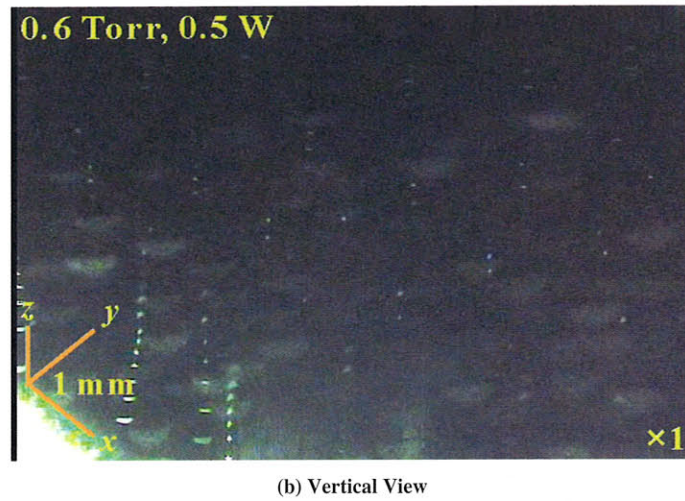


Fig.7 Typical Experimental Result of Coulomb crystal formation

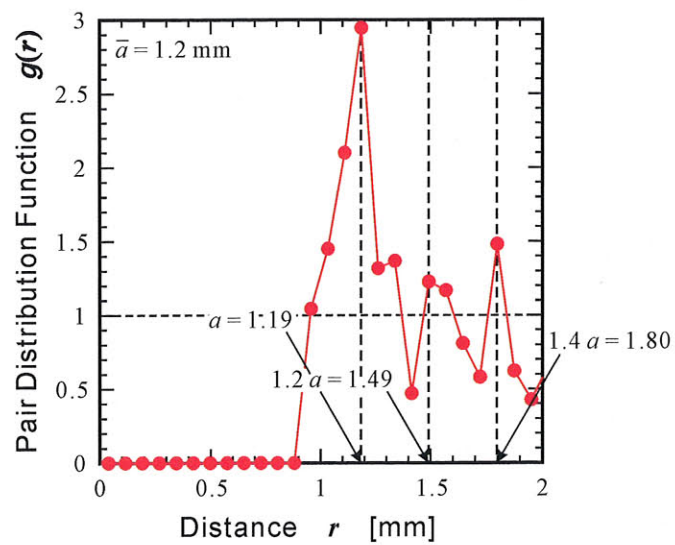


Fig.8 Example of Calculated Pair Distribution Function

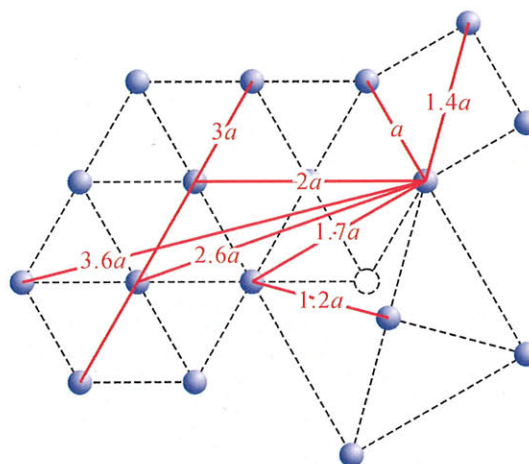


Fig.9 Two-dimensional Crystal Structures

pair distribution function is calculated and is shown in Fig.8.

$$g(r) = \frac{r_{max}^2 \sum_{i=1}^{N_j} N_i (r - \Delta r/2, r + \Delta r/2)}{N_j N_i^{total} \left\{ \left(r + \Delta r/2 \right)^2 - \left(r - \Delta r/2 \right)^2 \right\}}, \quad (1)$$

where r_{max} , N_i^{total} , N_j are the maximum observation radius, the number of particles within the maximum observation radius and the number of the centered particles in the circle of radius r_{max} . In the case of the experimental data shown in Fig.7 (b), the observation area is not so large but three peaks are obtained. The first peak is the same as the interparticle distance. In addition, the distance where the peaks exist indicates that the Coulomb crystal in this case has a mixture of two types of crystal system at least, that is, hexagonal one and face-centered tetragonal or simple tetragonal one by considering the crystal structure as shown in Fig.9. The latter crystal system may be ideally the face-centered cubic system if the gravity is none.

5. Discussion

In order to investigate dominant mechanisms of the Coulomb crystal formation, the interparticle distance dependency on various parameters are investigated. First, the interparticle distance dependency on the particle charge is obtained and is shown in Fig.10. From Fig.10, it is found that the interparticle distance increases with the value of the negative charge. This result indicates that the interparticle distance is affected by the Coulomb repulsive force. This is a reasonable result as expected.

