Charge Variations in Planar RF Discharge

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Abstract. In a complex plasma 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. There are two mechanisms that can lead to random fluctuations of particle charge relative to its equilibrium (time averaged) value [1]. The first is related to the random nature of ionic and electronic currents which charge the particles. The second is a result of random motion of the particles (for example due to their Brownian motion) in the spatially inhomogeneous plasma. Here we consider the influence of charge variations on the dynamics of a mono-layered structure levitated above the powered electrode in a planar rf discharge. Vertical oscillations in such a structure were first reported in [2].

THEORY

For explanation of the observed self-excited oscillations we have taken into account the random fluctuations of the particle charges caused by the stochastic variations of charging current, and also fluctuations of charges due to their random motion in the presence of gradient of particle charge in the vertical direction. In this 2-D case the dynamics of dust particles levitated in the plasma sheath are described by the following equations

$$m_p y'' = -m_p \nu_{fr} y' - (\alpha_y e\langle Z\rangle + \beta_y E_y) y + e\tilde{Z}_f E_y + F_y^{br}, \tag{1a}$$

$$m_p r'' = -m_p \nu_{fr} r' - \alpha_r e\langle Z\rangle r + e(\tilde{Z}_f + \tilde{Z}_s) E_r + F_r^{br}, \tag{1б}$$

where r'', y'', r', y' are derivatives with respect to time, and $\alpha_y = dE_y/dy$, $\alpha_r = dE_r/dr$ are spatial gradients of the electric field **E** = (E_y, E_r). The charge variations $\tilde{Z}_f$, $\tilde{Z}_s$ and their mean square displacements $\langle \tilde{Z}_f \rangle = \sqrt{\langle \tilde{Z}_f^{\,2} \rangle_t}$, $\langle \tilde{Z}_s \rangle = \sqrt{\langle \tilde{Z}_s^{\,2} \rangle_t}$ ($\langle \tilde{Z}^2 \rangle_t$ are given by

$$\frac{d\tilde{Z}_f}{dt} = -\eta\, \tilde{Z}_f + \tilde{F}_f\,, \quad \langle \tilde{Z}_f \rangle = \xi\sqrt{\langle Z\rangle}\,, \tag{2a}$$

$$\tilde{Z}_s = \beta_y y\,, \qquad \langle \tilde{Z}_s \rangle = \beta_y \sqrt{\langle y^2 \rangle}\,, \tag{2b}$$

where η and ξ are parameters determined by the plasma condition. Assuming no correlation between $\tilde{F}_f, F_y^{br}, F_r^{br}$ the total kinetic energy of a dust particle can be defined as $2\langle K\rangle = 3T_o + \Delta^f T + \Delta^s T$, where T_o is gas temperature, and $\Delta^{f(s)}T$ depends on the nature of the charge fluctuation. By solving the equations (1)-(2a) we found an expression for the value of oscillation kinetic energy acquired due to fluctuations of the charging currents:

$$\Delta^f T_{y(r)} = \frac{e^2 Z \xi^2 E_{y(r)}{}^2}{m_p \nu_{fr}(\nu_{fr} + \eta)}\,, \tag{3}$$

where the value of E_r is ~ $(eZ/l)^2$. Estimating $\Delta^f T$ for typical experimental conditions yields $\Delta^f T$ = $2\Delta^f T_r + \Delta^f T_y < 10T_o$. This is less than experimentally observed values which are about 100eV.

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The expression for the kinetic energy acquired due to random motion in the presence of a charge gradient can be obtain from equations (1)-(2b):

$$\Delta^s T_r = (T_o + \Delta^f T_y + \Delta^s T_y)\theta_1 , \tag{4}$$

where

$$\theta_1 \approx \left(\frac{\beta_y}{e\langle Z\rangle}\right)^2 \frac{2\alpha\omega_y^2 e^4 \langle Z\rangle^4}{m_p^2 g(\alpha_y / E_y + \beta_y / \langle Z\rangle)((\omega_r^2 - \omega_y^2)^2 + 2(\omega_r^2 - \omega_y^2)\nu_{fr}^2 + 4\omega_y^2 \nu_{fr}^2) l_p^4} \tag{4a}$$

And $\omega_r^2 = e\langle Z\rangle\alpha_r/m_p \sim (e\langle Z\rangle)^2 n_p$, $\omega_y^2 = (\beta_y E_y + e\langle Z\rangle\alpha_y)/m_p$. For $(\omega_r^2 - \omega_y^2) \ll \nu_{fr}^2$:

$$\theta_1 \approx \left(\frac{\beta_y}{e\langle Z\rangle}\right)^2 \frac{\alpha e^4 \langle Z\rangle^4}{2 m_p^2 g(\alpha_y / E_y + \beta_y / \langle Z\rangle)\nu_{fr}^2 l_p^4} . \tag{4b}$$

Taking into account that $\Delta^f T_y \approx \Delta^f T/3$ $l_p^2 \cong l^2 + \langle y^2\rangle$, where

$$\langle y\rangle^2 = \frac{(T_o + \Delta^f T_y + \Delta^s T_y)}{m_p \omega_y^2} ,$$

