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Dust Vortex in Complex Plasma

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Problems associated with the formation and development of vortices in dissipative systems of interacting macroparticles are under discussion in various fields of science (plasma physics, molecular biophysics, hydrodynamics etc.). Dusty plasma provides a good experimental model for the study of vortices in these systems.

The theoretical analysis and numerical simulation [1-3] have shown that in plasma with gradients of dust charge, various dust particle motions could be excited. The vertical vortices of dust particles were found to be rotating in inductively coupled plasma with an angular frequency of 0.2-1.5 sec^{-1}. Similar motion of dust structures was observed in striation region of a dc-discharge. There are two basic reasons which prevent the development of the dissipative instability in planar capacitive rf- discharges. The first is the homogeneity of plasma, and the second reason is concerned with the small number of observed layers of macroparticles and, accordingly with the small shift parameter γ_0 [3]. This explains the absence of experimental observations of vortex motion in the usual circumstances. Nevertheless, the formation of bulk dust clouds, for example, in microgravity, or the introduction of an extra electrode, leads to the convection of dust particles [4,5]. Below, we analyse the conditions for generation of dust vortex motion which was observed in an rf-discharge plasma with the different auxiliary electrodes.

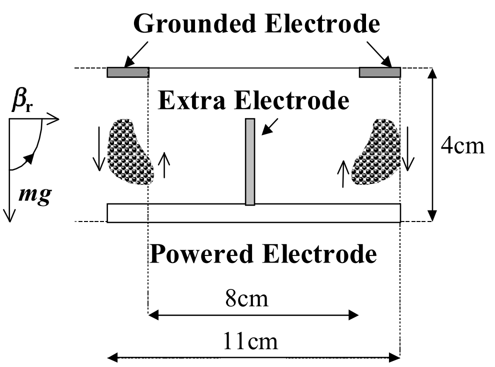

Figure.1 Experimental set up for vertical vortex producing

Experiments were carried out in argon (*Ar*) at the pressures in the range *P*=0.06-0.2 Torr, with the melamine formaldehyde particles ($a \cong 2.8$ μm (ρ = 1.5 g/cm^3). The presence of extra electrodes in the centre of the system allows displacement of the dust particles to the extreme region of system, where the gradient β_r of dust charges is greater. This increase in β_r is connected with the fast growth of the radial potential $\phi(r)$ of the electric field $E(r)$ near the edge of the powered electrode. It should be noted that the decrease of electron temperature near the edge of electrode could also play an important role in decreasing the dust charges in this case.

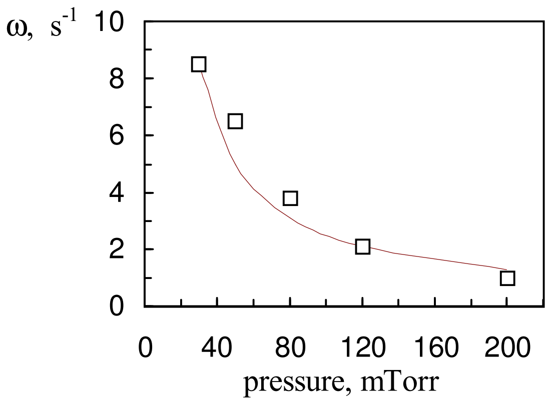

Figure 2. The dependency of rotation frequency ω on the pressure. The points are the experimental values, solid line corresponds to $\omega = g/4P$[mTorr].

A simplified schematic diagram of the experiment on the formation of bulk dust cloud in the presence of an extra electrode is shown in Fig. 1. The direction of dust rotation is in accordance with the theoretical forecast ($\Omega < 0$). Dependency of the rotation frequency ω on pressure is presented in Fig. 2. For our experimental conditions the friction frequency can be written, using a free-molecular approach, as $\nu_{fr}[s^{-1}] \cong 200P$ [Torr]. Assuming $F_{non} = m_p g$ and $\omega = \Omega/2 \approx g\beta_r/\{2\langle Z\rangle\nu_{fr}\}$, we obtain the value $\beta_r/\langle Z\rangle \approx 0.1$ cm^{-1}.

