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Vortices in dust clouds under microgravity: A simple explanation

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Clouds of dust particles in radio frequency discharges often show a periodic vortexlike motion, especially near the edges of the electrodes or near the tip of an electrostatic probe. These vortices often last as long as the discharge is powered. In a previous paper we have followed a small number of individual dust particles in a discharge under microgravity conditions, moving under the influence of forces computed by means of a self-consistent two-dimensional hydrodynamic model, and interacting via a screened Coulomb potential. The resulting motion showed the vortexlike rotation. In this paper we discuss this phenomenon in more detail, using a simplified model with harmonic forces, but extending the simulations to three dimensions. Stable vortices are observed, which show a more chaotic behavior than in the two-dimensional situation. Particles frequently jump up and down between two counterrotating vortices. The generation of the vortices can be ascribed to a nonzero rotation of the net global force vector field, which is the sum of the ion drag force, the electric force, and the thermophoretic force in case of the experiments. Comparison of experimental data with simulations using a model potential may open a way to unravel the forces inside a cloud of dust particles.

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INTRODUCTION

Plasma crystal experiments performed under microgravity conditions often show a coherent rotation of parts of the cloud of dust particles immersed in the discharge, while other parts stand still and eventually form a crystalline region. The driving mechanism behind this coherent rotation cannot easily be unraveled because the forces acting on the dust particles are modified due to the presence of the dust and because the charge on the dust particles may vary in the course of their trajectory. Previously [1], we have reported on a simulation of the motion of individual particles in a dust cloud, using the net global force resulting from the ion drag, and the electric and thermophoretic forces exerted by the discharge, while adding the short range particle-particle interaction by means of a screened Coulomb potential as well as friction with the background gas. This simulation, however, was done in a two-dimensional (2D) (r,z) geometry, not allowing the particles to move in the ϕ direction and also the number of particles was limited. In this paper we present similar simulations, but for a prescribed harmonic net axial and radial force, in three dimensions and with more particles. This approach is similar to those used to study ionic crystals [2,3].

FORCES ACTING ON A PARTICLE

Figures 1(a) and 1(b) show the net force in the axial (a) and the radial (b) direction acting on a dust particle according to one of the simulations with our (2D) cylindrically symmetric hydrodynamic model for the Plasmakristall experiment reactor under microgravity conditions [4,5] for the region in r and z where the vortices appear. The force is the sum of the ion drag force (from the ions leaving the discharge), the electric force (from the net space charge distribution and the applied voltage), and the thermophoretic force (from the temperature gradient of the gas). The influence of the presence of the dust on the discharge is fully accounted for. Drawn in Figs. 1(a) and 1(b) are lines of constant force. Due to symmetry the axial force vanishes in the midplane of the reactor $(z=2.7\text{ cm})$ and, going up or down, the force tends to push the particles back to this plane in the outer regions and away from this plane in the central part of the discharge. The radial force changes direction from outward in the central part to inward in the outer part of the region considered. This behavior of the forces is responsible for the generation of a dust-free central void [5]. An important feature is that the lines of constant force are not straight, yielding a nonzero rotation of the net force vector field and thus the possibility that a particle gains energy in a periodic motion.

The complexity of this force and the fact that it is only known at a limited number of computational grid points prohibits the study of a dust particle cloud with a large number of particles in three dimensions. Therefore, we have turned to an analytical expression for the force that is easy to calculate at any particle position, while keeping the main features of the force shown in Figs. 1(a) and 1(b). The force we have chosen is a harmonic force, $\vec{F}$, in both directions, but with the possibility that the axial position where the radial force vanishes becomes a function of the axial coordinate z,

$$\vec{F}_z=-\alpha_z m_p z\hat{e}_z,\quad \vec{F}_r=-\alpha_r m_p[r-r_0(z)]\hat{e}_r,$$

$$r_0(z)=r_{00}+\beta z^2,\quad \vec{F}_\phi=\vec{0}, \tag{1}$$

with m_p the mass of the particle. Thus, we can introduce a curvature of the lines with constant radial force by taking β different from 0 and vary the force strength by means of the Hook constants α_z and α_r. r_{00} defines the point where the radial force vanishes in the plane of symmetry $(z=0)$.

