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Large-scale vortices in dc glow discharge dusty plasmas

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Abstract

Formation of large-scale dust vortices in the striation of dc glow discharges was experimentally investigated. Dust clouds were formed by monodisperse MF particles with diameters ≈2 μm in the regions of stable striation. Vortices obtained were about 1 cm in size and contained $\sim 10^4$ particles. Structural (vortex configuration, dust particle flow filaments) and dynamic (rotation frequencies and velocity spectrum) characteristics of large-scale dust vortices were measured.

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1. Introduction

At present, the occurrence and development of various types of instabilities are of great interest to researchers in the field of dusty plasma physics. Dynamic phenomena in dusty structures (waves, regular or stochastic oscillations) are steady-state distributions of densities of macroparticles moving with nonzero directed velocity, as opposed to the mean velocity of particle thermal motion in quasi-stationary dust structures (similar to a liquid or solid). Occurrence of stable dynamical dust structures in a viscous medium, such as a weakly ionized laboratory plasma, can be possible due only to potential sources compensating dissipative energy losses. Rotation of dusty particles along the axis of a cylindrical system (dusty vortices) was first observed in numerical simulations [1]. In the experiments, dust vortices have been observed in various types of laboratory plasmas: dc glow discharges [2], RF discharges [3] and in nuclear-excited plasmas [4]. It should also be mentioned that vortex motions were observed in a dusty plasma under microgravity conditions [5, 6]. In [7], the analytical model that summarized the analysis of conditions for excitation of instabilities in a dusty plasma with gradient of particle charges in a nonelectrostatic field was proposed. The purpose of this work is a detailed experimental investigation of structural and dynamic properties of dusty vortices

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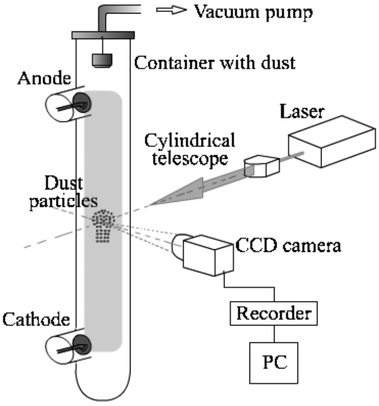

Figure 1. Scheme of the experimental setup.

in the striation of dc glow discharges. The approach of [7] was used for analysis of vortex formation.

2. Experimental results and discussion

The experiments were carried out in a cylindrical symmetric dc glow discharge generated in a vertically oriented glass tube with an inner diameter of 5.5 cm and an interelectrode distance of 90 cm (figure 1).

The discharge was generated in Ne at pressures $p = 0.1$–10 Torr and currents $I = 0.1$–10 mA. Particles were stored in a container with a grid at the bottom and positioned above the anode. When the container was shaken the particles fell downwards through the grid. We used monodisperse melamine formaldehyde (MF) particles with a diameter of 2.02 μm and a density of 1.51 g cm^{-3}. With the aid of a tube of such diameter we can obtain large dusty clouds of about 1 cm in size within the striation region. In order to visualize vortices we illuminated the particles with a diode laser beam of $\lambda = 532$ nm. For recording of scattered light from the particles a CCD video camera was used at a frame rate of 25 fps.

The number of trapped particles (i.e. the size of the dust vortex) was varied according to discharge parameters. The maximal size of the vortex was obtained at $p = 4.6$ Torr and $I = 0.4$ mA. In order to detail the dust motion observation we studied vortices just at these discharge parameters. Figure 2 shows the central vertical cross section of a large-scale dust vortex. The cross section was visualized by a thin laser sheet created by means of a cylindrical telescope. In order to obtain the configuration and dynamical parameters of the dust vortex we used a computer code that allows us to identify dust particles and their trajectories on the recorded video. Figure 3 shows the results of the particle tracks recognized during the time $t = 0.5$ s. Because of cylindrical symmetry of the striation electric field one can propose that the dust vortex is a toroid which is coaxial with the discharge.

In addition, we measured periods of dust particle rotation (figure 4) and particle velocity distribution in dependence on the distance from the centre of vortex motion (figure 5). As one can see, the dust vortex is slightly asymmetric. We can propose that this was due to asymmetry of external conditions such as influence of the laser and tube wall heating effects.

Figure 6 represents the plot of the dependences of particle velocities on the distance from the rotation centre. The dependences were measured along the largest and smallest axes of the vortex left cross section shown in the previous figures.

