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Confinement of microparticles in a quadrupole trap with rectangular voltage at atmospheric pressure

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The areas of confinement of charged microparticles with a diameter of 5–50 microns in a linear quadrupole trap with a pulsed alternating rectangular voltage in air at atmospheric pressure have been numerically calculated and experimentally confirmed. The influence of the voltage amplitude, its frequency, and the asymmetry of rectangular pulses on the position and width of the retention areas has been established. It is confirmed that the retention areas depend on the particle diameter. It has been found that in a trap with a sinusoidal voltage, it is possible to stabilize the trajectories of a particle or make them unstable by using additional rectangular pulses of an external alternating electric field by changing its frequency. The possibility of capturing and retaining microparticles in a quadrupole trap with a corona discharge on electrodes has been experimentally investigated.

Keywords: linear quadrupole trap, pulse-periodic voltage, charged microparticles, air, atmospheric pressure.

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Introduction

Linear electrodynamic traps with a sinusoidal confining voltage are used for various tasks: studying the properties of both individual particles and Coulomb structures, and determining the particle size and charge based on their trajectories in a quadrupole field, etc. [1–4]. Structurally, a linear quadrupole trap is close to mass spectrometers and mass filters. To improve the capabilities of the latter, the application of a rectangular (often called digital) waveform of the filtering voltage has recently been investigated [5–13]. Our studies have shown [14–16] that the rectangular voltage waveform has a number of advantages for confining micron-sized charged particles in quadrupole linear traps in air at atmospheric pressure. For rectangular voltage, theoretical studies of the stability regions of

filters [5–12] and ion traps [13] have been performed for vacuum conditions, where the particle dynamics depends only on the charge-to-mass ratio Q/m , i.e., the similarity law is true. Since the confinement of micron-sized charged particles in a trap in air at atmospheric pressure is significantly affected by gravity and viscous friction forces, the confinement region calculations made for a vacuum are inapplicable. Calculations considering gravity and viscous friction forces are required for each particle size. The aim of this paper is to calculate the confinement regions for particles of various sizes (5–50 μm) under asymmetric voltage pulses of different frequencies, to perform experimental studies, and to describe the effect of an external electric field and a corona discharge plasma on confinement.

Experimental Setup and Calculation Model

The experimental scheme is similar to that described in [14–16]. Linear cylindrical electrodes of the trap are 4 mm in diameter and 10 cm in length, and are fixed at the vertices of a square with a 2-cm side. A pulsed periodic alternating voltage of rectangular waveform with a frequency of 50 and 100 Hz and an adjustable amplitude V of up to 10 kV is applied to the linear electrodes. For asymmetric pulses, the ratio of the positive pulse duration to the pulse repetition period is defined as the positive pulse duty factor K_p . The effect of the corona discharge plasma was studied in a quadrupole trap with thin electrodes 110 mm in length and diameters of 63, 120, and 200 μm , spaced 1 cm apart. Dielectric polydisperse Al_2O_3 particles with sizes of 1–80 μm were used. Microparticles were charged inductively on a metal plate at a constant potential of 5–7 kV.

Since finding the confinement regions for such conditions through an analytical investigation of the equations is a complex task, a numerical method based on calculations of stable and unstable particle trajectories was used. The physical parameters of the model were chosen in accordance with the experiments. The calculation scheme is detailed in [15, 16] and consists of solving the Langevin equation considering the gravity and the friction force according to the Stokes' formula $F_f = -6\pi\mu r v$, where r is the particle radius, μ is the air viscosity, and v is the particle velocity. The initial position of the particle in the trap is 350 μm below the center of the trap potential well, and the initial particle velocity is zero. The calculation was performed for particles sized 5, 10, 20, and 50 μm in air at the atmospheric pressure for different waveforms of the voltage applied to the electrodes (sinusoidal and rectangular).

