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Self-excited vertical oscillations in an rf-discharge dusty plasma

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A self-excited vertical oscillation of dust grains in the sheath region of an rf-discharge plasma has been observed. The variation of amplitude with pressure and input power was measured. Dramatic increase of oscillation amplitude was found for pressures below 4.5 Pa. Possible excitation mechanisms are considered.

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Dusty plasmas are plasmas that contain small particles ranging in size from nanometers to micrometers. Usually the dust particles achieve electrostatic equilibrium with respect to the plasma by acquiring negative charge. This charge is extremely large compared to the ionic charge. In addition, the particle charge is not fixed but is coupled self-consistently to the surrounding plasma parameters. For this reason, new instabilities can develop in a dusty plasma, leading to different wave modes and oscillations. An enhanced level of dust particle oscillation has been reported in many experiments on dusty plasmas [1–6]. The most interesting type of oscillation is the vertical oscillation of single particles. Experimental study of these oscillations allows us to evaluate basic parameters of the dust system: the particle charge, interparticle coupling parameters, etc. [7,8]. Usually the vertical oscillations are excited by means of a wire located near the particles and driven by a sinusoidal voltage source [9–11]. Laser-excited vertical oscillations have also been reported [12]. In other experiments, vertical dust density fluctuations [4,5,13] or individual particle oscillations [3] were spontaneously excited. It should be mentioned that all previously observed self-excited oscillations were in dc-discharges or *Q*-machine dusty plasmas. We present here an experimental observation of self-excited vertical oscillation of dust particles trapped in the sheath region of an rf-discharge plasma. As the pressure was reduced the oscillation amplitude was found to increase dramatically starting at a relatively high pressure of about 4.5 Pa.

The experiments were carried out in a 40-cm inner diameter cylindrical stainless steel vacuum vessel with many ports for diagnostic access. The chamber height is 30 cm. We use a disk as the powered electrode and a ring as the grounded electrode (see Fig. 1). The diameters of the electrodes are 10 cm for the disk and 11.5 cm for the ring. The ring is centred on the axis of system and the distance between the electrodes is 30 mm. Argon plasmas are generated at pressures in the range 0.5–20 Pa by applying a 15 MHz signal to the disk electrode. A compensated single Langmuir probe is used to make measurements of the plasma parameters. The probe position can be moved vertically and radially, with respect to the electrodes. The typical plasma parameters measured in our experiments are $n_e \sim 0.8-10 \times 10^8\ \mathrm{cm}^{-3}$, $T_e \sim 2$ eV, and plasma potential $V_p \sim 40-80$ V with respect to the grounded electrode.

In these experiments, $2.1 \pm 0.1\ \mu$m diameter carbon (C) particles have been used. After the dust particles are dispersed into the plasma, they acquire sufficient charge for the electric force (due to the sheath electric field) to compensate the gravitational force and the dust particles stay in equilibrium vertical positions. In the radial direction, the particles usually become trapped within the radius of the ring electrode. The dust particles suspended in the plasma are illuminated using a helium-neon laser. Images of the illuminated dust cloud are obtained using a charged-coupled device (CCD) camera with a 60 mm microlens, or a digital camcorder (focal length: 5–50 mm). The camcorder was operated at 25 to 100 frames/s. The video signals are stored on a videotape recorder or are transferred to a computer via a frame-grabber card with an eight-bit gray scale and 640 ×480-pixel resolution. The coordinates of the particles were measured in each frame, and individual particles were traced from one frame to the next.

A one-layer structure has been investigated in the experiment. It was found that when the pressure was decreased below a critical value, the dust particles began to oscillate spontaneously in the vertical direction. Figure 2 shows typical images of the vertical oscillations at different pressures. The amplitude and frequency of the oscillations are several millimeters and greater than 10 Hz, respectively. When the rf input power was decreased, the oscillation amplitude was found to increase. Figure 3 shows the dependence of the oscillation amplitude on gas pressure and rf power. For pressures below 4.5 Pa the oscillation amplitude increased dramatically. This increase is greater for lower rf powers.

For rf powers of more than 80 W the effect was not ob-

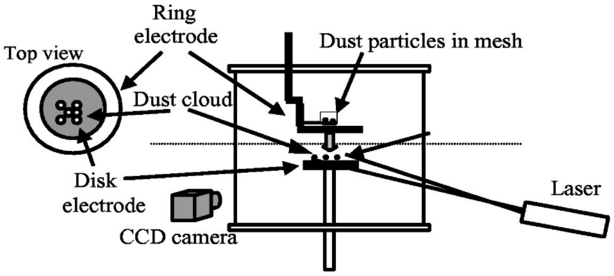

FIG. 1. Sketch of the experimental setup.

