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By

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Abstract : A new experimental apparatus for Coulomb crystal formation in dusty plasmas is developed. By using this apparatus, experiments of Coulomb crystal formation are carried out. The Coulomb crystals are successfully observed without artificial potential control. From the observation data, it is suggested that dust particles are self-organized due to some kind of particle trapping mechanism.

Key words : Coulomb crystal, Dusty plasmas, Self-organization

1. Introduction

Dusty plasmas are a mixture of plasmas and dust particles. The dusty plasma research were originally in a field of astrophysics such as interstellar or interplanetary dust particles [1, 2] or planetary rigs [3]. In 1986, a theoretical work on Coulomb crystal formation by using the dusty plasmas was published [4]. A prior theoretical work on Winger 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 on electrodes or grooves on electrodes were often used since a mechanism of the Coulomb crystal formation was expected as repulsive force due to the 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, existence of attractive force has been reported in some papers [19-22]. Therefore, we introduce a one-dimensional model of dusty plasmas, which is based on energy balance. By calculating energy change against particle distance, conditions of Coulomb crystal formation are discussed. Then, experimental apparatus is designed and developed. By using this apparatus, experiments for the Coulomb crystal formation is carried out. From observation data of the Coulomb crystal formation, a formation mechanism is discussed.

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2. One-dimensional Model

In this section, one - dimensional configuration with two particles is considered. This configuration is the simplest case and a potential profile between two particles is expressed as summation of potential profiles around a single particle since any potential profiles must satisfy the Poisson's equation. The configuration is shown in Fig. 1. Figure 1 (a) shows an initial condition. Two particles are far away each other so that Coulomb interaction should be negligibly small. Figure 1 (b) shows a condition that particles approaches each other . Thus the potential profile between the two particles changes due to the Coulomb interaction. The potential profile must satisfy the following Poisson's equation in both cases,

$$\nabla^2\phi = -\frac{e}{\varepsilon_0}(Z n_i - n_e) - \frac{\rho}{\varepsilon_0}\delta(r_0), \tag{1}$$

where ϕ is potential, e is the elementary charge, ε_0 is permittivity in vacuum, Z is number of charges of ions, ρ is charge density on a particle, δ is the delta function, r_0 is the x coordinate where the delta function is equal to 1. The n_i and n_e are ion and electron density, respectively. The potential profile in the no interaction case, which is the same as the single particle case, is described as

$$\phi_1(x) = -\left(\phi_p - \phi_0\right)\exp\left(-\frac{|x-K|}{\lambda_D}\right) + \phi_p, \tag{2}$$

where λ_D is the Debye length. The ϕ_p and ϕ_0 are plasma potential and potential on the particle surface, respectively. The value of K varies when the location of x varies, that is,

$$K = \begin{cases} -x_0 - r_0 & (x \le -x_0 - r_0;\ \text{left side at particle A}) \\ -x_0 + r_0 & (x \ge -x_0 + r_0;\ \text{right side at particle A}) \\ x_0 - r_0 & (x \le x_0 - r_0;\ \text{left side at particle B}) \\ x_0 + r_0 & (x \ge x_0 + r_0;\ \text{right side at particle B}) \end{cases}. \tag{3}$$

Equation (2) corresponds to the configuration in Fig. 1 (a). On the other hand, the potential profile in the case of existence of the potential interaction between two particles is described as

$$\phi_2(x) = -\left(\phi_p - \phi_0\right)\exp\left(-\frac{x + x_0 - r_0}{\lambda_D}\right) - \left(\phi_p - \phi_0\right)\exp\left(\frac{x - x_0 + r_0}{\lambda_D}\right) + \Phi, \tag{4}$$

where

$$\Phi = \phi_p + \left(\phi_p - \phi_0\right)\exp\left(-\frac{2x_0 - 2r_0}{\lambda_D}\right). \tag{5}$$

