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IIIII Short Note IIIII

Estimation of Plasma Parameters in Dusty Plasmas for Microgravity Experiments

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Abstract

Dust particles of micro-meter size are levitated around a sheath in discharges. Gravity pushes the dust particles from a bulk of plasma to the sheath on the ground. Microgravity conditions brought by sounding rockets, parabolic flights of aircract and the International Space Station allow the dust particles to suspend in the bulk of plasma. Many researches have required phenomena of the dust particles under microgravity to be understood with connected to plasma parameters. Here several examples estimating the plasma parameters of microgravity experiments were shown, and described as manners to elucidate the phenomena in dusty plasmas with the plasma parameters. A rough estimation of ion density was obtained in observing wave propagation, and spatial distribution of the dust particles changed by a discharge control was understood in measuring electron density.

Keyword(s): Dusty Plasma, Complex Plasma, Microgravity, ISS
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1. Introduction

Dusty plasmas generated by gas discharges with micrometer-sized particles have attracted much interest of scientists for several decades. Dust particles have charges given by fluxes of electron and ion in the plasmas. The charges of the dust particle is typically estimated to be in the order of a few hundreds or thousands of elementary charge in laboratory dusty plasmas. The charged dust particles interact each other and take on an aspect of strongly-coupled Coulomb system. Several physical phenomena, observed in solid or liquid state matter, can be seen in the particles regarding as atoms. The particles make regular arrangements of crystal, of which lattice constant is a few hundred micrometers. The crystals of the dust particles can be melted with changing discharge parameters, which show phase transitions visible for naked eyes. Vibration of the particles propagates as the wave, which is an example enable to understand behavior of the atoms in the matters.

In discharges, electrostatic, ion drag forces and gravity act on the dust particles. Balance of the forces determines position of dust particles levitating in the discharges. The dust particles are typically located around a plasma-sheath boundary. Without gravity, the dust particles are possibly sustained in bulk of plasma, which enable to be observed in a domain wider than on the ground. The wide spatial distribution of dust cloud is preferable in order to analyze the phenomenon requiring the strongly-coupled, i.e., highly-charged dust particles, which should be large and massive to gain charges. The microgravity experiments have contributed to make the dust clouds large and homogeneous, which have been brought by sounding rockets, parabolic flights of aircrafts and boarding on the International Space Station (ISS). A joint Russian/German scientific project have obtained successfully many experimental data with apparatuses of rf discharge, PKE-Nefedov [1)] and PK-3 plus [2)] on the ISS.

Estimating plasma parameters e.g., electron and ion densities, temperatures and so on, is necessary to understand physical phenomena in the dust cloud. Nevertheless it has not been performed enough to be involved in analyzing the phenomena. It should have been difficult for small volume of dusty plasmas to have diagnostic especially in apparatuses sophisticated for space experiments. Here several approaches to the plasma parameters are shown and discussed, with results on the ISS of wave phenomena and void formation.

2. Plasma Parameters in Wave Phenomena

Experiments for dust acoustic wave were performed with the PKE-Nefedov apparatus on the ISS [3,4)]. Wave properties with pa-

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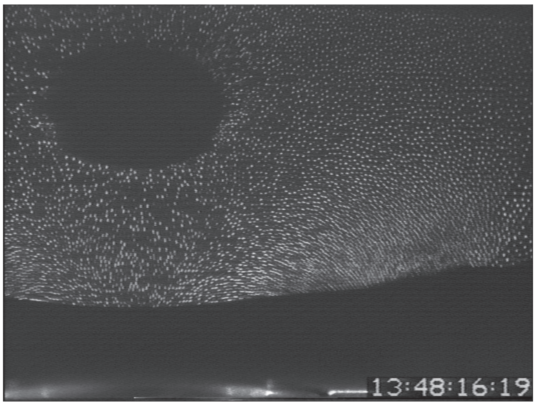
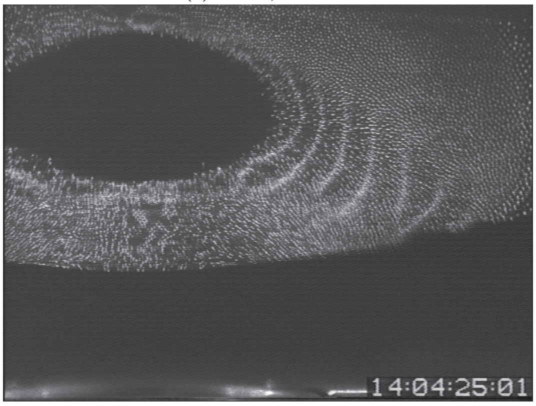