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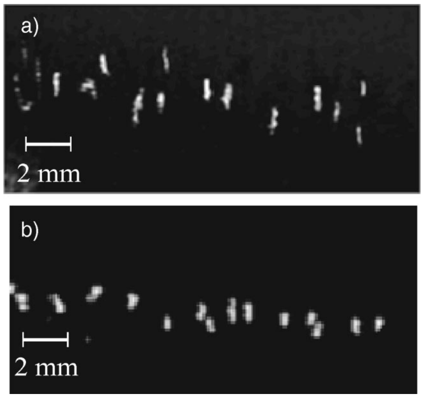

FIG. 2. Side view of a self-excited vertical oscillation of dust particles. Input power $P=35$ W, pressure (a) -2.9 Pa, (b) -4.0 Pa.

served. In this case, when the pressure was decreased there were similarly increasing amplitudes of both horizontal and vertical oscillations. This is consistent with the well-known fact that when the power is increased or the pressure is reduced in a dust plasma system a melting transition from ordered to fluid states can be induced [14–16]. However, in previous works, authors have reported increases of horizontal oscillations only and increased vertical migration of particles. In contrast we observe a dramatic growth of the amplitude of vertical oscillations of the dust relative to horizontal oscillations. Figure 4 shows the dust particle oscillation amplitude in the vertical (z) and horizontal (x) directions as a function of pressure. In this figure we can see also that for high pressures the oscillation amplitude in the z direction at low powers is less than at higher powers; as the pressure is reduced, however, the lower power amplitude exceeds the higher power amplitude. For oscillation in the x-direction, the amplitude grows proportionally with power.

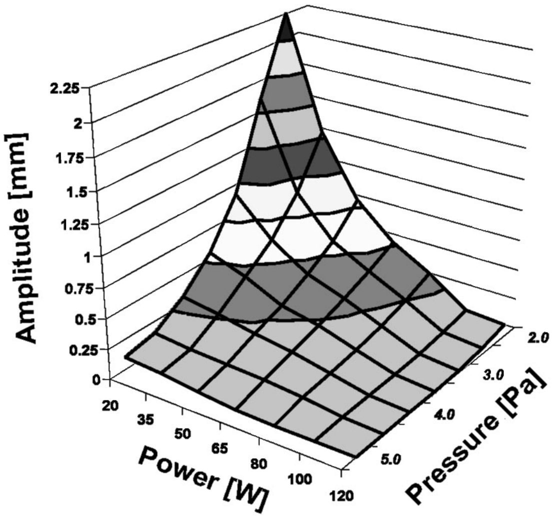

FIG. 3. Variation of the vertical oscillation amplitude (mm) as the function of the rf power and the pressure.

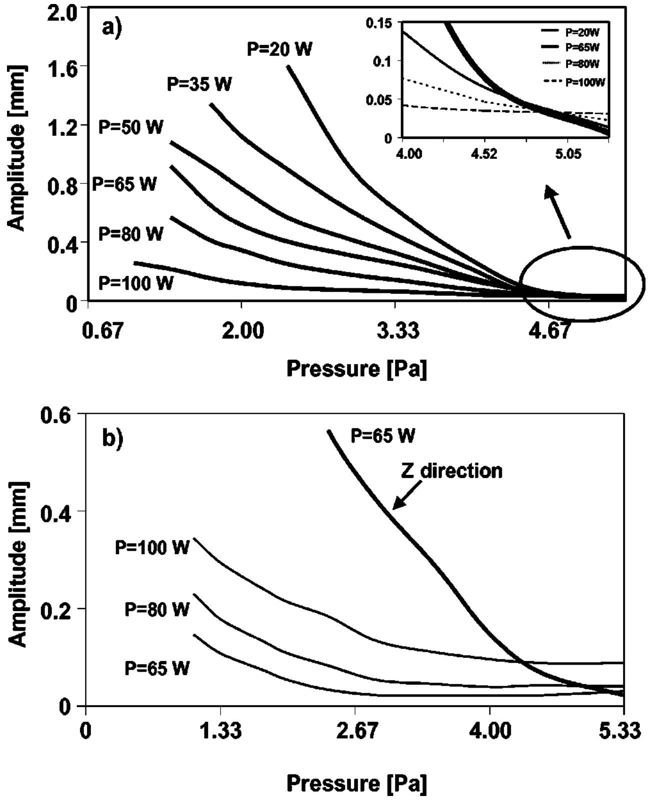

FIG. 4. Dependence of oscillation amplitude in the z (a) and x (b) directions. For comparison, the dependence of oscillation amplitude in the z direction for input power 65 W is also plotted in (b). The inset in (a) is enlarged part of the 4–5 Pa region.

