

Charged particles confinement condition in a microparticle electrodynamic ion trap

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Abstract. Conditions of the charged particles confinement in a vertically oriented microparticle electrodynamic ion trap have been determined experimentally. The experiment included two stages. At the first stage, charge-to-mass ratio of the trapped particle was measured by its position in a non-uniform electric field while at the second stage the ac voltage frequency was varied until the particle fell out of the trap. This frequency was taken as the boundary of particle confinement.

1. Introduction

The first demonstration of the charged particles confinement in microparticle electrodynamic ion traps (MEITs) was made in 1955 [1]. In paper [2], a single particle was confined in vacuum for three months. The possibility of levitating particles confinement turned up to be very useful for measurements of detailed properties of individual charged particles. In addition to individual particles, MEIT can also trap a large number of charged particles self-organized into Coulomb crystalline structures [3]. In paper [4], the motion of particles affected by the trap time-varying electric fields have been simulated numerically and particle confinement parameters, such as the dynamic viscosity of the gas medium, the charge-to-mass ratio of particles, frequency and amplitude of ac voltage applied to the trap electrodes, have been determined.

This paper presents the results of experimental studies to determine the conditions of the charged particles confinement in a vertically oriented MEIT.

2. Experimental setup

The experimental setup includes a corona discharger and a linear electrodynamic quadrupole trap. The sketch of the trap is shown in figure 1. Trap electrodes were made of 4 mm steel rods and were placed on a circle with a diameter of 50 mm. The electrodes were mounted on polycaprolactam flanges. The trap was placed in a metal box to shield external electric fields. Four rectangular windows were made on the side walls of the box. Three of them were covered with glass plates. The corona discharger was connected to the fourth window. The trap was oriented vertically. The ac voltage with amplitude U_A was applied to the trap electrodes with a phase shift of π between adjacent electrodes, $U = U_A \sin(\omega t)$. A cylindrical electrode with a 10 mm ball was mounted on the bottom flange. The dc voltage was applied to this electrode to prevent falling down of the particles. The sign of the electric potential applied to the ball



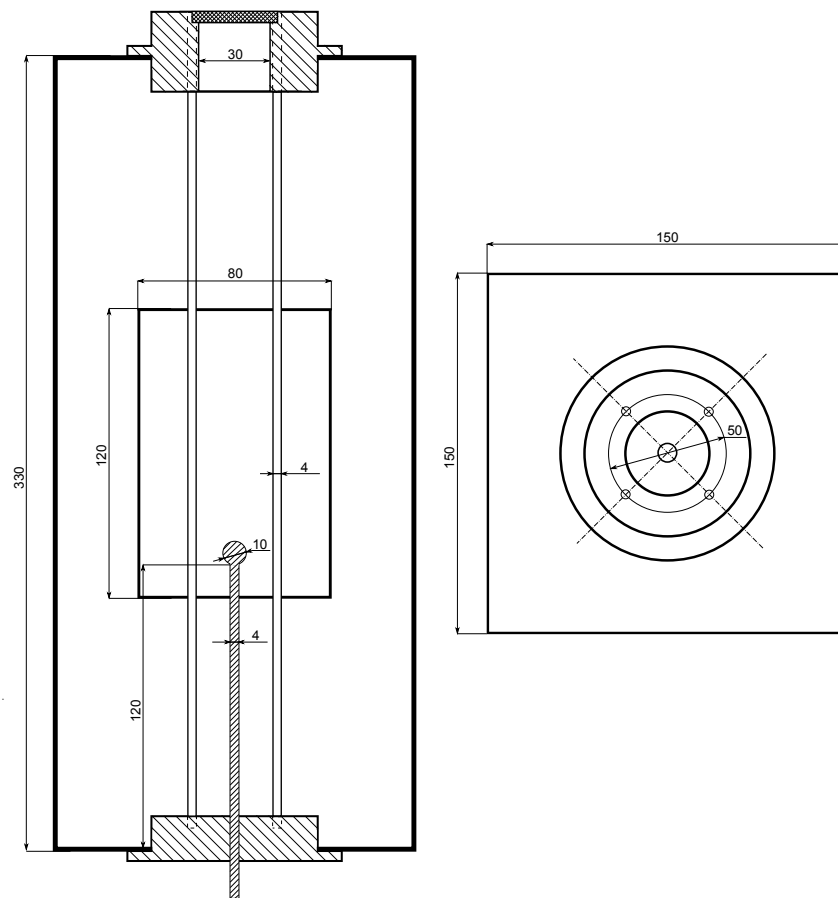


Figure 1. Sketch of the electrodynamic trap.

was the same as the sign of the particle charge. The charged particle levitated at some distance from the ball.