Equation (4) also corresponds to Fig. 1 (b). Density is obtained by integrating a velocity distribution function in velocity space, that is,

$$n_1 = \int_{-\infty}^{\infty} f(v_x)\,dv_x = n_0 \exp\left[-\frac{q\left(\phi - \phi_p\right)}{kT}\right] \tag{6}$$

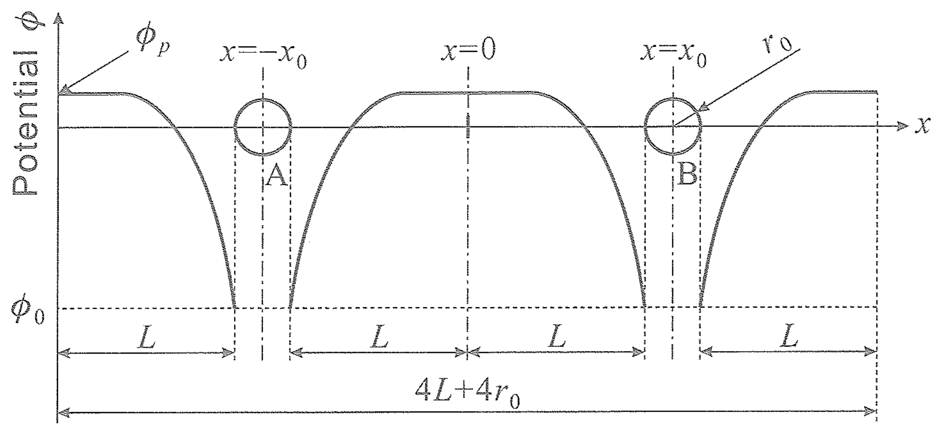
in Fig. 1 (a) case. In Fig. 1 (b) case, the density between the two particles is expressed as

$$n_2 = n_0 \exp\left[-\frac{q(\phi - \Phi)}{kT} \right]. \tag{7}$$

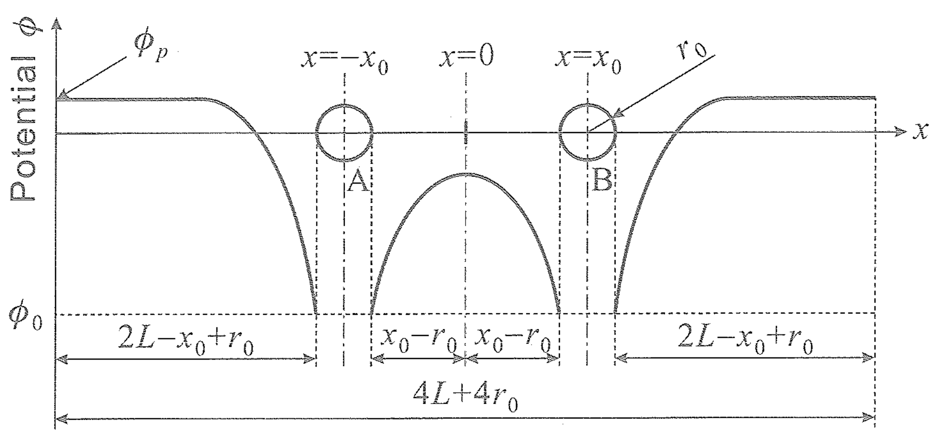
Here, we consider the power flow in this system. The power flow is shown in Fig. 2. First, power from a power source is absorbed by the plasma. The absorbed power is partially consumed for plasma production and plasma heating and for dust particle heating. The rest of the absorbed power is lost by several processes such as plasma losses diffused from core plasma or recombination. The dust heating power is also partially consumed for increase of dust kinetic energy and dust potential energy. The rest of the dust heating power is lost by dust particles escaping from the system. As a summary, the effective incident power, subtracting the power losses from the absorbed power by the plasma, is balanced to summation of the power of the plasma production and heating, the power of the increase of the dust kinetic energy and the power of the increase of the dust potential energy. The dust kinetic energy is consumed to the work required to approach each other. Here, we assume that the power of the plasma production and heating is constant. This means that temperature, density, plasma potential of the plasma is constant. This should be true under the quasisteady state condition. In this case, the dust potential energy is also constant. In addition, it is assumed that the dust kinetic energy is constant. This may be true when the collision between the plasma and the particle is high enough. Thus the difference between the energy at the initial condition and the energy at the approaching stage is the summation of the plasma energy and the work for approaching each other. This is expressed as