The frequency and amplitude of oscillations are independent of the number of particles while we have a monolayer structure, which in our experiment corresponds to a structure consisting of a few to a few tens of particles. When the number of particles in the structure reaches hundreds the dust particles form several layers where the self-excited oscillations are also observed. However, their nature is more complicated and requires additional study.

To excite oscillations the energy input must be sufficient to overcome the gradual damping by friction. One possible way for a particle to gain energy is the delayed charge effect, proposed in Ref. [3]. The energy gain for the one oscillation cycle can be estimated as $W_{\mathrm{gain}}=\Delta Q_d EL$, where E and L are respectively the electrostatic field at the equilibrium height and oscillation amplitude, and ΔQ_d is the difference in the charge for a particle moving up, compared to a particle moving down. This difference can be written in the form $\Delta Q_d=\Delta Q_d^{eq}\exp(-\nu_{ch}/\omega_0)$ where ω_0 is the frequency of the dust oscillation, ν_{ch} is the steady-state dust charging frequency, and ΔQ_d^{eq} is the difference of the equilibrium charge in the extreme points of oscillations. The energy losses, which primarily occur due to friction with gas molecules, can be estimated as $W_{\mathrm{loss}}=\pi r_d^2 v_d m_n v_n P_n L/kT_n$, where r_d and v_d are respectively the radius and velosity of the dust particles, v_n and m_n are respectively the thermal velocity and mass of the gas molecules, and P_n and T_n are respectively the pressure and temperature of the neutral gas.

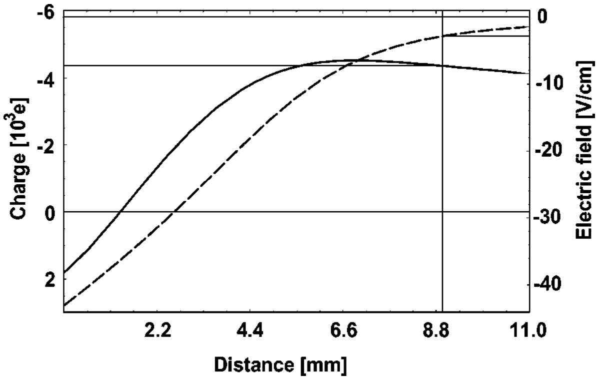

FIG. 5. Dependence of the electrostatic field E (dashed curve) and the equilibrium dust charge Q_d (solid curve) on the distance from the electrode.

We can obtain the velocity of the dust particles and the oscillation amplitude from analysis of the images. To estimate the values of E and Q_d we use the model described by Vladimirov and Cramer [17]. Based on data obtained from probe measurement ($T_e = 1.8$ eV, $n_e = 1.4\times 10^8$ cm^{-3}) we use the model to calculate the spatial dependencies of E and Q_d (see Fig. 5) for a pressure of 4 Pa and an electrode potential of -10 V. The results indicate that at the levitation point $E = 3.5$ V/cm, $Q_d = 4350e$, and $\Delta Q_d^{eq} = 0.1 Q_d$ for the oscillation amplitude $L = 1$ mm. We also use the technique proposed in Refs. [18,19] to calculate E and Q_d, obtained values $E = 2.5$ V/cm and $Q_d = 7200e$ close to those obtained from the model.

For our experimental condition (Ar, $P = 4$ Pa, $T_n = 300$ K, $r_p = 1$ μm, $L = 1$ mm, $E = 3$ V/cm, and $\Delta Q_d = 0.1 Q_d$) we obtain that energy losses is $W_{\mathrm{loss}} \sim 10^{-18}$ J. In our case the oscillation frequency is $\omega_0/2\pi \sim 14-16$ Hz, the charging frequency $\nu_{ch} \sim 10^5$ s^{-1}. This means that the above rough estimate gives us that only negligible portion of energy (less than 10^{-20} J) can be gained.