(a) 24 Pa, 0.25 W



(b) 12 Pa, 0.25 W

Fig. 1 Waves propagating in the dusty plasmas observed in the PKE-Nefedov apparatus. Reducing pressure from 24 to 12 Pa opens a channel of the wave at a constant rf power of 0.25 W.

rameters of frequency (ω), wave number (k) and speed (v) are determined by the states of dust particles represented by charge, mass, diameter and density, and of plasmas represented by electron and ion densities, temperatures and so on. This indicates that observation of waves can be a tool for plasma diagnostics.

Longitudinal waves were observed in dusty plasmas under microgravity (**Fig. 1**). The plasmas were generated in Ar gas excited by 13.56 MHz rf voltage. Dust particles of 3.4 μm in diameter were injected to the plasma. A sinusoidal voltage was applied to guard rings surrounding rf-powered electrodes. The electric perturbation induced oscillation of the dust particles and wave propagation. Pressure and rf power were changed from 12 to 24 Pa and 0.25 to 0.30 W, respectively. The dust particles were oscillated and a wave was propagated at the bottom of the dust cloud in case of high pressure of 24 Pa, shown in a right bottom part of **Fig. 1 (a)**. With pressure decreased to 12 Pa, a wave channel was opened from center to the right bottom part. The wave number (k) was estimated in measuring intervals between stripes of the waves on the images such as **Fig. 1** with changing the frequency of the sinusoidal voltage as ω.

Speed of dust acoustic wave (v_d) is given by the ratio of frequency (ω_d) to wave number (k_d)[4],

$$v_d = \frac{\omega_d}{k_d} = \frac{Z_d}{\sqrt{n_i}}\sqrt{\frac{n_d T_i}{m_d}}, \tag{1}$$

where Z_d, n_d, m_d are parameters of dust particles, charge number, density and mass, and n_i and T_i correspond to those of ion, density and temperature, respectively.

Figure 2 shows a dispersion relation, $\omega_d - k_d$ obtained at the pressure of 24 Pa and the power of 0.25 W (**Fig. 1 (a)**). The density of dust particle was measured to be 1.3×10^5 cm^{-3}. The long-wavelength-limit allows to linearly fit to the relation expressed by the Eq. (**1**). Here the speed of wave is determined to be 0.98 cm/sec. Then density of dust particle can be measured on the image of **Fig. 1 (a)**. These values change the Eq. (1) to relation between charge number of dust particle (Z_d) and ion density (n_i) with assuming ion temperature (T_i).

Conversely, one can estimate charge number of dust particles by the formula, $eZ_d = |Q| = 4\pi\varepsilon_0 r_d \phi_f$, where e, Q, ε_0, r_d, and ϕ_f are elementary charge, charge of dust particle, permittivity in vacuum, radius of dust particle, and floating potential of dust particle, respectively. The orbit-motion-limit (OML) theory suggests currents of electron (j_e) and ion (j_e) flowing to the dust particles as followings[5], and they are balanced on the dust particles, $j_e + j_i = 0$,

$$j_e = -4\pi r_d^2 e n_e \sqrt{\frac{T_e}{2\pi m_e}} \exp\left(\frac{e\phi_f}{k_B T_e}\right), \tag{2}$$

$$j_i = 4\pi r_d^2 e n_i \sqrt{\frac{T_i}{2\pi m_i}} \left(1 - \frac{e\phi_f}{k_B T_i}\right), \tag{3}$$