The presence of additional electrodes in the rf-plasma can not only destroy the homogeneous conditions in the plasma, but can also lead to additional forces F_{non}, which in conjunction with the electric forces leads to rotation of the macroparticles. A simplified schematic diagram of the experiment on the formation of horizontal vortex in the presence of an extra electrode is shown in Fig. 3. The typical images of induced dust rotation in the horizontal plane for the few layers of macroparticles in a rf-plasma source with a heated pin electrode are presented in Figs. 3. To achieve heating by electron current a positive potential U_1 (with respect to the surrounding plasma) was applied to the pin electrode.

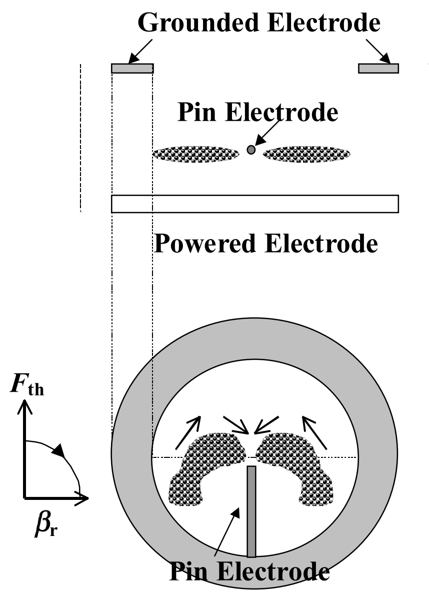

Figure 3. Simplified schematic diagram of the apparatus used for the formation of horizontal dust vortex

Dependencies of rotation frequency ω on the pressure P for U_1=40B, and on the potential U_1 of the extra electrode for P=0.2Torr are presented in Figs. 5.

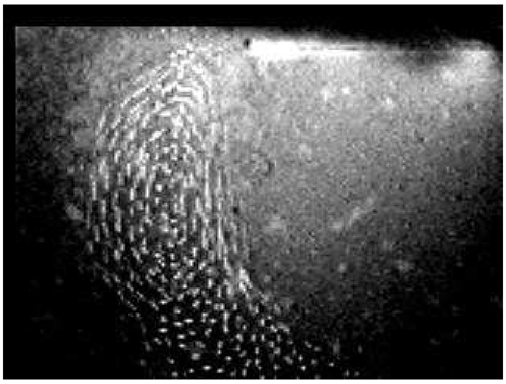

Figure 4. Typical video image of dust vortex

The direction of dust rotation is in accordance with the direction of the thermophoretic force and the decrease of dust charges from the pin electrode ($\Omega < 0$). There are two basic reasons that can lead to an increase in dust charges towards a positive pin electrode. The first is the reduction of ratio n_i/n_e, and the second is connected with the growth of electron temperature in the region of high electric field. A lower limit estimate of angular velocity ω_{min} of dust rotation can be obtained from $\omega_{min}[s^{-1}] = \Omega_{min}/2 \approx \beta_r F_{th}/\{2m_p<Z>\nu_{fr}\} \approx 50\beta_r[cm^{-1}]\frac{\partial T}{\partial y}[Kcm^{-1}]/\{<Z>\nu_{fr}[s^{-1}]\}$. In turn a lower limit estimate of gas temperature gradient can be obtained from a calculation of $\frac{\partial T}{\partial y}$ for a heated sphere with radius R equal to the radius of the extra electrode (~ 50µm): $\frac{\partial T}{\partial y} = \frac{R\Delta T}{\Lambda^2} \sim 0.1\Delta T$, where $\Lambda \sim 0.5$ cm is the characteristic distance from the extra electrode to the edge of dust cloud, and ΔT is the difference between the electrode and gas temperatures, respectively T_1 and T_o. The value of T_1 can be estimated by equating the input power density $P_1/\pi hR^2$ to the heat looses $\chi_1\Delta T/2\pi Rh$ through the electrode, where h is the length of electrode, and $\chi_1 = 0.8$ W/cmK is the thermal conductivity of steel. Thus for P_1=1.1 W (U_1=40V), we have $\Delta T \approx 100$K, and $\beta_r/<Z> \approx 0.6cm^{-1}$.