In this work the corona discharge was used for particle charging. The corona and the grounded electrodes in a charging device formed two flat lattices. The corona electrode was made of tungsten wire with a diameter of $70\ \mu\text{m}$. The electrode spacing was equal to 10 mm. The grounded electrode was made of metal rods with a diameter of 3 mm. The electrode spacing was equal to 13 mm. The multiple electrode system minimizes the spatial inhomogeneity of the electric field in the area of the particles charging. The electrodes were mounted in a square cross section channel with a distance between the walls equal to 6 cm. The dc voltage of positive polarity was applied to the corona electrodes. The voltage value was close to the breakdown to obtain rather a high charge on particles. In most experiments, the voltage was about 15 kV.

The charging device was connected to the trap box by a channel. The particles were injected into the channel before the electrodes and flew through the corona discharge region. The airflow was produced by the flux of ions in the corona discharge.

In our experiments, we used polydisperse Al_2O_3 powder. Figure 2 shows the particle-size distribution of the powder.

The particles were illuminated by a laser with a wavelength of 532 nm and a maximum power of 150 mW. Particle imaging was done by a CCD camera HiSpec 1 with a maximum resolution of 1280×1024 pixels. The camera allows us to record video frames with a maximum resolution up to 506 frames/s.

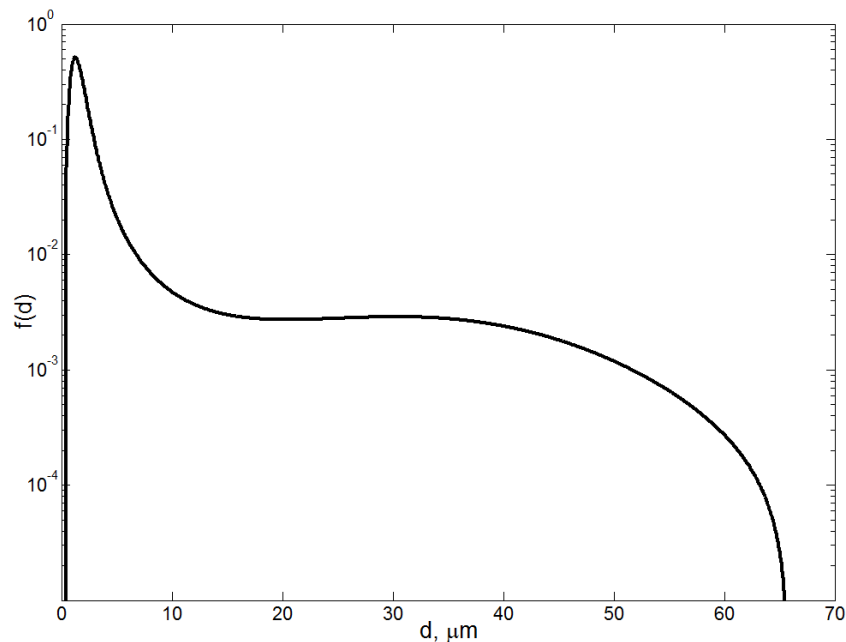


Figure 2. The particle-size distribution Al_2O_3 powder.

3. Experimental results

The confinement conditions were determined in the following way. Charged particles were injected into the trap operating at frequency of 50 Hz and amplitude of the ac voltage of 4.5 kV. Then, all particles but one were removed from the trap using an electrified glass rod. The charge-to-mass ratio of the remaining particle satisfied the formula

$$\frac{q}{m} = \frac{\mathbf{g}}{\mathbf{E}},$$

where q is the particle charge, m is the particle mass, $\mathbf{g}$ is acceleration of gravity and $\mathbf{E}$ is the electric field intensity. The electric field intensity was calculated numerically. Detailed description of the method for measuring the charge and the mass of a single dust particle is given in [5]. The relative error of the charge-to-mass ratio measurements was between 10% and 15%. After determining the charge-to-mass ratio, the ac voltage frequency was increased or decreased until the particle fell out of the trap.

Figure 3 shows the experimentally obtained confinement conditions of particles in the vertically oriented MEIT. The experimental results are well approximated by straight lines, starting at the origin of coordinates.