where n_e, T_e, m_e, m_i, and k_B correspond to three parameters for

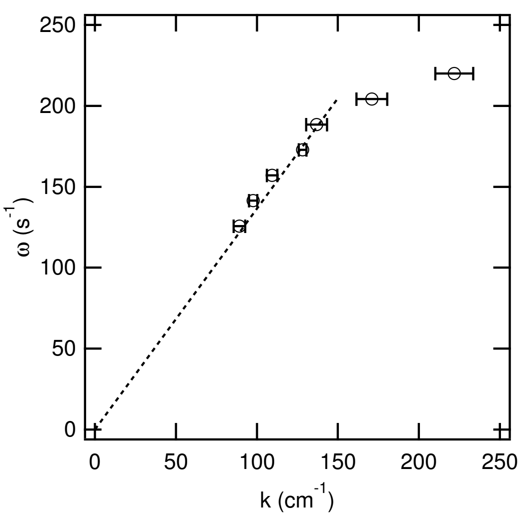


Fig. 2 Dispersion relation of the wave propagating in the condition at a pressure of 24 Pa and a power of 0.25 W shown by **Fig. 1 (a)**. The dotted line shows a linear part fitted to the long-wavelength-limit.

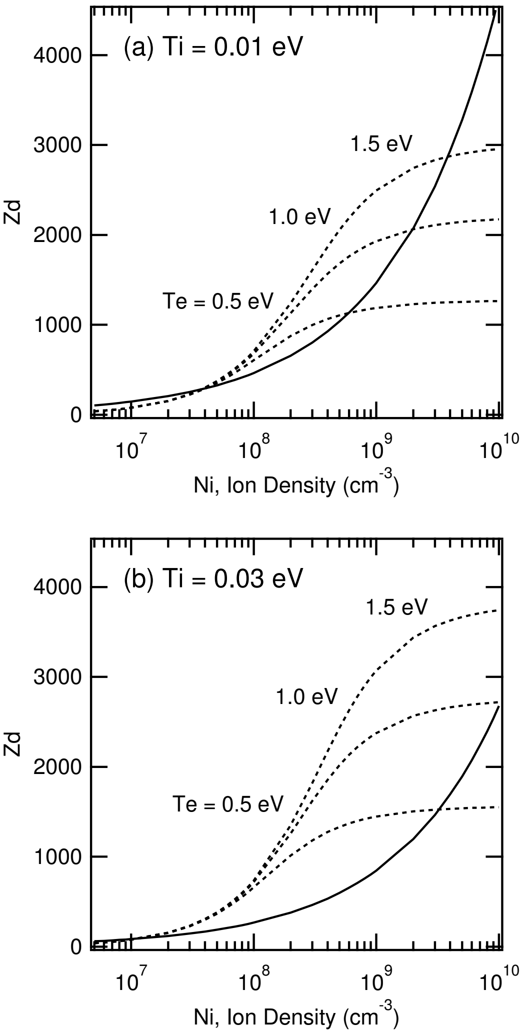


Fig. 3 Charge numbers of dust particle (Z_d) plotted as functions of ion density (n_i), and derived from the relations found in speed of dust acoustic wave and neutrality in plasmas involving the OML with assuming (a) $T_i = 0.01$ and (b) 0.03 eV.

electron, density, temperature, mass, mass of ion, and Boltzmann constant, respectively. Neutrality of charge in plasma taking into account, $n_e + Z_d n_d - n_i = 0$, Z_d is derived as a function of several plasma parameters.

Here the speed of acoustic wave (v_d) and density of dust particle (n_d) have been obtained in the experiment. With assuming T_i = 0.01 or 0.03 eV reasonable for laboratory plasmas and taking a constant of mass of dust particle (m_d), charge number of dust particle (Z_d) is expressed as a function of ion density (n_i) from the relation of Eq. (1) and plotted by solid lines in **Figs. 3 (a)** and **(b)**. Furthermore the procedure above with OML and neutrality in plasmas describes the charge number of dust particle as functions of ion density with electron temperature with the parameters assumed. This leads to the charge number of dust particle plotted by dotted lines in **Figs. 3**. One can find the plasma parameters on the points, where solid and dotted lines are crossing, i.e., the conditions from the dust acoustic wave and from the charge of dust particle are fulfilled. It is reasonable that ion density is in the order of 10^9 cm^{-3} and electron temperature is a few eV with regarding ion temperature as around room temperature. However, the ion density seems to be a bit larger than that reported[3)4)]. In fact, ion density and electron temperature were measured in a similar apparatus of PK-3 plus at 40 Pa and 0.4 W with a double-probe method[6)]. **Figure 4** shows their spatial distributions at axial center and edge of electrode between top and bottom electrodes. The ion density was ranging in $10^8 - 10^9$ cm^3 and the electron temperature was around 3 eV. Although there is a difference of factor a few between parameters from wave phenomena and those from measurement, a rough estimation of plasma parameters can be performed on the graphs derived from measurements of waves and neutrality in plasmas involving the OML.