$$\Delta\varepsilon_{total} = \Delta\varepsilon_{plasma} - \Delta W, \tag{8}$$

where $\Delta\varepsilon_{plasma}$ and ΔW represent the plasma energy corresponding to $nkT + ne\phi$, the work for the approaching, respectively. By calculating Eq. (8), we obtain the energy change and show it in Fig. 3. Figure 3 shows that the energy minimum exists in small diameters. This indicates that the particles may stay at the location where the energy minimum exists. This is similar to the attractive-repulsive system. In addition, the energy minimum decreases with the increase of the diameter. Finally, the energy minimum disappears in large diameters. In such case, an external confinement potential should be indispensable to form a Coulomb crystal. This is similar to the repulsive system.



(a) Initial condition



(b) Approaching each other

Fig. 1 Model Configuration

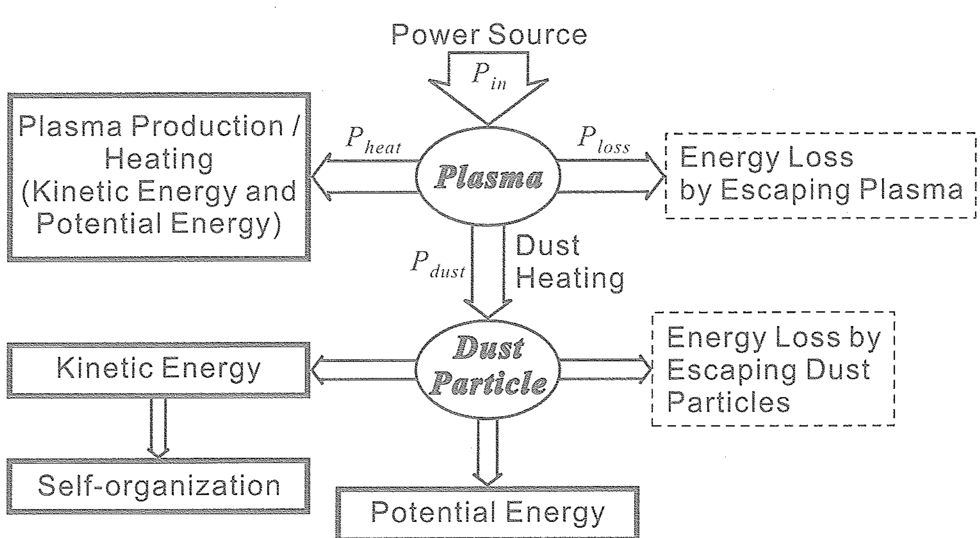


Fig. 2 Power Balance

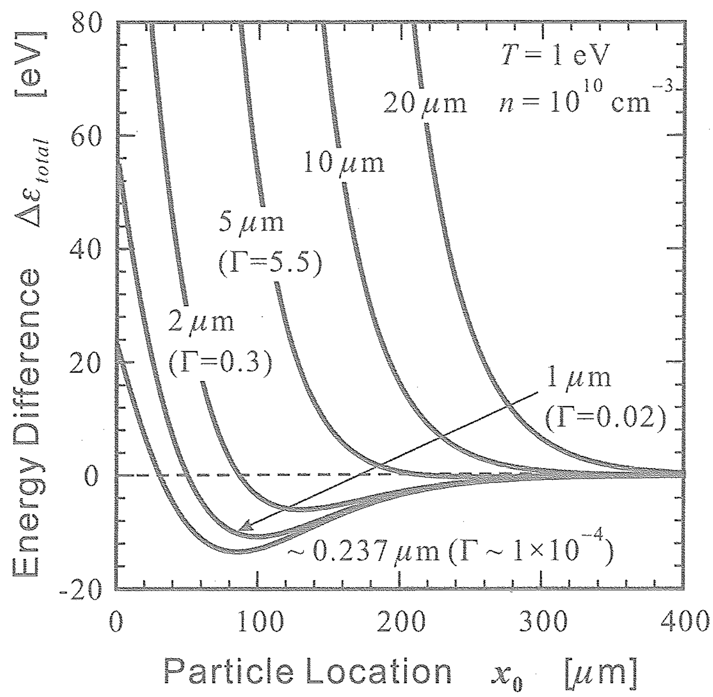


Fig. 3 Energy Difference against Particle Distance in Some Particle Diameters

3. Experimental Apparatus

In the design of the apparatus, we eliminate artificial potential control as much as possible. For example, there are no walls and grooves on the electrodes. Although the RF power is usually supplied between the two electrode, the RF power is supplied to each RF electrode to reduce voltage