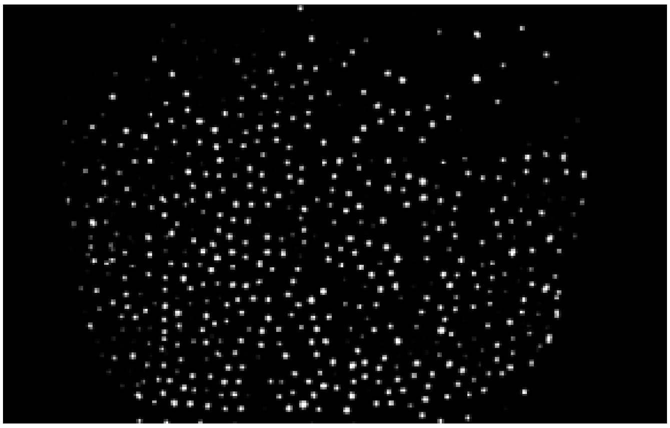

Figure 2. Video image of large-scale dust vortex in striation of dc glow discharge at $p = 4.6$ Torr and $I = 0.4$ mA. Size of the image is 6.7 × 9.3 mm.

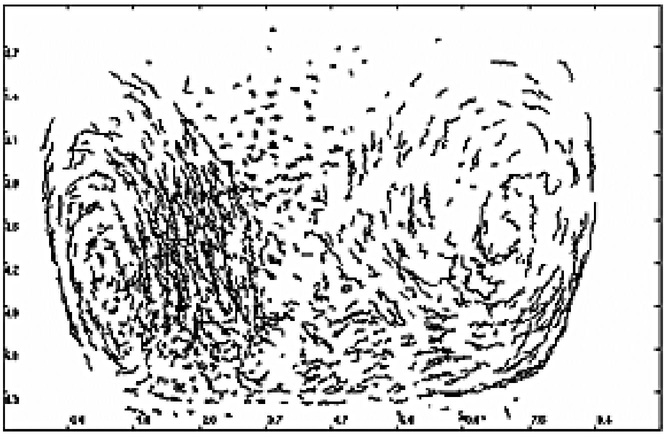

Figure 3. Tracks of the particles in a dust vortex ($t = 0.5$ s).

In accordance with [7], formation of dust instabilities can occur only in the presence of the dust charge spatial gradient $\boldsymbol{\beta}$ which is orthogonal to nonelectrostatic force ($\boldsymbol{F}_g$). Moreover, conditions of dissipative instability (vortex) development do not depend on forces of friction but are defined by topological parameters of the dust–plasma system, such as the dust particle charge Z_p and its gradients β_y, β_r as well as by dust and plasma densities. Let us estimate the value of dust particle kinetic energy $K_{(i)}$, when the dissipative instability developed in the field of gravity for the case of charge linear function $Z(r) \sim Z_0 + \beta_\mathrm{r} r$. Therefore, the value of ω^2 (ω—frequency of instability) can be taken as $\omega_\Omega{}^2 \equiv \Omega^2/4 = (g\beta_\mathrm{r})^2/(2Z_0\nu_\mathrm{fr})^2$, and the kinetic energy $K_{(i)}$ can be written as follows:

$$K_{(i)} = m_\mathrm{p} g^2 \chi^2 \big/ \big(8\nu_\mathrm{fr}^2\big), \tag{1}$$

where Ω is the module of the rotor of dust particle velocity. Parameter $\chi = A\beta_\mathrm{r}/Z_0$ (A—dust rotation amplitude) defines relative variations of the charge $Z(r)$ within the bounds of the dust particle motion trajectory. We can make an estimation $\nu_\mathrm{fr} = 20$ c^{-1}, which approximately corresponds to pressure $p = 0.46$ Torr in neon at room temperature according to the

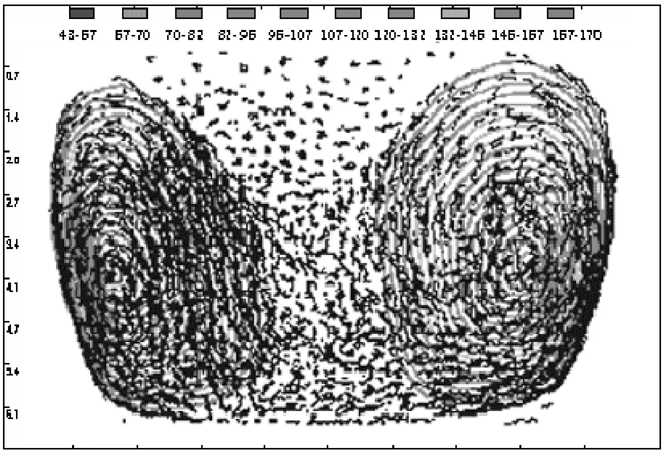

Figure 4. Flow filaments of particles in the dust vortex. Colours specify period of particle rotation (10^{-1} s).