Findings and Discussion

Figure 1 shows the confinement regions (calculation) in “voltage amplitude – particle charge” coordinates for sinusoidal and rectangular (meander) voltages at a frequency of 50 Hz for particles sized 50 and 20 μm . The regions expand as the voltage decreases. The electric field forces of the trap at the lower

boundary are insufficient to compensate for gravity, and the particle falls out of the trap. At the upper boundary, the electric forces are so large that the particles escape from the trap. For 50- μm particles, the regions for the sinusoidal (1) and rectangular (2) voltages are similar in size, but region 2 is shifted toward lower charges, which agrees with the previously obtained experimental result [14], where a charged particle was confined at a lower amplitude of the rectangular voltage. Since in the case of the rectangular potential, the electric field at its peak value acts for a significantly longer time than in the case of the sinusoidal one, particles are confined at a lower voltage amplitude. For the same reason, particles at the upper boundary escape from the trap at a lower voltage amplitude, and as a result, the entire confinement region shifts to the left and downward. Confinement region 3 for particles sized 20 μm is shifted to even lower charges compared to region 2 for 50- μm particles. As the diameter decreases, the gravity force and viscous friction decrease, so the particle is more easily confined at a low charge.

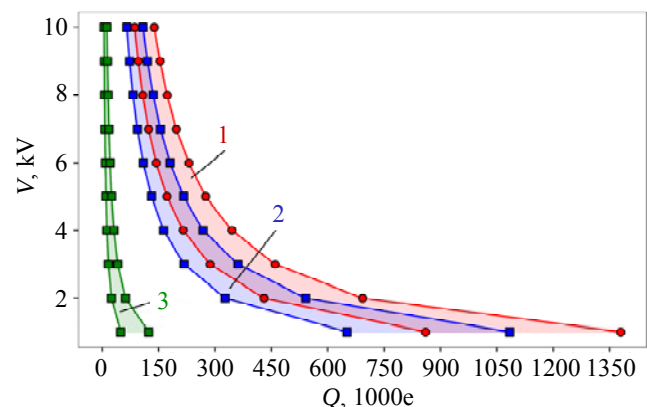


Fig. 1. Confinement regions of particles for different voltage waveforms at the frequency of 50 Hz (calculation): 1 (red) – sinusoidal, 50 μm ; 2 (blue) – rectangular (meander, $K_p = 50\%$), 50 μm ; 3 (green) – rectangular, 20 μm

Figure 2 shows the confinement regions (calculation) for 50- μm particles under meander voltage at frequencies of 50 Hz (2, blue) and 100 Hz (1, red). When the frequency was increased to 100 Hz, confinement region 1 shifted toward higher particle charges so far that regions 1 and 2 did not overlap. Consequently, particles that were confined in the trap at a frequency of 50 Hz would not be confined when the frequency was increased to 100 Hz. This fact was verified

experimentally. At a voltage amplitude of 4 kV (meander) and a frequency of 50 Hz, a cloud consisting of a large number of particles was confined in the trap. As the frequency was increased in 20-Hz steps, the number of particles gradually decreased, and at 100 Hz, no particles remained in the trap.

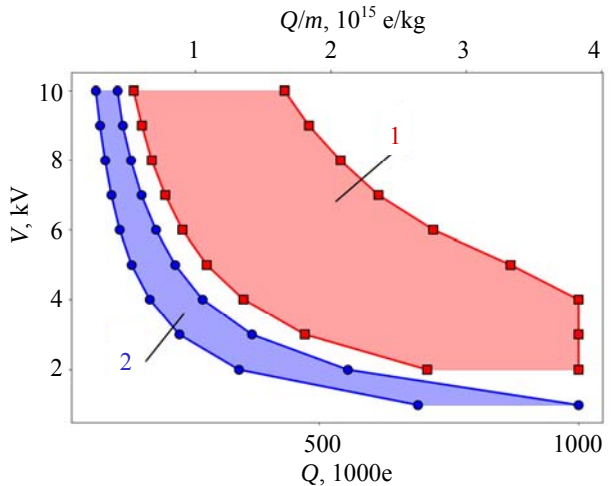


Fig. 2. Confinement regions for particles with a diameter of 50 μm under meander voltage. 1 (red) – frequency of 100 Hz; 2 (blue) – 50 Hz

For a sinusoidal confining voltage with a 5 kV amplitude, a 50 Hz frequency, and a 2.5-kV voltage on the charging plate, particles sized from 2 to 60 μm were confined in the experiment, with an average size of 26 μm . The estimate of the physically possible charge for 20- μm particles (15,625–195,312 e) completely covers the calculated confinement region (12.600–32.800 e). For 5- μm particles, the overlap is 87% (976–12.207 e vs. 2.600–9.300 e); for 50 μm particles, it was about 30% (97.656–1.220.703 e vs. 178.100–278.100 e). Since the original mixture initially contained few particles smaller than 10 μm or larger than 40 μm – the experimentally obtained particle size distribution was similar to that of the original mixture. Thus, the experiment confirms the calculations.