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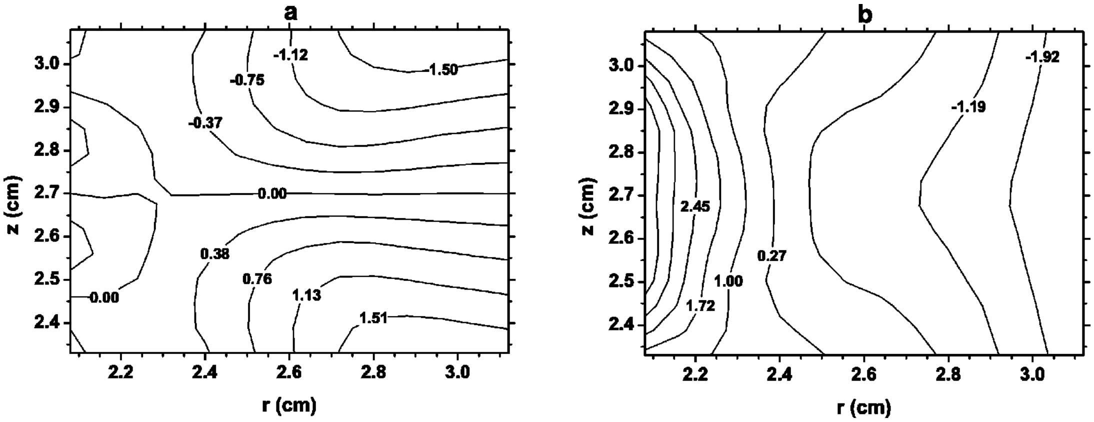

FIG. 1. The global net axial (a) and radial (b) force (in 10^{-12} N) acting on a dust particle. Result from a 2D hydrodynamic simulation for the region of the discharge where vortices appear.

The particle-particle interaction is modeled according to the screened Coulomb potential, assuming a prescribed fixed charge Q_p, screening distance λ_{sc}, and a particle radius r_p that is much smaller than the screening length:

$$\vec{F}_{ij}=\frac{Q_p^2}{4\pi\epsilon_0\|\vec{r}_i-\vec{r}_j\|^3}\left(1+\frac{\|\vec{r}_i-\vec{r}_j\|}{\lambda_{sc}}\right)\times\exp\left(-\frac{\|\vec{r}_i-\vec{r}_j\|}{\lambda_{sc}}\right)(\vec{r}_i-\vec{r}_j). \tag{2}$$

This screened Coulomb interaction is usually observed in particle clouds in a discharge [6,7]. The results of the simulations, however, will not change when an unscreened interaction is used. Friction with the background gas is accounted for by the standard expression

$$\vec{F}_f=-\alpha_f m_p\vec{v}_p, \tag{3}$$

where in reality the friction coefficient α_f will depend on the density of the background gas [8].

All these straightforwardly lead to the equation of motion for particle i,

$$m_p\frac{d\vec{v}_i}{dt}=\vec{F}(\vec{r}_i)+\sum_{j\neq i}\vec{F}_{ij}+\vec{F}_f(\vec{v}_i). \tag{4}$$

This equation is integrated in time with a leap-frog scheme, with a sufficiently small time step to avoid spurious heating. All particle-particle interactions are taken into account.

RESULTS

Figures 2(a) and 2(b) show the result of a simulation with 1800 (a) and 3600 (b) silicon ($\rho=2200\ \mathrm{kg\,m^{-3}}$) particles of radius 7.5 μm ($m_p=3.9\times10^{-12}$ kg) with a charge of 30 000 electrons, using a screening length of 2 mm in a rotation-free force with $\alpha_z=\alpha_r=160$, $\alpha_f=1$, $\beta=0$, and $r_{00}=0.02$. The charge and screening length are larger than expected in reality, (typical values 15 000 and 0.5 mm) to reduce the number of particles needed in the simulation. The projection of the positions of the particles on the r-z plane is plotted. The position of the center is dictated by the value of r_{00}, being slightly different from the situation depicted in Figs. 1(a) and 1(b).

