Response to "Comment on 'Dynamic behaviors of dust particles in the plasma–sheath boundary'" [Phys. Plasmas 9, 1057 (2002)]

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The Comment made by Resendes *et al.* is composed of two parts:

(1) comment on the delayed charging model, and
(2) new model.

First we discuss the validity of delayed charging model. But, before proceeding to the details, there are several misunderstandings about our experimental observations on self-excited vertical oscillations of dust particles.

The Comment describes that the equilibrium position approaches the electrode when one is reducing the plasma density and gas pressure. However, Fig. 9 of the paper with which we were concerned (Ref. 1) clearly shows the opposite tendency for the density, which is very reasonable and comes from the sheath expansion. The pressure dependence of the equilibrium position is rather weak. The levitation position moves to the electrode by only around 0.5 mm when changing the pressure from 1 through 9 mTorr, as shown in Fig. 1 of the present paper. This is reasonable, since the sheath structure does not depend much on the gas pressure because the ion mean free-path is more than at least a few times as large as the sheath thickness.

The Comment tells us that the time trace of the particle position is of a stochastic nature and does not show exponential grow characteristics. The motion of the dust particles, around 15 Hz, shown in Fig. 2(a) of Ref. 2, was observed using a conventional charge coupled device (CCD) video camera with 30 frames/second, so that the picture sometimes shows a vertical bar due to poor time resolution. In these cases, the data points are plotted at the middle of the vertical bar. Such a technical procedure may show apparent amplitude oscillation-like traces. When the amplitude grows, there may be a saturation mechanism, which we consider to come from the reduction of effective spatial gradient of dust charge ∇Q. The saturation was reproduced in our numerical simulation as shown in Fig. 5 of Ref. 2. In addition, we should note that the average equilibrium position around which the oscillation develops does not drift vertically in time.

Concerning the energy gain of the dust particles due to the delayed charging, the arguments described in Ref. 2 are phenomenological. More accurately, the paper (Ref. 1) and Ref. 3 gave the growth rate more generally as follows:

$$\omega^i = -\frac{\beta}{2} + \frac{\tau_c}{2m}\frac{\partial Q}{\partial z}E.$$

This expression was derived also by Ivlev *et al.*[4] independently of our work. The growing time given by $(\omega^i)^{-1}$ is estimated to be a few to 10 seconds in the case of the Child–Langmuir sheath model as shown in Fig. 4(b) of the paper (Ref. 1). The growing time estimated by the Poisson sheath model using the electron energy distribution function with an energetic tail also gives a similar time scale as shown in Fig. 2 of the present paper. Such a small amount of high temperature electrons has been confirmed by experiment and also checked by comparing the observed equilibrium height with this sheath model as shown in Fig. 9 in Ref. 1. The estimated growing time is consistent with that experimentally observed.

The delayed charging model gives a threshold line for the vertical instability in the plasma density–gas pressure 2D parameter space, as shown in Fig. 6(b) of the paper (Ref. 1), which is very similar to the experimentally observed threshold curve shown in Fig. 2(b) of Ref. 2.

Concerning an inhomogeneity of dust particle oscillations, we have discussed the possibility of standing wave of transverse dust lattice wave in Refs. 1, 5, and 6. In fact, the self-excited transverse dust lattice wave is really observed in the vertically unstable parameter range, low plasma density and low gas pressure, and is compared with the theoretical dispersion relation.[1,6,7] Motions of dust particles on 1D string have a coherent phase relation among dust particles, that is, a wave structure. Other reasons for the inhomogeneity to be considered are the dispersion of dust size distribution, nonuniform sheath structure over the area where the dust particles are levitated. An additional one might be the presence of threshold amplitude above which the energy gain owing to delayed charging works because of a possible charge fluctuation.

Now we proceed with the second topic: discussion of Resendes' model, mainly a comparison with our experimental observation and the need for detail in the modeling and numerical simulation.