3. Plasma Parameters and Void Closure

Experiments under microgravity with the PKE-Nefedov apparatus had notified that dust particle free region, so-called void, appeared at center of dust cloud in several conditions. The void became larger with increasing discharge power and gas pressure. In experiments with the PK-3 plus apparatus, the fact was empirically well-known that the void was reduced or closed with biasing to discharge voltage of 13.56 MHz rf. In the apparatus, two electrodes surrounded by grounded guard rings were set at the upper and bottom sides. The rf voltage was supplied to each electrode with a phase difference of 180 deg. Furthermore direct or sinusoidal alternating currents was possibly added to basis of the rf as additional biasing.

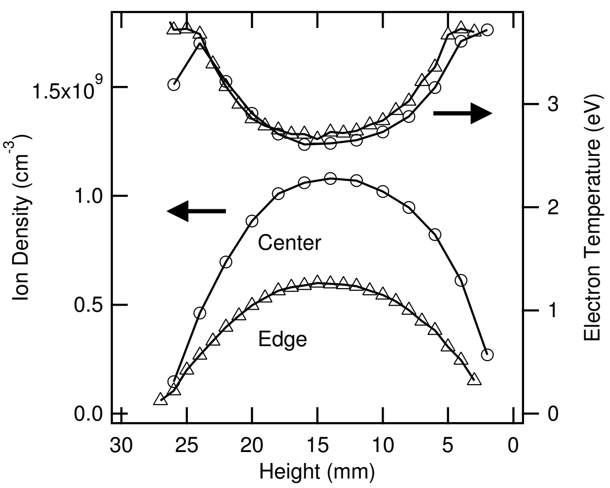
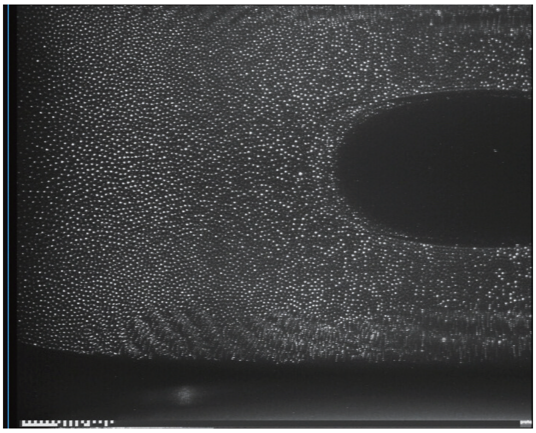
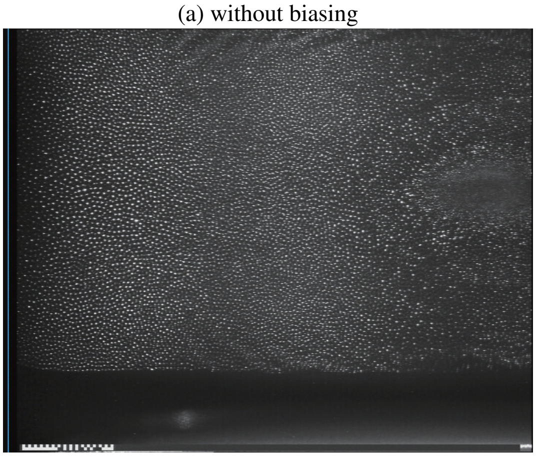


Fig. 4 Spatial distributions of ion density and electron temperature between top and bottom electrodes measured with a double-probe methods. They were measured at axial center (shown by open circles) and edge (shown by open triangles) of electrode.



(a) without biasing



(b) with biasing at 100 Hz

Fig. 5 The dust clouds were observed at 40 Pa and 1.0 W in a mission on the ISS. (a) the plasma was generated by the 13.53 MHz rf only. The void appeared in the high-density dust cloud. (b) additional biasing of sinusoidal voltage at 100 Hz and an amplitude of 20 V was applied.