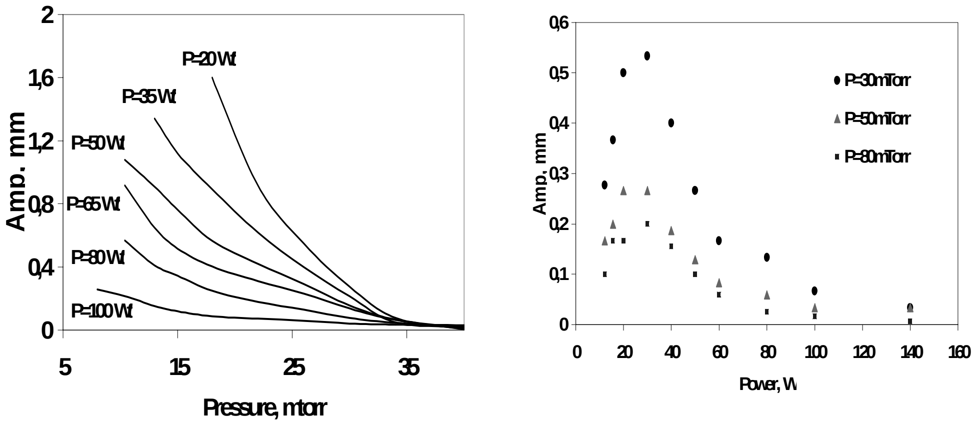
$\Delta^f T_y \approx \Delta^f T/3$, $\Delta^s T_y = \gamma\Delta^s T_r$, and γ is the parameter of kinetic energy redistribution, for $l^2 \gg \langle y^2\rangle$ and $\gamma = 1$ ($\Delta^s T = \Delta^s T_y \equiv \Delta^s T_r$) we finally obtain:

$$\Delta^s T = \frac{(T_o + \Delta^f T/3)}{1 - \theta_1} \tag{5}$$

Estimates of the maximum value of kinetic energy and oscillation amplitude using a linear approximation in the case $l^2 \ll \langle y^2\rangle$ give us

$$\Delta^s T^{\max} = \theta_1 l^2 \omega_y^2 m_p , \qquad A_y^{\max} \approx l\sqrt{2\sqrt{\theta_1}} \tag{6}$$

where $A_y^{\max} = \sqrt{2\langle y^2\rangle}$.



a) b)

FIGURE 1. Experimental chamber and image of test gains levitated above the electrode.

EXPERIMENT

The one layer dust structure in Ar plasma of planar rf discharge was investigated (the experiment details can be find in [2]). It was found that when the pressure was decreased bellow a critical value the dust particles began to oscillate spontaneously in the vertical direction. The amplitude and frequency of the oscillations are several millimetres and about ten Hz, respectively. When the rf input power was decreased the oscillation amplitude was found to increase. Fig. 1 shows the dependence of oscillation amplitude on gas pressure and rf power. For pressures below 35 mTorr the oscillation amplitude increased dramatically. This increase is greater for lower rf powers. For the 6.28 mm particles, saturation and decrease of the oscillation amplitude is observed.

Comparison of theoretical and experimental dates better provide using the relative parameters. In our case we normalised the oscillation amplitude to the definite value $A_y(P_o)$ and look on the dependence on pressure.

The dependencies of the ratio $A_y^{max}(P_i)\ /A_y(P_o)$ on pressure is shown in Fig.2. Taking into account $\theta_1\ (P_i) = \theta_1\ (P_o)\ (P_o/P_i)^2$, the value of $\theta_1\ (P_o)$ can be obtained using equation (Fig.3) by fitting the simulation data to the experimental results. Using this routine $\theta_1 \approx 0.5$ for P_o = 50 mTorr (a=1µm) and $\theta_1 \approx 0.28$ for P_o = 100 mTorr, (a=3.07 µm) were obtained.

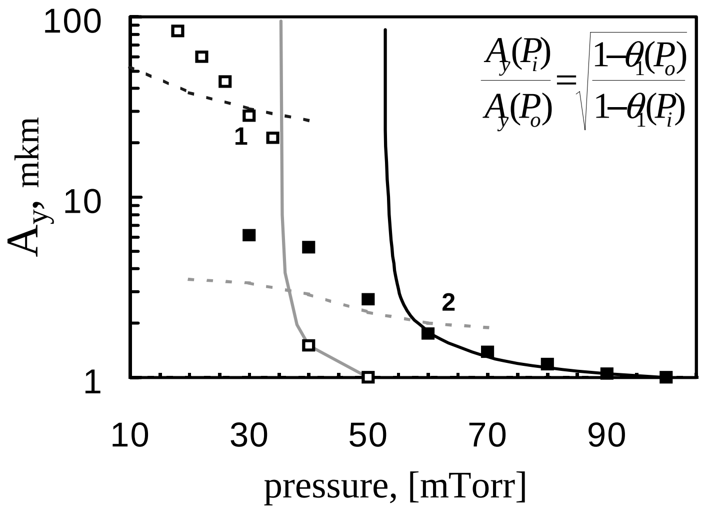


FIGURE 2. Normalised amplitude versus pressure. 1-for a=1.05 µm, 2- for a=3.07 µm.

Solid lines are simulation results. Dotted lines $A_y \approx n_p^{-1/3}$. $A_y(P_i)$ is oscillation measured for different pressures P_i .

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REFERENCES

1. Khrapak S.A., Nefedov A.P., Petrov O.F., Vaulina O.S., Phys.Rev. E **59**, 6017 (1999).
2. Samarian, A., James, B., Vladimirov, S., and Cramer, N., *Phys. Rev*. **64**, 025402(R) (2001).