As expected, the friction causes the particles to go to an equilibrium position determined by the balance of all forces, including the particle-particle interaction forces. When the

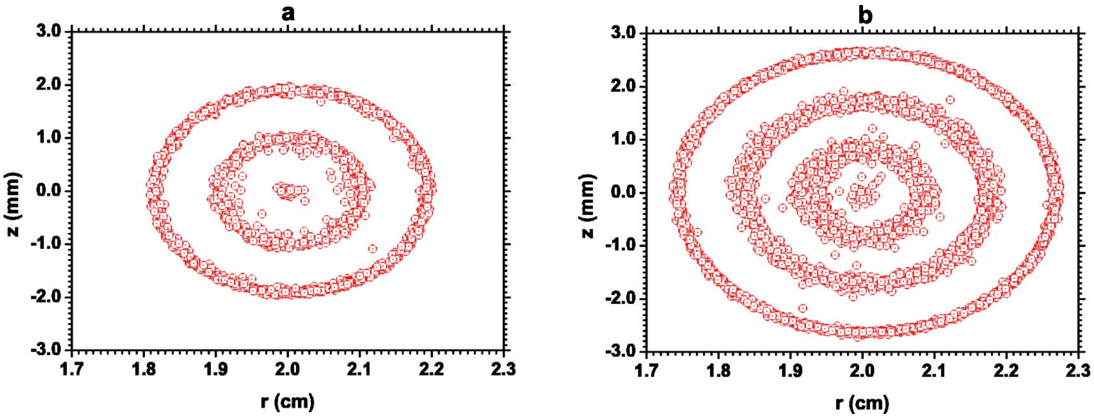

FIG. 2. Projection of the position of 1800 (a) and 3600 (b) particles on the r-z plane for a harmonic force with $\vec{\nabla}\times\vec{F}=\vec{0}$. The force was chosen such that all components vanish at a radial coordinate $r=2$ cm.

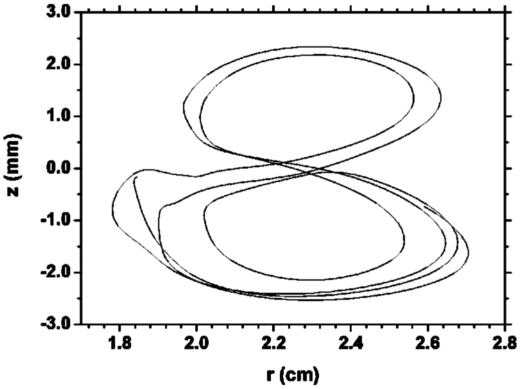

FIG. 3. Projection of the position of one of the particles on the r-z plane for a model force according to Eq. (1), with $\beta = 10^3$ and $r_{00} = 2$ cm. This force has $\vec{\nabla} \times \vec{F} \neq \vec{0}$, which leads to a chaotic periodic motion of the particle.

amount of particles is low, they find enough space in the ϕ coordinate and first form a circle. When this is no longer possible due to the particle-particle interaction the particles fill concentric tori. A similar simulation for a harmonic potential centered at the origin would give concentric spheres [2]. In fact, the results presented here resemble those of a particle cloud confined in a cylindrical potential [3] with periodic boundary conditions. There is a slight difference, however, because in our case the distribution is not symmetric around r_{00} because at smaller r values the particles have less volume available than at larger r values.

When the curvature of the lines with constant radial force is introduced, by giving β a value of 10^3, the particles can pick up enough power during one round trip to compensate the losses due to friction (we took $\alpha_f = 10$ in this case) and keep rotating, because $\vec{\nabla} \times \vec{F} \neq \vec{0}$. This resembles the actual situation depicted in Fig. 1(b). We have followed 3600 particles in time, starting with the static distribution of the rotation-free case. An example of the motion of a particle is shown in Figs. 3, 4(a), and 4(b). All particles rotate clockwise in the upper half of the reactor and counterclockwise in the lower half, in agreement with the sign of $\vec{\nabla} \times \vec{F}$. The motion is chaotic due to short range interactions with other particles, which also cause the jumping up and down.