change. This method is similar to the usage of the RF antenna. Since wave length of 13.56 MHz is about 15 m, the voltage change on the antenna is about 4 percents of the peak-to-peak voltage at maximum. This configuration is schematically shown in Fig. 4. The apparatus based on the configuration shown in Fig. 4 is developed and is shown in Fig. 5. Figure 5 (a) shows the outside view of whole system. In Fig. 5 (a), the letter (b) can be seen. Figure 5 (b) is the inside view around the RF antenna took through the window marked by the letter (b) in Fig. 5 (a). The RF antenna has a disk shape. The diameter of the RF antenna is 10 cm. The distance between the upper antenna and the lower antenna is also 10 cm. The inner diameter of the vacuum chamber is 16 inches. The maximum output power of the RF oscillator is 1 kW. The oscillator output is divided by two through the power divider. The power divider can change the phase difference between the two outputs, 0 or π. From results of the plasma production experiments, it is found that the plasma is much easily produced with more than 2 W oscillator output in the case of the phase difference of π as compared with that in the case of the phase difference of 0. Therefore, the phase difference is set to π in the present experiments.

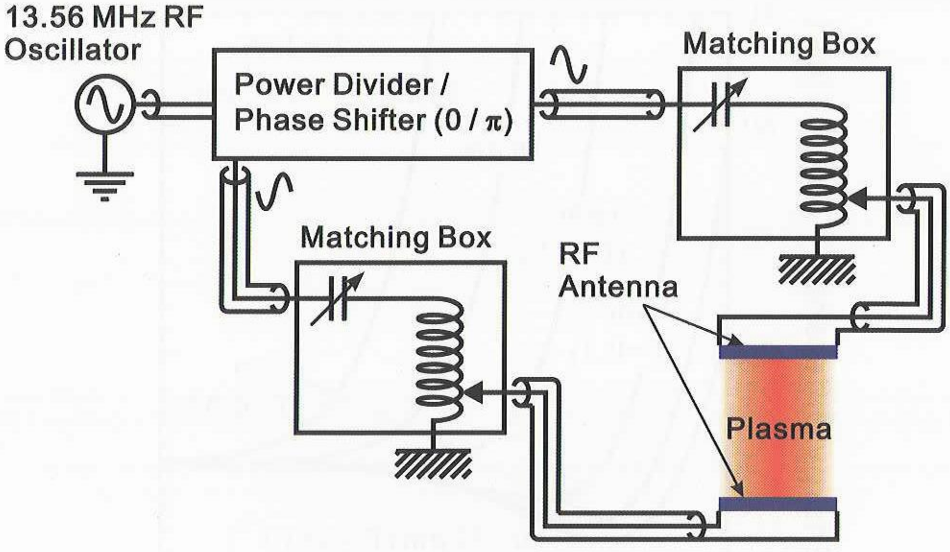
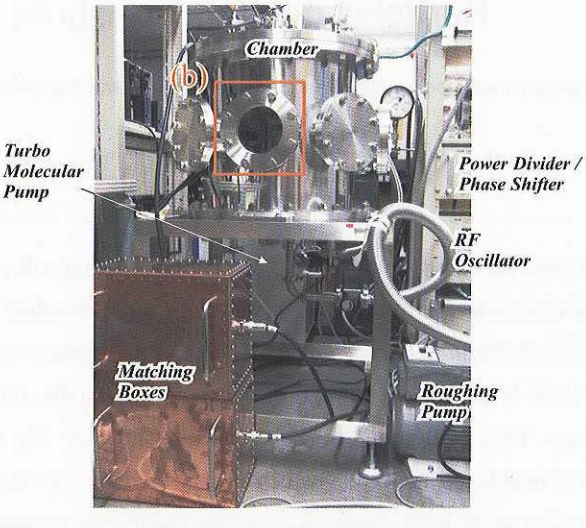