By considering the power flow in dusty plasmas, it is obvious that the dust particles receives the power from only the plasma. The power from the plasma should be expressed as a function of the plasma pressure. If the received power is consumed for approaching each other against the repulsive force by the particles, the plasma pressure is originated as a sort of attractive force. On the other hand, the Coulomb repulsive energy is a function of the square of the particle charge. Therefore, the ratio of the plasma pressure to the square of the particle charge should dominate the interparticle distance. In order to confirm this hypothesis, we obtain the dependency of the interparticle distance on the ratio of the plasma pressure to the square of the particle charge as shown in Fig.11. From Fig.11, it is clarified that the interparticle distance linearly decreases with the increase of the ratio of the plasma pressure to the square of the particle charge. This result strongly supports our hypothesis, that is, the interparticle distance is determined by the balance of the attractive force and the repulsive force. In addition,

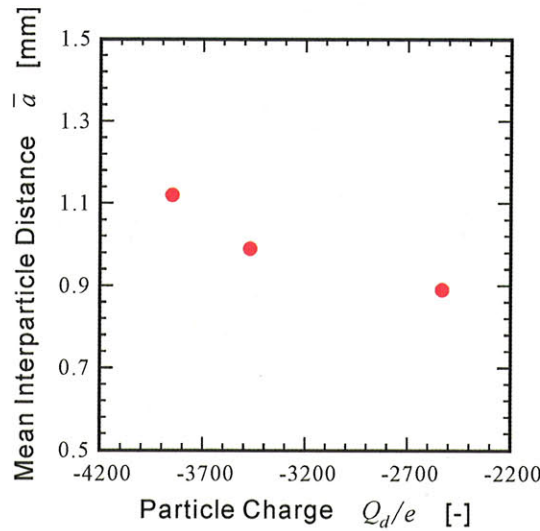


Fig.10 Interparticle Distance Dependency on Particle Charge

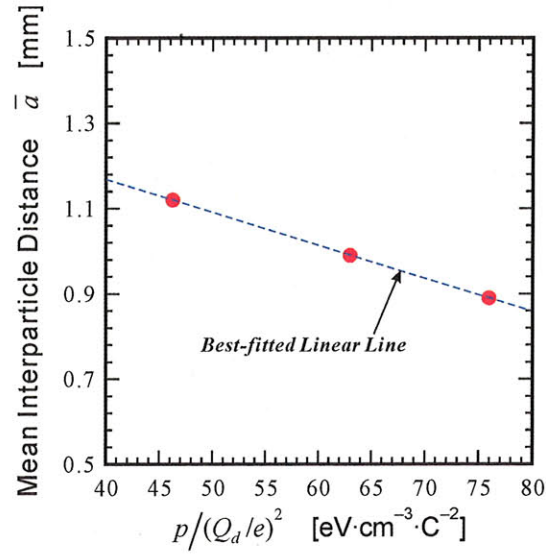


Fig.11 Interparticle Distance Dependency on Ratio of Plasma Pressure to Square of Particle Charge

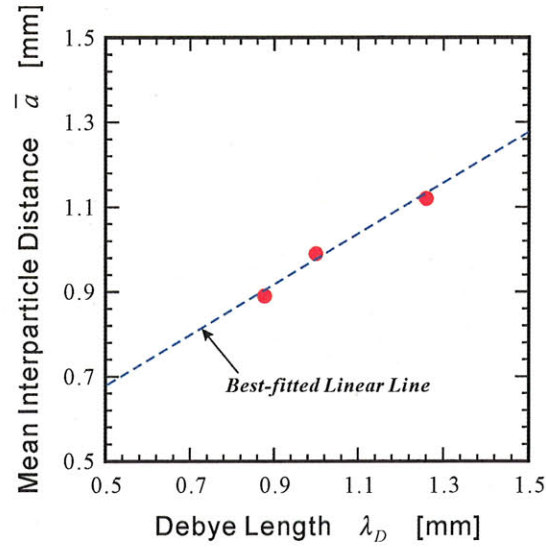


Fig.12 Interparticle Distance Dependency on Debye Length

tion, the attraction is driven by the plasma pressure.

If our hypothesis is correct, the interparticle distance is in the order of the Debye length because the proper Coulomb interaction must exist. In order to confirm this inference, the dependency of the interparticle distance on the Debye length is also obtained as shown in Fig.12. From Fig.12, it is found that the interparticle distance is almost the same as the Debye length but is proportional to the Debye length. This result also supports our hypothesis.