For a more detailed analysis of this delayed charging mechanism we should consider the equation of vertical motion for a single particle

$$M_d \frac{d^2 z}{dt^2} + 2\beta M_d \frac{dz}{dt} = F_n, \tag{1}$$

where $\beta = (4 P r_d^2 / 3 M_d)(2\pi m_n / T_n)^{1/2}$ is the damping rate due to neutral gas friction [20], M_d is the mass of the dust particle and F_n is the net force acting on the particles. Ivlev et al. [21] presented a model of dust particle vertical oscillation taking into account for the net force only electrostatic $F_e = Q_d E$ and gravity $F_g = M_d g$ forces. They suggested that the threshold for the instability due to the charging delay in the case of the regular charge variation and the stochastic charge fluctuations can be evaluated as: for the regular charge variation

$$\mathrm{Im}\,\omega = \beta - \left[\frac{Q_d' E_0}{(Q_d E)_0'}\right] \frac{\omega_0^2}{2\nu_{ch}}, \tag{2}$$

where $\mathrm{Im}\,\omega$ is the damping rate, the prime denotes the derivative at the equilibrium point $z = z_{eq}$. We note that the instability develops when $\mathrm{Im}\,\omega > 0$, and, correspondingly, $W_{gain} > W_{loss}$. For the stochastic charge variation

$$\frac{\Gamma_\varepsilon}{2} = \beta - \left[\sigma \frac{Q_d E_0'}{(Q_d E)_0'}\right]^2 \frac{\omega_0^2}{2\nu_{ch}}, \tag{3}$$

where Γ_ε is the energy damping rate, and σ is the dimensionless dispersion of the charge distribution [21]. Taking into account the values of $\Delta Q_d / Q_d \sim 0.1$ and $\Delta E / E \sim 0.2$, we obtain that the second term in the right-hand side of Eq. (2) is about 2×10^{-2} s^{-1}. This means that we should expect the instability when the pressure is less than 0.01 Pa. A similar analysis of Eq. (3) for $\sigma = 0.1$ gives the pressure threshold for stochastic fluctuation as 5 mPa.

We can consider the net force in Eq. (1) taking into account the ion drag force

$$F_i = \pi a^2 m_i n_i v_s^2 (\chi_1 + \chi_2), \tag{4}$$

where m_i is the ion mass, n_i is the number density of positive ions, v_s is the velocity of ions in the sheath, χ_1 and χ_2 are given by

$$\chi_1 = 1 - \frac{2 Q_d e}{m_i v_s^2 a},$$

$$\chi_2 = 2\left(\frac{Q_d e}{m_i v_s^2 a}\right)^2 \ln\left[\frac{(\lambda_D / a)^2 + \left(\frac{Q_d e}{m_i v_s^2 a}\right)^2}{\left(1 - \frac{Q_d e}{m_i v_s^2 a}\right)^2}\right]. \tag{5}$$

The resulting equation can be analyzed numerically. However, some analytical results can be derived in several limiting cases for the ion drag force. If we consider only the orbit force contribution to $F_i = \pi e^2 n_i(z) Q_d^2(z,t) / m_i v_s^2$ [17], the damping rate is given by

$$\mathrm{Im}\,\omega = \beta - \left[\frac{Q_d' E_0 + 2\pi e^2 Q_d n_{i0} Q_d' / m v_i^2}{(Q_d E)_0' - 2\pi e^2 Q_d (n_i Q_d)_0' / m v_i^2}\right] \frac{\omega_0^2}{2\nu_{ch}}. \tag{6}$$

For F_i including only the collection force, $F_i = 2\pi a^2 m_i n_i(z) v_s^2(z)$, the damping rate is

$$\mathrm{Im}\,\omega = \beta - \left[\frac{Q_d' E_0}{(Q_d E)_0' - 2\pi a^2 m (v_i^2 n_i)_0'}\right] \frac{\omega_0^2}{2\nu_{ch}}. \tag{7}$$

For both cases the pressure threshold is less than 0.4 Pa (for purposes of estimation we use the values $\Delta n_i / n_i \sim 0.2$ and $\Delta v_i / v_i \sim 0.35$ obtained using the model in Ref. [17]), in disagreement with the experimental results. A similar value for the pressure threshold was obtained if we use the model considered by Fortov *et al.* [13] for instability due to charge variations in the presence of external charge-dependent forces together with the ion drift effect.

To summarize, a self-excited vertical oscillation of dust grains in the sheath region of an rf-discharge plasma has been observed. The amplitude dependence on pressure and input power was measured. Possible excitation mechanisms were considered, and all of them gave the pressure thresholds no greater than 0.4 Pa. However, we observe oscillations for larger values of pressure up to 5 Pa. This suggests a different excitation mechanism. Two mechanisms are proposed by the authors for future consideration. The first is based on the spatial variation of grain charges [22] and the second is based on instability of the layer of charged particles as a virtual wall (resonator) [23]. Both approaches consider the dust-plasma layer as a dissipative structure (static in Ref. [22], and dynamic in Ref. [23]) and suggest a new kind of instability in dust plasma systems, which is a self-confinement instability.

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