Fig. 4 Conceptual Configuration of Experimental Apparatus



(a) Outside view of whole system

(b) Inside view around RF antenna

Fig. 5 Experimental Apparatus

4. Experimental Results

By using the apparatus shown in Fig. 5, the Coulomb crystal has been successfully formed. Helium gas is used to produce the plasma. The pressure of the helium gas is about 0.5 Torr, which is measured by a Pirani gauge without calibration for helium gas. The RF oscillator output power is in the range from 10 W to 120 W. The typical result obtained from CCD camera observation is shown in Fig. 6. The particle diameter is 1 μm, and is made of silica in this experiment. By irradiating a green sheet laser light into the chamber, the particles can be observed. In Fig. 6, the green dots are the reflection from the silica particles. The vertical dashed lines are the lines passing through the particles. These lines shows that the particles are linearly aligned. On the other hand, the horizontal dashed lines indicate that the particles are not linearly aligned. This structure may be something like a body-centered cubic or face-centered cubic. The structure will be clarified next year by using two CCD cameras. The Coulomb crystal is stable in the quasisteady state for at least a few hours even though any artificial potential is not applied. Hence, the Coulomb crystal seems to be self-organized. This is not inconsistent with our prediction described in the section 2. Although the Coulomb crystal is stable in the quasisteady state, each particle moves from a lattice point to another at an initial phase. This is similar to the crystal growth. The typical result in the initial phase is shown in Fig. 7. In Fig. 7 (a), the Coulomb crystal is shown at the time is 0. Red and yellow arrows are indicated in this figure. In Fig. 7 (b), the data at 10 frames passed after t = 0 are shown. In this figure, it is found that the red-arrow-marked particle moves to the right side and the yellow-arrow-marked particles move to the left side when the black-arrow-marked particles approach the observation plane. Fig. 7 (c) shows the data at 20 frames. The black-arrow-marked particles reach the observation plane. Then it seems that the red- and yellow-arrow-marked particles are trapped to the corresponding lattices. The particles suddenly stops horizontally and sometimes move vertically to a certain location. This should be caused by some kind of particle trapping mechanism. This is the reason why the word of "trapped" is used. This trap may be caused by the energy minimum, which is predicted by our model, but quantitative investigation is required to clarify the trapping mechanism. The more quantitative investigation will be carried out next year. Finally, in Fig. 7 (d), the black-arrow-marked particles are also trapped to the lattice. Therefore, totally two particles increased on this observation plane. From Fig. 7 (d), it is found that there is no particle at the right side of the red-arrow-marked particle. This means that the red-arrow-marked particle is at an end of the crystal at this horizontal layer. If there is no trapping mechanism, the red-arrow-marked particle moves to the right side and may not stop at any horizontal location. For example, only the repulsive force exists, this particle is pushed towards the right side and will be lost from the observation area. However, the particle is trapped and stays. This fact also supports the existence of the trapping mechanism in the Coulomb crystal.