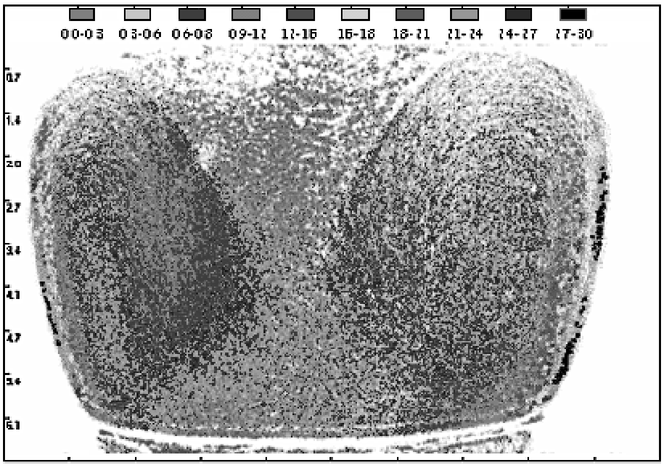

Figure 5. Diagram of particle velocity distribution (mm s^{-1}) in the dust vortex.

free-molecule approach. Estimation of β_r can be made from the results of measuring the dust particle velocity $V \approx A\Omega/2$ and amplitude A. Therefore, we can find

$$\beta_r/Z_p = 2V\nu_{fr}/Ag \approx 0.054\,\mathrm{cm}^{-1}. \tag{2}$$

The value of the screening length λ can be estimated from

$$E(r) \approx -\frac{T_e}{en_e}\frac{\partial n_e}{\partial r} \approx \frac{T_e}{e\Lambda}, \tag{3}$$

where Λ is the characteristic diffusion length, which is defined by boundary conditions with accuracy up to a factor close to 2 [8]. For a cylinder with radius $R : \Lambda \sim R/2.4$, $E \cong 2.4T_e/(eR)$. Assuming $2\pi eZ_p \exp(-\kappa)\big/l_p^2 \approx E$, we can exclude unknown T_e ($Z_p \sim T_e$) and estimate screening parameter $\kappa = l_p/\lambda$. For the cloud observed $\kappa = 0.56$ ($l_p \sim 300\ \mu$m) was obtained and, therefore, $\lambda \approx 535\ \mu$m.

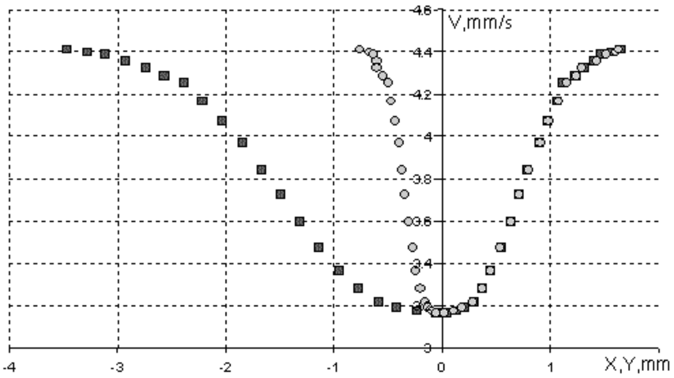

Figure 6. Particle velocity distribution along the largest (squares) and the smallest (diamonds) axes (X, Y) of the vortex cross section (left rotation on figures). Point '0' is the centre of the rotation.

3. Conclusions

Large-scale dust vortices which are ≅1 cm in size and contain $\sim 10^4$ particles in the stable striation of dc glow discharge were experimentally obtained. Vortex configuration and dust particle velocity distribution were measured.

The formation of the dust vortices in the gas-discharge plasma was analysed using the analytical model [7]. The gradient of particle charges in the dust vortex as well as plasma screening length was estimated. It was shown that in the presence of gravity a small charge gradient (∼1%) is an effective source of kinetic energy for the dusty vortex motion formation.

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