Nanoparticle confinement by the linear Paul trap

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Abstract. In this article, the possibility of nanoparticle confinement by electrodynamic Paul trap is shown. The areas of nanoparticle confinement as the dependencies of particle charge density on voltage frequency and geometry of the trap are found. The nanoparticle charge density for its confinement should be of order \(10^{13} - 10^{14}\) e/m\(^2\).

1. Introduction

Micro- and nano-particles are present in atmospheric aerosols [1, 2], astrophysical dusty plasmas [3] or plasma membranes in biological cells. Recent investigations have demonstrated a strong correlation between the presence of aerosols in the atmosphere, and their effect on climate parameters and the quality of life [2, 4, 5]. Particles with diameter less than 10 µm can enter the bronchi, while those whose diameter is lower than 2.5 µm are able to reach the pulmonary alveoli where they can harm human health. The presence of certain aerosols (especially anthropogenic ones, such as smoke, ashes or dust) is associated with high levels of the industrial pollution and is considered to be responsible for respiratory and cardiovascular diseases, as well as for the ever increasing incidence of human allergies in town areas. Hence, investigation of atmospheric aerosols, viruses, bacteria, and chemical agents responsible for environment pollution, requires measurements of physical properties of micron sized particles and nanoparticles. In the previous works [6–11] the confinement of micron sized particles by the alternating electric fields has been studied in the static gas media and in the gas flows. The goal of this work is theoretical study of charged nanoparticles confinement by the electrodynamic Paul trap [12] in air at normal conditions. The regions of the nanoparticle and trap parameters necessary for particle confinement are investigated at the normal conditions.

2. Mathematical simulation of charged nanoparticle dynamics in electrodynamic trap

The sketch of linear Paul trap is presented in figure 1 [12]. The trap consists of four cylindrical electrodes with radius \(R_1 = 3\) mm and length \(L_m = 10\) cm. The alternating voltages \(U_\omega \sin(\omega t)\) and \(U_\omega \sin(\omega t + \pi)\) were applied to electrodes of the trap on mutually perpendicular diagonals. In simulation we used 2 traps that differed in distance between the axes of the neighboring electrodes: \(L_b = 0.9\) cm and 1.6 cm. The gravity force was directed opposite to the direction of the z axis (figure 1). The magnitude of the alternating voltage was \(U_\omega = 2\) kV and the voltage frequency varied from 30 to 200 Hz.
To simulate the charged nanoparticle dynamics in the trap and to find the regions of nanoparticle confinement the Brownian dynamics has been used. The simulations took into account stochastic forces of random collisions with neutral particles, viscosity of the gas medium, regular forces of the trap electrodes and the gravitational force. Thus, the particle dynamics was described by the following Langevin equation [13]:

\[ m_p \frac{d^2 r}{dt^2} = F_t(r) - 6\pi \eta \frac{r_p}{C_x} \frac{dr}{dt} + F_b + F_g, \] (1)

where \( m_p \) and \( r_p \) are the particle mass and radius, \( \eta \) is the dynamic viscosity of gas medium (about 18.2 \( \mu \text{Pa s} \) [14]), \( C_x \) is the Cunningham factor [15], \( F_t(r) \) is the force of trap electrodes, \( F_b \) are stochastic delta-correlated forces accounting for stochastic collisions with neutral particles, \( F_g \) is the gravitational force. To solve the stochastic differential equation (1) we used the numerical method developed in [16].

To simulate nanoparticle dynamics in the air at the normal conditions the Cunningham correction factor \( C_x \) was taken into account as the dependency on particle size [15]. In figure 2 the dependence of \( \eta/C_x \) on the particle size is presented obtained from the data in [15].

To simulate the interaction of the electric field of the trap with the charged nanoparticle the model of point charges distributed along each electrode [17] was used.

Figure 3 presents the confinement regions for different linear Paul traps and different particle radii \( r_p \). To avoid the influence of the interparticle interaction the confinement regions were found for single particles. In figure 3, regions are bounded by the upper and lower values of charge density in assumption of spherical particles.

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**Figure 1.** The sketch of the linear Paul trap.

**Figure 2.** The dynamic viscosity with the relevant Cunningham correction factor \( \eta/C_x \).
Figure 3. The regions of a single particle confinement as the dependence of the frequency $f$ of alternating voltage on charge density for $L_b = 0.9$ cm (a) and 1.6 cm (b).

Figure 3 demonstrates that confinement regions become wider with the decreasing of particle radius. To confine nanoparticle its charge should be $(10–1000)e$ depending on particle radius. Nevertheless, the patterns of behavior of the regions of particle confinement are similar and depend on the charge density.

3. Conclusion

In this article the possibility of nanoparticle confinement by the electrodynamic Paul trap is shown. The areas of nanoparticle confinement as the dependencies of particle charge density on voltage frequency and geometry of the trap are found. The nanoparticle charge density for its confinement should be of order $(10^{13}–10^{14})e/m^2$.

Acknowledgments

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