Coulomb stable structures of charged dust particles in a dynamical trap at atmospheric pressure in air

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Abstract. A mathematical simulation of a dust particle’s behavior in the electrodynamic linear quadrupole trap with closing end electrodes allowed us to reveal several features of the phenomena. Regions of stable confinement of a single particle, in dependence of frequency and charge-to-mass ratio, were determined. With an increase of the medium’s dynamical viscosity, the region for confining charged particles by the trap becomes wider. We obtained values of the maximum quantities of charged particles confined by the trap at atmospheric pressure in air. Firstly, we presented observations of ordered Coulomb structures of charged dust particles obtained in the quadrupole trap in air at atmospheric pressure. The structures consisted of positively charged oxide aluminum particles 10–15 µm in size and hollow glass microspheres 30–50 µm in diameter. The ordered structure could contain particles of different sizes and charges. The trap could confine a limited number of charged particles. The ordered structures of charged micro-particles obtained in the experiments can be used to study Coulomb systems without neutralizing the plasma background and action of ion and electron flows, which are always present in non-homogeneous plasma.

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1. Introduction

Systems of charged dust particles in plasma are of great interest at this time [1–3]. If the potential energy of the Coulomb interaction between charged dust particles significantly exceeds their kinetic energy then they can form ordered structures, which are called Coulomb or plasma crystals. To study particle dynamics and properties, the sizes of particles and interparticle distances allow us to use rather simple diagnostic means, e.g., optical measurements in the visible range. The results of such investigations can be used to interpret the properties of crystals, liquids and colloidal suspensions [4]. Up to now plasma crystals have been obtained in glow plasmas and high-frequency discharges at low pressures (1–100 Pa) and in the beam of a charged particle accelerator [1, 2]. Studies have been carried out into crystal–liquid–gas phase transitions [1, 2], the influence of temperature on dusty structures in the range of temperatures from normal to cryogenic ones [5] and the oscillations and waves propagating in dusty plasma structures [1, 2]. The reaction of dusty plasma structures on external actions such as pulsed electric [6, 7] and magnetic fields, laser radiation, the electron beam [8], the thermophoretical force [9] etc have been investigated. Three-dimensional structures with a great amount of particles under microgravity conditions were studied on the orbital space station ‘MIR’ and the International Space Station [1]. Some technological applications of dusty plasmas have been considered in [3].

Since Coulomb crystal is unstable when it consists of dust particles with charges of the same sign where particles are pushed apart, stable Coulomb crystal could only be obtained in the potential trap. Such traps are formed in low pressure electrical discharges in regions of a non-uniform electrical field. The trap may be formed in the near-electrode layer of the capacitive radio frequency (rf) discharge or in the striation of the glow discharge positive column. The gravity force of the charged particle is balanced by the longitudinal electrical field in the axial direction, in the case of a discharge with cylindrical symmetry. The radial electric field appears due to the ambipolar diffusion of electrons and ions to the walls, which confine charged particles in the radial direction. The charge of the dust particles reaches a value of several thousands of an electron charge and is determined by electron temperature and particle size [1, 2]. The sizes of the confined dust particles are in a rather narrow range, between 1–20 µm. This range is determined by the particle charge and electrical discharge fields that provide its levitation. The fields of parameters for existing ordered dusty structures in low pressure electrical discharges are determined by plasma parameters that limit the investigated properties of plasma crystals.

The additional restriction for forming Coulomb crystals in the gas-discharge plasma is due to the fact that the charges on the dust particles depend on the electron temperature, which in turn depends on the reduced electrical field intensity. If the charges on the dust particles and the
trap confining them are created independently, then ordered structures of charged dust particles can be produced in other conditions as well. Such a method of producing dusty plasma crystals was realized with the help of a proton beam with an energy of about 2 MeV. The proton beam produced an ionization of the gas; the trap’s additional electric fields were formed by the system of electrodes to which direct potentials were applied [10].

When the pressure is increased, the crystal is destroyed. Then the levitation of charged particles stops and the particles move out of the discharge since the trap formed by the electrical fields is destroyed. For example, in the case of the glow dc discharge, striations disappear and correspondingly the gradients of the longitudinal electrical field providing the stability of the levitating particles along the gravity force also disappear. When the pressure increases the radial electrical force decreases. Therefore, under the action of the ion drag force and thermophoretical forces, which appear due to the temperature gradient, confining particles in the radial direction also becomes impossible.

In the case of atmospheric pressure, there were attempts to obtain structures of charged dusty particles in the thermal plasma of a gas burner and in the air corona discharge. In the thermal plasma, Coulomb crystals were not obtained [2] due to the strong gas-dynamic flows and high temperature gradients, as well as a consequence of the fast destruction of dust particles in the high temperature gas. A corona discharge is applied over a period of years to remove dust in electrostatic precipitators, separate particles and powder coloring. Therefore, the mechanisms of charging dust particles and their motion in the corona discharge field have been explored [11]. Nevertheless, stable dusty structures in the corona discharge have not yet been obtained.