6. Conclusions

In order to understand the Coulomb crystal formation mechanisms, the Coulomb crystal formation experiments are carried out by using an experimental apparatus without any particle confinement mechanisms. It is successfully observed the Coulomb crystal by using this apparatus. This result suggests that a sort of attractive force exists. In order to investigate the formation mechanisms in more detail, the interparticle distance dependencies on various parameters are obtained. One of the

dependency indicates that the interparticle distance is affected by the Coulomb repulsive force as expected. In addition, another result shows that the interparticle distance is affected by the plasma pressure, which should work as the energy source for the attraction. This suggests that the attractive force may be different from the ion shadowing force and the ion drag force, which are the existing attractive force models. Another result of the interparticle distance dependency on the Debye length is obtained. This result indicates that the distance is around the Debye length. This also supports our hypothesis of the attractive force.

References

- [1] B. T. Draine and B. Sutin, "Collisional charging of interstellar grains", *Astrophys. J.* 320, 803–817 (1987).
- [2] T. Northrop, "Dusty Plasmas", *Phys. Scr.*, 45, 475–490 (1992).
- [3] O. Havnes, T. Aslaksen, F. Melandsø and T. Nitter, "Collisionless braking of dust particles in the electrostatic field of planetary dust rings", *Phys. Scr.* 45 (1992) 491.
- [4] H. Ikezi, "Coulomb solid of small particles in plasmas", *Phys. Fluids*, 29, 1764–1766 (1986).
- [5] S. Ichimaru, "Strongly coupled plasmas : high-density classical plasmas and degenerate electron liquids", *Rev. Mod. Phys.*, 54, 1017–1052 (1982).
- [6] R. T. Farouki and S. Hamaguchi, "Phase transition of dense systems of charged "dust" grains in plasmas", *Appl. Phys. Lett.*, 61, 2973–2975 (1992).
- [7] J. H. Chu and Lin I, "Direct Observation of Coulomb Crystals and Liquids in Strongly Coupled Dusty Plasmas", *Phys. Rev. Lett.*, 72, 4009–4012 (1994).
- [8] J. H. Chu and Lin I, "Coulomb lattice in a weakly ionized colloidal plasma", *Physica A* 205, 183–190 (1994).
- [9] H. Thomas, G. E. Morfill and V. Demmel, "Plasma Crystal : Coulomb Crystallization in a Dusty Plasma", *Phys. Rev. Lett.*, 73, 652–655 (1994).
- [10] Y. Hayashi and K. Tachibana, "Mie-Scattering Ellipsometry for Analysis of Particle Behaviors in Processing Plasmas", *Jpn. J. Appl. Phys.*, 33, 476–478 (1994).
- [11] A. Melzer, T. Trottenberg and A. Piel, "Experimental determination of the charge on dust particles forming Coulomb lattices", *Phys. Lett. A*, 191, 301–308 (1994).
- [12] H. Totsuji and S. Ichimaru, "Dielectric Response Function of Electron Liquids. III – Numerical Investigation of Static Properties–", *Prog. Theor. Phys.*, 52, 42–53 (1974).
- [13] J. Pieper, J. Goree and R. Quinn, "Experimental studies of two-dimensional and three-dimensional structure in a crystallized dusty plasma", *J. Vac. Sci. Technol. A*, 14, 519–524 (1996).
- [14] G. Morfill, and H. Thomas, "Plasma Crystal", *J. Vac. Sci. Technol. A*, 14, 490–495 (1996).
- [15] K. Tachibana and Y. Hayashi, "Analysis of the Coulomb–solidification Process in Particle Plasmas", *Aust. J. Phys.*, 48, 469–477 (1995).
- [16] J. Pieper and J. Goree, "Dispersion of Plasma Dust Acoustic Waves in the Strong–Coupling Regime", *Phys. Rev. Lett.*, 77, 3137–3140 (1996).
- [17] S. Nunomura, D. Samsonov and J. Goree, "Transverse Waves in a Two-Dimensional Screened–Coulomb Crystal (Dusty Plasma)", *Phys. Rev. Lett.*, 84, 5141–5144 (2000).
- [18] V. Nosenko, S. Nunomura and J. Goree, "Nonlinear Compressional Pulses in a 2D Crystallized Dusty Plasma", *Phys. Rev. Lett.*, 88, 215002–1–215002–4 (2002).
- [19] S. V. Vladimirov and M. Nambu, "Attraction of charged particulates in plasmas with finite flows", *Phys. Rev. E*, 52, R2172–R2174 (1995).

- [20] M. Nambu, S. V. Vladimirov and P. K. Shukla, “Attractive forces between charged particulates in plasmas”, *Phys. Lett. A*, 203, 40–42 (1995).
- [21] U. Mohideen, H. U. Rahman, M. A. Smith, M. Rosenberg and D. A. Mendis, “Intergrain Coupling in Dusty-Plasma Coulomb Crystals”, *Phys. Rev. Lett.*, 81, 349–352 (1998).
- [22] K. Takahashi, T. Oishi, K. Shimomai, Y. Hayashi and S. Nishino, “Analyses of attractive forces between particles in Coulomb crystal of dusty plasmas by optical manipulations”, *Phys. Rev. E*, 58, 7805–7811 (1998).

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