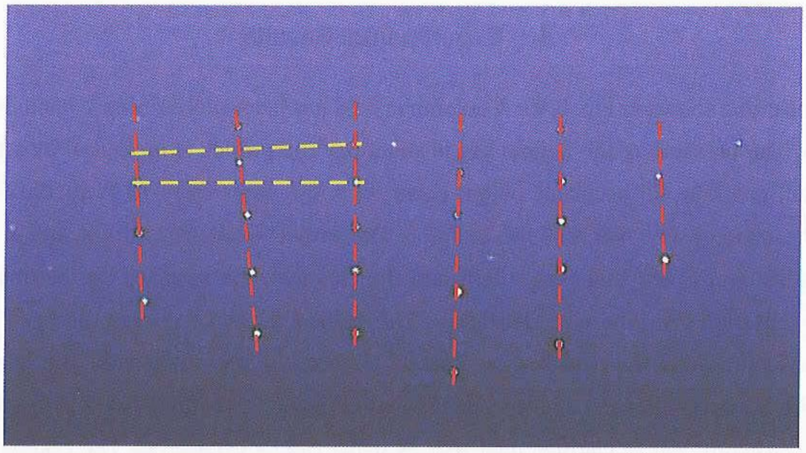
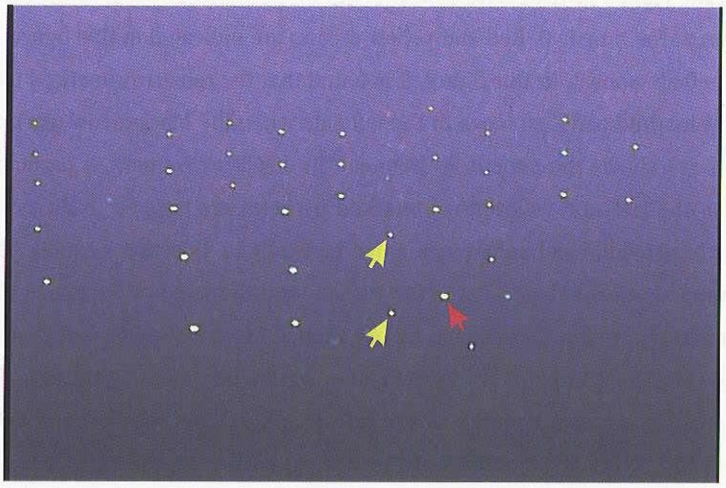


Fig. 6 Structure of Coulomb Crystal



(a) $t = 0$

(b) after 10 frames ($t \sim 0.33$ sec.)

(c) after 20 frames ($t \sim 0.66$ sec.)

(d) after 30 frames ($t \sim 1$ sec.)

Fig. 7 Time Evolution of Structure of Coulomb Crystal

5. Conclusions

The one-dimensional model of the Coulomb crystal is introduced by considering the power balance. This model predicts the existence of the energy minimum at a certain particle distance in small diameters. On the other hand, there is no energy minimum in large diameters. By considering the theoretical results, the experimental apparatus is designed and developed. This apparatus has a feature that any artificial potential is eliminated as much as possible. By using this apparatus, the Coulomb crystal is successfully formed. From the observation results, it is found that the structure of the Coulomb crystal is stable in quasisteady state for at least a few hours. This is not inconsistent with the prediction from our model. In addition, it is found that each particle moves from a lattice point to another at an initial phase. When the particle moves from one to another, the particle seems to be trapped. For example, the particle suddenly stops horizontally and sometimes moves vertically. In order to clarify the trapping mechanism, the more quantitative investigation is required. Such the investigation will be carried out next year.

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