Thus, to obtain ordered structures at atmospheric pressure we need to use additional traps. The problem of making traps of different types for confining particles or plasmas also arose previously, e.g., traps for confining the high temperature plasma and ions. To confine levitating charged micro-particles, the dynamic Paul traps and their modifications were used [12, 13]. Micro-particles were confined there by alternating the electrical fields. The motion of particles is described by the Mathieu equations; an analysis of the Mathieu problem has shown that such traps are capable of confining levitating charged micro-particles in the wide range of charge-to-mass ratios by changing the frequency and alternating the electrode voltage amplitude [12, 13]. As a rule, when studying light scattering, the photoemission from the particle surface, processes of evaporation and condensation of a drop and the chemical reactions of solid particles [12–15]—one preliminary charged particle was placed in the trap. The confinement of the particle was realized at low gas pressures in the trap. The motion of the charged dust micro-particles and the possibility of forming Coulomb structures in the Paul trap at low pressures were studied in [16]. The single particle moved across the trap on Lissajons trajectories depending on the parameters of the applied voltage. As has been mentioned [16], such a trap with one particle could serve as an analogue computer for solving the Mathieu equation. A large number of particles can be confined in a trap, but in this case the particles move chaotically depending on the frequency and amplitude of the voltage applied to the electrodes. At high frequencies, micro-particles are confined in definite points of the space making oscillations round them. Some particles in the center of the trap could be practically motionless. The oscillation amplitudes of peripheral particles increase as they get further from the trap center. In photos of dusty structures made with a long exposure time, one can clearly see the trajectories of particles in the form of solid lines. As has been mentioned, the trajectories can be used as a map of the electrical fields in a trap. When the frequency of the applied voltage decreases, the particles remaining in the trap move chaotically. The structure of charged particles with a strong Coulomb interaction formed
in the trap at high frequencies was named conditionally the ‘quasicrystal’ in [16]. In the low frequency case, the chaotic motion of the transition of particles was called ‘melting’ [16]. The Coulomb cloud of atomic ions in the quadrupole vacuum trap was obtained in [17].

In order to confine charged dust particles in a dynamical trap at atmospheric pressure, it is necessary to take into account the friction of the charged particles on the air and to choose corresponding parameters of the trap since a shift of the stability region takes place [13]. An additional difficulty in the experiments is the necessity to charge the solid aerosol particles with the same charges [18]. Charged oil drops were used [19] to provide particles with the same charge-to-mass ratio. The drops formed the Coulomb structure in the Paul trap at atmospheric pressure. To confine charged particles of silicon carbide (SiC) and alumina (Al$_2$O$_3$) at atmospheric pressure, classical quadrupole traps [20] with end electrodes were used, to which a cut-off voltage was applied, as well as multi-electrode traps consisting of 8 or 12 cylindrical brass electrodes 4 mm in diameter [21–23]. The trap with 12 electrodes provided a higher stability and smaller amplitude of oscillations of the captured particles. However, the conditions of the particles’ confinement were very sensitive to the trap geometry. Therefore it was necessary to test different radii and to perform a precise tuning of the trap geometry. The quadrupole traps are used more frequently since in their case it is easier to select conditions for confining several particles. The electrodes were placed at a distance of 1–1.5 cm from the trap axis. The negatively charged particles of Al$_2$O$_3$ with diameters of 60 or 200 µm (with masses of $4.18 \times 10^{-10}$ and $1.55 \times 10^{-8}$ kg correspondingly) were located at the trap axis line if their number was small, from one to –six particles. If the number of particles exceeded this value, they moved chaotically and formed a dusty cloud along an axis. To determine a particle’s charge, the cloud was subjected to the action of acoustic waves thereby inducing parametric oscillations of the particles [24]. The experimentally determined charge-to-mass ratio was equal to $5.4 \times 10^{-4} \text{C kg}^{-1}$.

In this paper we report for the first time on the observation of stable Coulomb structures consisting of more than 50 charged dust particles in a quadrupole trap at atmospheric pressure.

### 2. Mathematical simulation of a dust particle’s behavior in electrodynamic traps

To determine the regions of a stable particle’s capture and the confinement of structures, we performed a mathematical simulation of the dynamics of the motion of a single particle as well as an ensemble of charged particles in a quadrupole trap at different air pressures. The sketch of the quadrupole trap is presented in figure 1. The trap consists of four cylindrical dynamic electrodes (diameter $d = 3$ mm and length $L_m = 15$ cm) to which an alternating voltage is applied and two closing end electrodes (length 4.5 cm) to which a direct current voltage is applied. The closing end electrodes are placed at each side at the geometrical trap axis at the distance $L_b = 6$ cm apart. The distance between the axes of the dynamical electrodes was $L_b = 1.3$ cm.