Comparison of experimental observations with simulation results is now given as follows: Figure 1 of the Comment shows a downward movement of equilibrium position as large as 2 mm from 5 down to 1 mTorr. However, the ex-

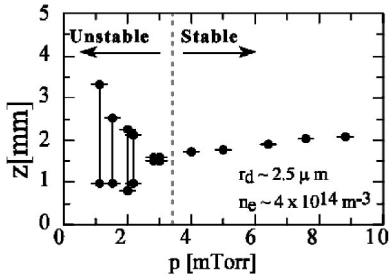

FIG. 1. Experimentally observed equilibrium height of dust particles as a function of gas pressure.

perimentally observed equilibrium position is insensitive to the change in gas pressure, as mentioned already. The observed downward shift is 0.5 mm through the change in the gas pressure. Figure 2 of the Comment shows a slow temporal drift of average vertical position over the oscillation amplitude. This is not the case in the experiment. The average vertical location stays almost constant, at least through the amplitude growing time scale. Moreover, the instability does not depend on the means of changing the gas pressure.

The Comment tells us that a similar phenomena is reproduced in the simulation when the plasma density decreases. In the experiment, the equilibrium position moves upward, going away from the biased mesh electrode when the density decreases.

Next we describe several points which will hopefully be reproduced in the simulations. It makes it possible to compare the simulation with the observation in more detail: The most outstanding characteristics of the experimentally observed phenomena is the presence of clear threshold line in the plasma density–gas pressure 2D parameter space as shown in Fig. 2(b) of Ref. 2. We hope to have such a representation of the simulation results.

We are very curious to know the detail of the modeling and the quantitative parameters in numerical simulation performed by Resendes *et al.*

First, concerning the sheath model. We cannot, of course, fix the sheath edge, rather the biasing voltage of the mesh electrode is fixed at -10 V with respect to the plasma potential, which is almost equal to the chamber potential. The model is hoped to take this into account.

The fact shown in the simulation, that the potential energy of the dust particle depends strongly on the gas pressure, is considered to mean that a strong neutral gas flow is working on the dust particles in the sheath. The origin of this neutral gas flow and the magnitude need to be described in detail. In our experimental condition, the ion drag force on dust particles is smaller than the gravitational force and the electrostatic force due to sheath electric field by an order of magnitude. The force due to the flow of charge-exchanged neutral atoms is considered to be weaker than the ion drag force. Therefore, the equilibrium position is determined mainly by the balance between the gravitational downward force and the electrostatic upward force. It has been confirmed in the experiment, like in Fig. 9 of Ref. 1, and the weak dependence of equilibrium position on the gas pressure.

Concerning the gas flow, the gas inlet and pumping port are located at 75 cm below the experimental area in the big chamber (0.4 m in diameter and 1.1 m in height) so that the gas flow due to the gas injection and pumping is considered not to be important.

In summary, the delayed charging model can explain many experimental observations quantitatively as well as qualitatively, so that we think that the delayed charging model is a strong candidate for the physical model of our experimental findings. Moreover, we believe that this effect would be a very important process in many situations of dusty plasma phenomena. However, the delayed charging model might not be a perfect one for our experimental observation. If the alternative model would be able to explain the experimental results more thoroughly than our model, we believe that many research scientists working on dusty plasma would have strong interest in it. At the moment we do not know that Resendes' model corresponds to this, so that we hope and appreciate that they will submit a more complete paper describing the above requests.

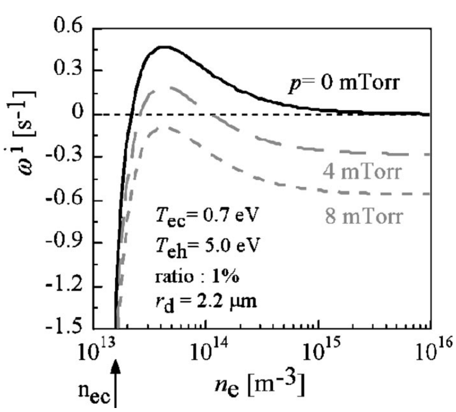

FIG. 2. Growth rate for vertical instability as a function of plasma density taking gas pressure as a parameter in the Poisson sheath model.

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