Fig. 3 shows the effect of positive half-cycle duty factor K_p on the confinement regions (calculation) for 20- μm particles at a 50-Hz frequency. Confinement was possible at $K_p = 50\%$, 40%, 35% due to the balance of forces. At $K_p = 40\%$, region 2 lies inside region 1 ($K_p = 50\%$) and was shifted to the right toward higher charges; at $K_p = 35\%$, region 3 became even narrower and shifted further to the right,

extending beyond the boundary of region 1. Consequently, as the pulse asymmetry increased, the range of stable charges narrowed. For particles sized 5 and 50 μm , confinement was possible only at $K_p = 50\%$ (meander). Light particles (5 μm) were more strongly shifted under asymmetric pulses and were attracted to the electrodes, while large particles (50 μm) did not have time to return during the short half-cycle due to inertia. Particles sized 10 μm were confined at $K_p = 50\%$ и 40%. The experimental data on the deposition of trapped particles were in qualitative agreement with the calculations.

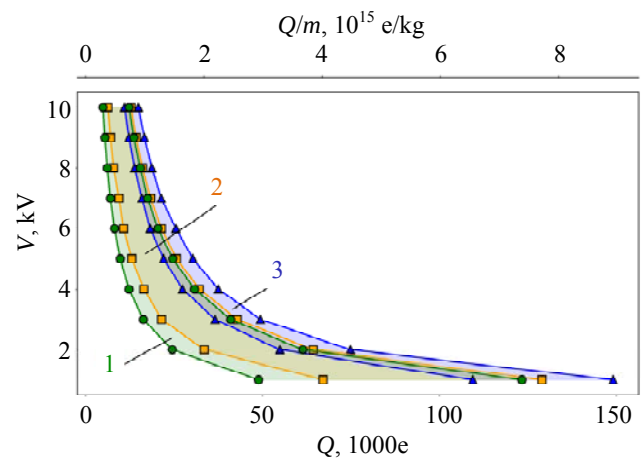


Fig. 3. Confinement regions for microparticles with a 20- μm diameter at a 50-Hz frequency for different values of positive pulse duty factor K_p : 1 – meander $K_p = 50\%$ (green region); 2 – 40% (orange); 3 – 35% (blue)

The effect of an external pulsed periodic alternating electric field, with the frequency varying in the range of 20–170 Hz, on the particle trajectories in the trap under a sinusoidal confining voltage (5–7 kV, 50 Hz) was studied experimentally and numerically. The external electric field was generated by two metal plates placed at a distance of 2 cm from the trap electrodes, to which a meander-shaped pulsed voltage (3–5 kV) was applied. It was found that the external electric field excited two different instabilities: particle ejection at a 27 Hz frequency and particle loss at 200 Hz, both in calculations and experiments. At 125 Hz, the trajectories stabilized, particle oscillations decreased and the distance between particles was reduced. The calculation results are in alignment with the experiments. Figure 4 shows the calculated trajectories: a stable trajectory without

an external electric field is shown on the left; the instability excited at an external field frequency of 27 Hz is shown on the right, where the trajectory amplitude increased with each oscillation, causing the particle escapes from the trap.

The effect of the plasma on particle confinement was studied in a quadrupole trap with electrodes having diameters of 63, 120, and 200 μm , 11 cm in length, and a 1-cm distance between the electrodes. The threshold ignition voltage was 2.6 kV for the 63 and 120- μm electrodes, and 4.0 kV for the 200- μm electrodes.

With the electrodes of 63 and 120 μm , particles sized 2–8 μm were trapped; for the electrodes of 200 μm , particles sized 40–60 μm were trapped. Stable particle confinement was observed at corona discharge currents of 15–70 μA . Figure 5 shows an image of particles confined in the trap with an electrode diameter of 63 μm under rectangular voltage pulses (meander) with a 3.2 kV amplitude, a 50 Hz frequency, and 30 μA corona discharge current. The number of trapped particles at the meander voltage was much larger than at the sinusoidal voltage of the same amplitude.