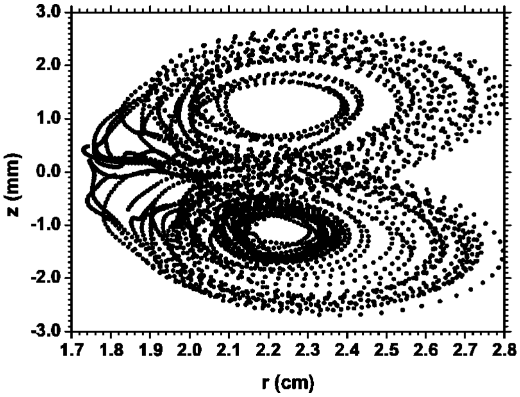

FIG. 5. Projection of the position of 20 particles on the r-z plane for the model force with $\vec{\nabla} \times \vec{F} \neq \vec{0}$, showing the two emerging vortices.

Figure 5 shows the trajectories of 20 particles during the last 2 sec of the simulation. The vortex structure is clearly visible. Note that the up-down asymmetry is only due to the selection of the particles for which the data are plotted.

These results are similar to what we found in our previous 2D simulations. The axial and radial components of the force exerted by the discharge on the dust particles are shaped by the charge distribution and the potential distribution (electric force), the positive ion flux (ion drag), and the profile of the gas temperature (thermophoretic force) in such a way that $\vec{\nabla} \times \vec{F} \neq \vec{0}$. Due to this no equilibrium exists in which the total force, including the interparticle forces, vanishes for all particles. The particles can keep rotating in a vortexlike configuration where the energy loss due to friction with the background gas is compensated by energy gain from the force exerted by the discharge. Since curvature is important in generating a force vector field with rotation, it is plausible that the generation of vortices is favorably triggered by the presence of sharp edges, such as probe tips [9].

Measuring the particle trajectories and comparing them with those obtained from model forces opens a possibility to unravel the forces inside a dust cloud. This is not restricted to microgravity conditions, but would also apply to experiments where gravity plays a dominant role.

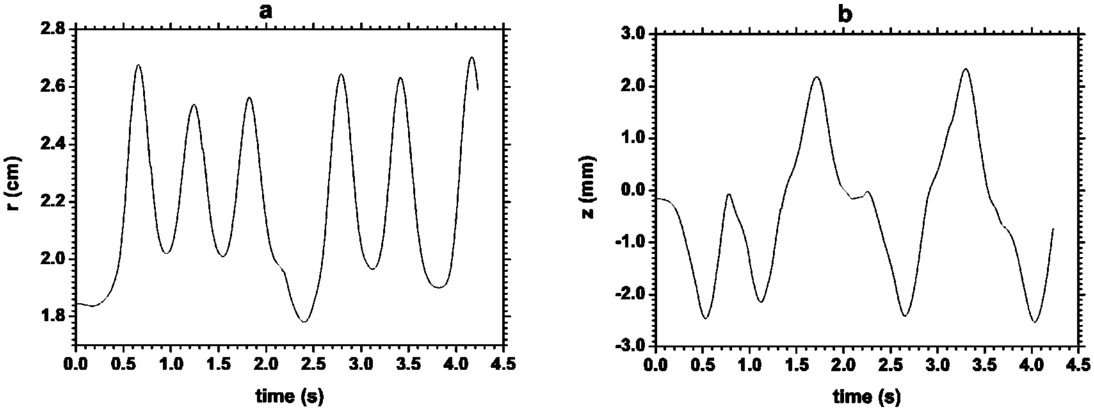

FIG. 4. Variation in time of the r (a) and z (b) position of the particle in Fig. 3.

CONCLUSIONS

The behavior of particles in a dusty discharge under microgravity conditions can be analyzed by a molecular dynamics simulation of electrostatically interacting particles in a radially and axially harmonic force. Making the force vector field not rotation free results in the generation of vortex-like structures, similar to those observed in experiments. The simulations show that the cloud of particles becomes a dissipative nonlinear system, driven by the applied (harmonic) force and showing chaotic behavior due to the short range particle-particle interaction. Comparing actual trajectories with those obtained from a simulation for a model force (not necessarily harmonic) opens a way to analyze the forces acting on particles in a dust cloud.

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