In a mission on the ISS, spatial distribution of dust particles was observed with the additional biasing. The Ar gas was introduced to a chamber, and pressure was maintained at 40 Pa. The 13.56 MHz rf power was set at 1.0 W. Particles of 9.2 μm in diameter were injected until the dust cloud reaching to a high density. **Fig. 5 (a)** shows the dust cloud which had the waves in a left-bottom part caused by an instability due to the high density of the particles. The dust cloud had also a void at the center. With additional biasing of sinusoidal voltage at 100 Hz and an amplitude of 20 V comparable with that of the 13.56 MHz basis, the void was reduced and almost disappeared.

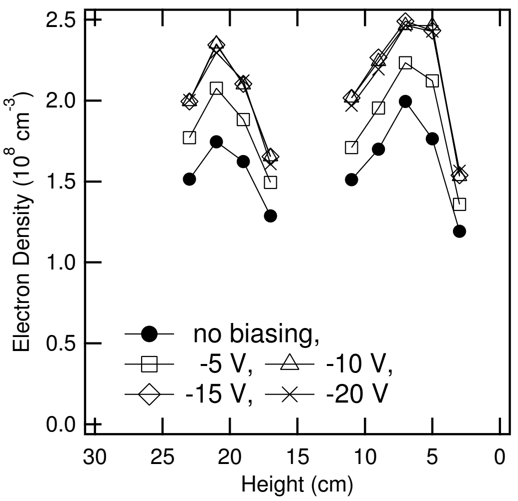
The spatial distribution of the dust cloud, which was changed by additional biasing, seemed to be related to plasma parameters also changed by additional biasing. However, no tools for diagnostics enabled to verify it on the ISS. In an experiment on the ground, one of the plasma parameters, electron density was measured in order to find changes of the plasma with additional biasing. The frequency shift probe was employed to measure electron density, which detected electron with resonance of microwave on wires working as cavity [7–9]. The probe with long wires of antenna was developed for a chamber of the PK-3 plus apparatus and confirmed to be applied for plasmas of very low density near sheath and taken away electrons by negatively-charged dust particles [10]. Although the long antenna occupied large volume in the plasmas and reduced electron density around it [6], it was useful to detect small changes of the electron density with high sensitivity. Hence, in the present study, values of the electron density makes no sense and changes of the value are focused in discussing effects of additional biasing on plasmas. On the ground, the particles of 9.2 μm are not levitated anymore in discharge due to gravity in the condition same as on the ISS. Therefore electron densities were measured in pristine Ar plasmas at 40 Pa and 1.0 W. For preventing from making an error in measurements by fluctuation of additional biasing at 100 Hz, sinusoidal waves with ranging between positive/negative voltages were broken down to direct current (dc) voltages.

The electron densities are shown in **Figs. 6 (a)** and **(b)** in plasmas generated by 13.56 MHz basis of 1.0 W and additional biasing from -20 to +20 V. Figures show spatial distributions of electron density between electrodes with a gap of 30 mm. The distributions have two peaks around plasma-sheath boundary near the electrodes, which indicates that the antenna forces the plasmas to change their shapes. It is trustworthy, however, to take relations in magnitude of electron density depending on voltages for additional biasing. With changing negative voltage for additional biasing from 0 to -20 V, the electron densities were enhanced. This is resulted from suppressing electrons missed on the electrodes by recombination and plasmas well-confined between the electrodes by additional biasing. Conversely, positive voltages for additional biasing reduce the electron densities, which allow the electrons to escape to the electrodes.

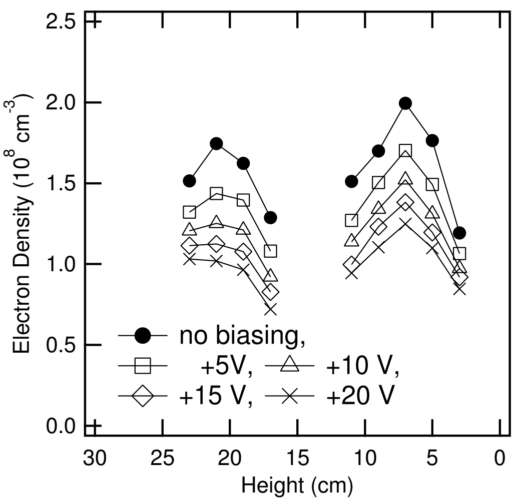
Additional biasing to the electrodes changed the electron density in bulk of plasma. This means that it changed also potential in the bulk. On the ISS, ac voltages for additional biasing were added to the electrodes at 100 Hz with phase difference of 180 deg as the basis of 13.56 MHz rf. The additional biasing shook a potential well confining the dust particles. The dust particles do not follow flip-flop of the potential at 100 Hz higher than plasma frequency for the dust particles. However, electrons and ions follow the additional biasing and are perturbed. Without the additional biasing, ions flow from center of the plasma to outside and ion drag force pushes the dust particles from center to outside, resulting in the void formation [11]. With the additional biasing, ion flow is not static and the ion drag force pushing the dust particles from the center can be missed. Hence the void was reduced and closed by the additional biasing.