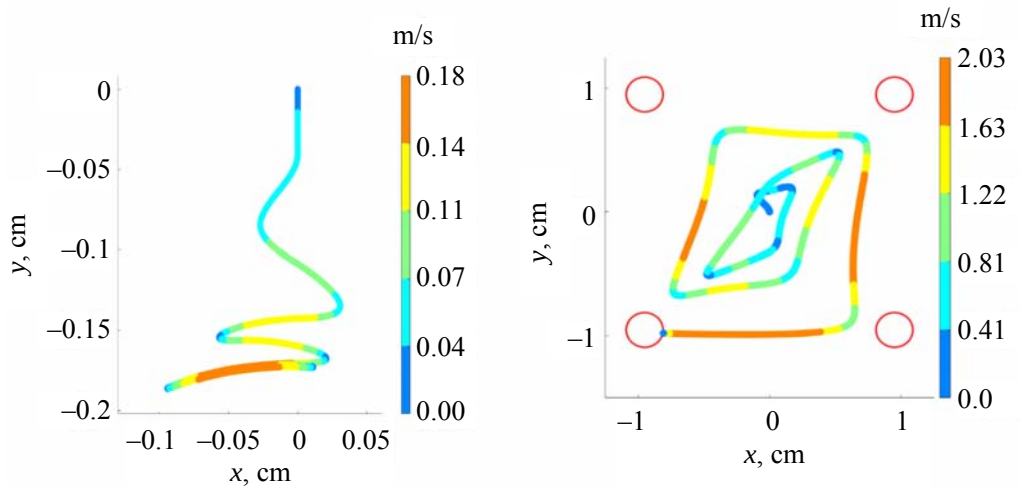


Fig. 4. Left: stable trajectory without the external electric field. Right: trajectory of the particle escaping from the trap at the external field frequency of 27 Hz. The colour indicates the particle velocities. Particle: charge 98,000 e , diameter 20 μm . Rectangular voltage (meander) on the plates: $V = 5 \text{ kV}$. Confining sinusoidal voltage on the trap electrodes: $V = 7 \text{ kV}$, 50 Hz

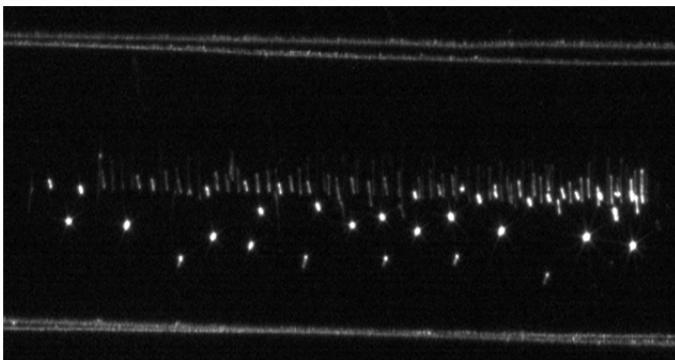


Fig. 5. Photo of microparticles trapped by the trap with corona discharge plasma

Conclusion

Experimental and numerical studies have shown that the confinement regions depend on the particle sizes, and the similarity law for the charge-to-mass ratio does not hold. This

difference allows for selectively influencing particles of a specific size. The waveform of the confining voltage has been found to have a significant effect on the stability regions. The rectangular confining voltage (meander) allows for the confinement of particles with a lower

charge than the sinusoidal voltage does, due to the longer application of the electric field at its amplitude value. An increase in the frequency of the confining voltage shifts and expands the confinement regions toward higher voltages and charges, which allows for the selective screening of particles. As for asymmetric rectangular voltage pulses, as the duty factor K_p decreases, the confinement region narrows and shifts toward higher charges, thus allowing for the selective confinement or screening of particles of different sizes. An external meander-shaped electric field allows for controlling the particle dynamics in a trap with a sinusoidal confining voltage: by varying the frequency of the external electric field, one can cause a loss of particles or the excitement of instability, leading to particle

escape from the trap. There is a frequency range in which the external electric field stabilizes unstable particle trajectories in the trap, thus reducing the oscillation amplitude and the distance between particles. It was experimentally found that, in a quadrupole linear trap with a corona discharge plasma under a meander-shaped rectangular voltage, much more particles are confined than under a sinusoidal voltage. This occurs only in a narrow range of corona discharge currents, while the size of the confined particles depends on the diameter of the corona electrodes.

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