The dynamics of a particle trapped in the MEIT is characterized by a stochastic Langevin differential equation [3]

$$m \frac{d^2 \mathbf{r}}{dt^2} = \mathbf{F}_{\text{trap}} + \mathbf{F}_{\text{fr}} + \mathbf{F}_b + \mathbf{F}_g,$$

where we account for the main forces acting on the particle in our experiment. Here $\mathbf{F}_{\text{trap}}$ is the electric force of the trap, $\mathbf{F}_{\text{fr}}$ is the friction force. The $\mathbf{F}_b$ term stands for the stochastic delta-correlated force accounting for stochastic collisions with molecules of gas, while $\mathbf{F}_g$ is the gravitational force. In principle, in order to explain the experimental results and the existence of particle confinement it is necessary to solve numerically this stochastic Langevin differential equation, which is quite a difficult task.

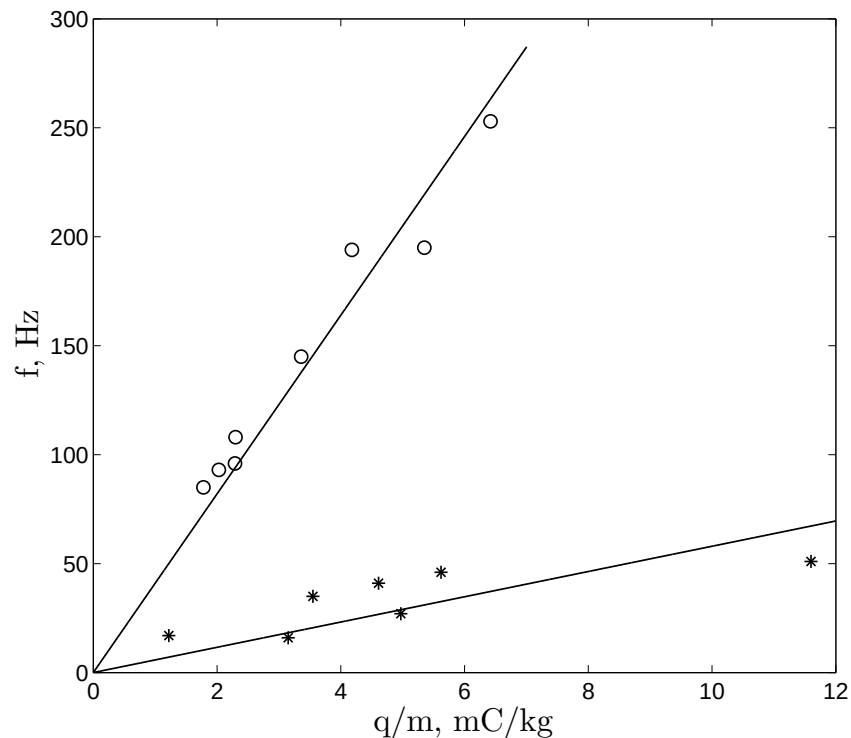


Figure 3. The conditions of the particle confinement in the vertically oriented MEIT. The experimental data are indicated by asterisks (bottom boundary) and circles (top boundary).

In this paper, however, we are going to give a qualitative explanation. If a charged particle moves in an alternating electric field $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r}) \sin(\omega t)$ the particle is affected by the Gaponov–Miller force [6, 7]

$$\mathbf{F}_{\text{gm}} = -\frac{q^2}{2m(\omega^2 + \nu^2)} \nabla \mathbf{E}^2(\mathbf{r}), \quad (1)$$

where $\omega = 2\pi f$ is the angular frequency. It should be noted that equation (1) is correct if the friction force acting on the particle depends linearly on the particle velocity ($\mathbf{F}_{\text{fr}} = -m\nu\mathbf{v}$). In our case, the friction force is defined by Stokes' law $\mathbf{F}_{\text{fr}} = 6\pi\mu a\mathbf{v}$; thus, $\nu = 6\pi\mu a/m$, where a is the particle radius. During the experiments trapped particles were located in the middle of the trap and the force was directed perpendicularly to the symmetry axis of the trap. It should be noted that the Gaponov–Miller force is the time-averaged electric force. From equation (1) it follows that the force decreases as frequency increases and from a certain value it can no longer trap particles. In the opposite case, with reducing frequency, the force increases and the particle starts to oscillate. The amplitude of these oscillations increases with further decrease in frequency. The frequencies, at which the particle falls out of the trap, determine the top and the bottom boundaries of particle confinement.

4. Conclusion

In this paper, we experimentally determined the conditions of particle confinement in a vertically oriented MEIT. The boundaries of particle confinement are well approximated by straight lines, starting from the origin of coordinates.

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