4. Conclusion

Estimation of plasma parameters is necessary to elucidate phenomena in dusty plasmas. Behavior of the dust particles is easily



(a) negative bias



(b) positive bias

Fig. 6 Spatial distributions of electron density between the upper and lower electrodes in the plasma generated by the 13.56 MHz rf basis without dust particles. (a) negative dc bias added to the basis from 0 to -20 V, and (b) positive dc bias added to the basis from 0 to +20 V.

captured from images recorded by cameras in experiments. Conversely, the plasma parameter was hardly measured by tools for diagnostics. The dust particles make the diagnostics difficult to be used, since some of effects of the dust particles on plasmas are not understood. The diagnostics has been proceeded by trial and error up to now. It is necessary to calculate backward to plasma parameters in observation of, e.g., wave phenomena. Some practical tools, e.g., frequency shift probe are immediately applied to measure the plasma parameters in dusty plasmas. The preliminary results as shown here brings other ideas and tools to estimate the plasma parameters. In fact, the double-probe method with disturbance to plasmas less than the frequency shift probe seems to be the way better for rf discharges with the dust particles[6]. In addition, estimating and measuring the plasma parameters should have a technological impact for design of a new apparatus to go further in microgravity experiments.

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References

1) A. P. Nefedov, G. E. Morfill, V. E. Fortov, H. M. Thomas, H. Rothermel, T. Hagl, A. V. Ivlev, M. Zuzic, B. A. Klumov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, Y. P. Gidzenko, S. K. Krikalev, W. Shepherd, A. Ivanov, M. Roth, H. Binnenbruck, J. A. Goree and Y. P. Semenov: New J. Phys., **5** (2003) 33.
2) H. M. Thomas, G. E. Morfill, V. E. Fortov, A. V. Ivlev, V. I. Molotkov, A. M. Lipaev, T. Hagl, H. Rothermel, S. A. Khrapak, R. K. Suetterlin, M. Rubin-Zuzic, O. F. Petrov, V. I. Tokarev and S. K. Krikalev: New J. Phys., **10** (2008) 033036.
3) S. Khrapak, D. Samsonov, G. Morfill, H. Thomas, V. Yaroshenko, H. Rothermel, T. Hagl, V. Fortov, A. Nefedov, V. Molotkov, O. Petrov, A. Lipaev, A. Ivanov, and Y. Baturin: Phys. Plasmas, **10** (2003) 1.
4) V. V. Yaroshenko, B. M. Annaratone, S. A. Khrapak, H. M. Thomas, G. E. Morfill, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, A. I. Ivanov and M. V. Turin: Phys. Rev. E, **69** (2004) 066401.
5) H. M. Mott-Smith and I. Langmuir: Phys. Rev., **28** (1926) 727.
6) K. Takahashi, S. Adachi and H. Totsuji: JAXA Res. Devel. Rep. **14-012E** (2015) 7.
7) R. L. Stenzel: Rev. Sci. Instrum., **47** (1976) 603.
8) P. B. Piejak, V. A. Godyak, P. Garner, B. M. Alexandrovich and N. Sternberg: J. Appl. Phys., **95** (2004) 3785.
9) S. Yajima, K. Nakamura and H. Sugai: Proc. Int. Symp. Dry Process (Jeju, 2005) (2005) 213.
10) K. Takahashi, Y. Hayashi and S. Adachi: J. Appl. Phys., **110** (2011) 013307.
11) J. Goree, G. E. Morfill, V. N. Tsytovich and S. V. Vladimirov: Phys. Rev. E, **59** (1999) 7055.