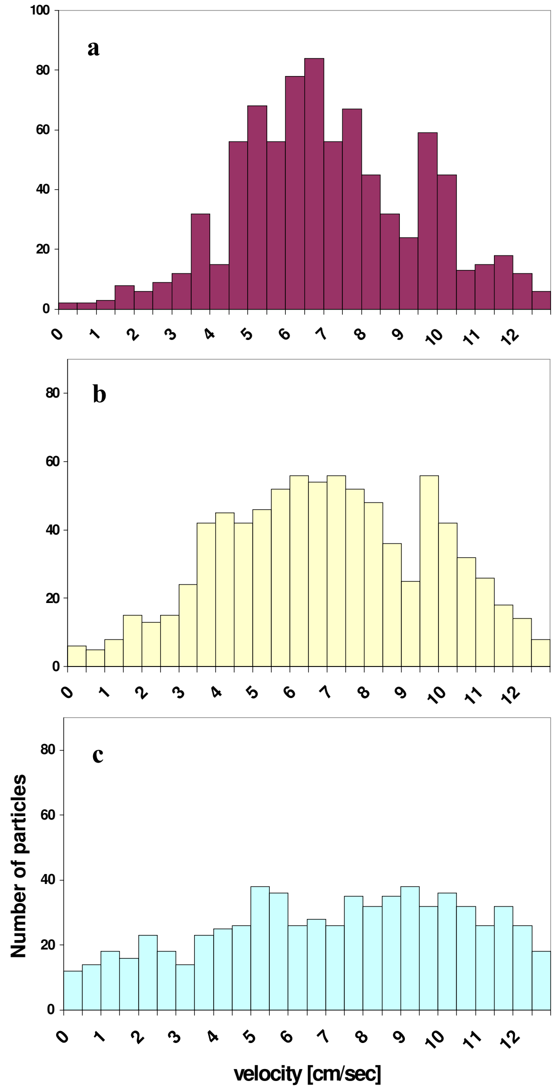

Figure 5. Velocity distribution function for different input power. a- 100W b- 70W c-

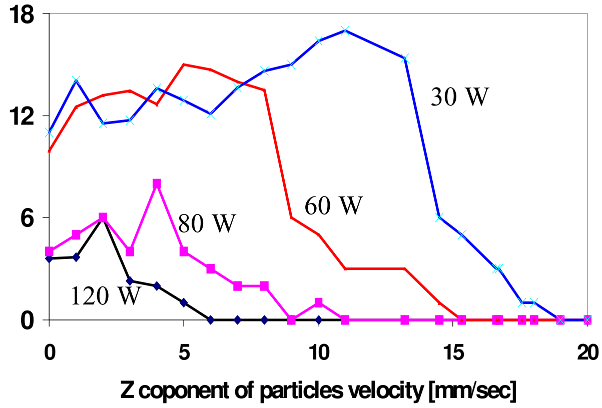

Figure 6. The effect of power on z – component of the velocity of particles

In addition to the angular velocities of the vortices the distribution of linear velocities in the vortices was obtained. The velocity distribution was measured for different input rf powers. The distribution is computed by binning particles in steps of 0.5 cm/s from 0 to 14 cm/s. A comparison of the velocity distribution for three different input rf powers is shown on Fig. 5. It observed that at the lowest power the velocity distribution is fairly broad. As input rf power is increased the velocity distribution becomes peaked around 6 m/s. The broadening of the velocity distribution function with decrease in input power was attributed to the expansion of vortex in vertical direction and occurrence of vertical (z) component of particles velocity (see Fig.6)

The results of experimental observation of two types of self-excited dust vortex motions (vertical and horizontal) in a planar rf-discharge are presented. The first is vertical rotation of macroparticles in bulk dust clouds. The second is formed in the horizontal plane for a monolayer structure of particles. We attribute the occurrence of these vortices with the development of dissipative instability in a dust cloud with a dust charge gradient, which has been produced by an extra electrode. The presence of an additional electrode also produces an additional force which in conjunction with the electric forces leads to rotation of dust structure in the horizontal plane.

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References

1. Vaulina, O.S., Nefedov, A.P., Petrov, O.F. and Fortov, V.E., *JETP* **91,** 1063 (2000).
2. Vaulina, O.S., Samarian, A.A., Nefedov, A.P., and Fortov, V.E., *Phys. Lett.* A. **289**, 240 (2001)
3. Vaulina, O.S., Samarian, A.A., Petrov, O.F, James, B.W., and Fortov, V.E., (*Phys. Rev. E.*, to be published)
4. G. Morfill, H. Thomas, U. Konopka, *et al.*, *Phys. Rev. Lett.* **83**, 1598 (1999)
5. D.A. Low, W.H. Steel, B.M. Annaratone and J.E. Allen, *Phys. Rev. Lett.* **80**, 4189 (1998)