The motion of the dust particles in the trap is described by the system of stochastic differential Langevin equations

$$m_d \frac{d^2 r_j}{dt^2} = F_{tr}(r_i) + F_{int}(r_i) - 6\pi \eta R_d \frac{dr_j}{dt} + F_{Br}(r_i) + F_{mg},$$

where $m_d$ is the dust particle mass, $r_j$ is the radius of $j$th particle, $j = 1, 2, \ldots, N$, $N$ is the number of dust particles, $F_{tr}(r_i) = -Z_d \nabla \Phi$ is the external potential force of the trap,
Figure 1. Sketch of the linear quadrupole trap with closing end electrodes 1, 2, 3, 4 are dynamic electrodes, 5 are closing end electrodes.

\( F_{\text{int}}(r_i, r_s) \) is the force of the paired interaction between particles \( i \) and \( s \), \( F_{mg} \) is the gravity force and \( F_{Br}(r_i) \) is the Langevin delta correlated source of forces that models the random forces acting on a dust particle from the other particles. To take friction into account, we used Stokes’ Law. The behavior of dust particles was simulated with the help of the Langevin equation’s numerical integrator.

To model the voltage applied to the cylindrical electrodes (rods), we assumed that the rods are placed in the center of an infinitely long grounded cylinder with inner radius \( R = 25 \) cm. This value is much greater than the radii of electrodes and the inter-electrode distance. Using such an assumption, each electrode and the surrounding cylinder can be considered as a cylindrical capacitor. Assigning a voltage difference between the electrode and the external cylinder, one can calculate the charge existing at the internal electrode. To calculate the alternate forces acting on a dust particle, each electrode was mathematically divided into small sections and it was assumed that each of these sections appeared as a point charge. The resulting force acting on a charged dust particle was calculated as the total Coulomb force from each point charge at the electrodes:

\[
F_{\text{int}}(r, t) = \sum_k \frac{LU \sin(\omega t)Q_i}{2T \ln(R_2/R_1)(r_i - r_k)^2},
\]

where \( L \) is the electrode length, \( U \) is the amplitude of the alternating voltage at the electrode, \( \omega = 2\pi f \) is the cyclic frequency of the alternating voltage, \( Q_i \) is the charge of the \( i \)th dust particle, \( R_2 \) and \( R_1 \) are the radii of the grounded electrode and the rod electrode correspondingly, \( r_i \) and \( r_k \) are radii-vectors of the dust particle and the point charge at the electrode correspondingly. The uniform distribution of the charge along the cylindrical electrodes of the trap could take place only in the case of infinitely long electrodes or in the central region near the electrode. In our problem’s case, this approximation is correct since all particles in the longitudinal direction gather at an approximately 1 cm section of the total electrode length, equal to 15 cm. Other parameters are important for capturing particles besides the amplitude and frequency of the voltage applied to the electrodes, for example, the geometry of the linear trap, the scheme of the applied alternating voltage as well as the characteristics of the gaseous media and dust particles.

Let us consider the regions of the stable confinement of a single particle in a dependence of the applied voltage frequency. The confinement region for each frequency is limited by the upper
Figure 2. Regions of stable confinement of a single particle in dependence of the frequency $f$ and charge-to-mass ratio of a dust particle $Q/m$ at different dynamical viscosity $\eta = 1.7 \, \mu\text{Pa s}$ (shaded region 1) and $\eta = 17 \, \mu\text{Pa s}$ (unshaded region 2). The calculation was performed for the following parameters of particle and trap that have a practical interest: $Q = 20,500–685,000e$, $U = 4400 \, \text{V}$, dc closing voltage $900 \, \text{V}$, density of particles $\rho = 0.76 \times 10^{-4} \, \text{kg m}^{-3}$ and the particle radius is $9 \, \mu\text{m}$.

and lower values of the charge-to-mass ratio $Q/m$, where $m$ is the dust particle’s mass (figure 2). Similarly for each charge-to-mass ratio $Q/m$, the confinement region is limited by the lower and upper frequencies. Beyond this region, the trap is not capable of confining particles. With an increase of the medium’s dynamical viscosity, the region for confining charged particles by the trap becomes wider. As an example, in figure 2 the results of the simulation for two different dynamical viscosity values are presented: $\eta = 17 \, \mu\text{Pa s}$ that corresponds to air at atmospheric pressure (squares in the figure) and $\eta = 1.7 \, \mu\text{Pa s}$ that corresponds to conditions of a rarefied medium (circles in the figure). In the case of the medium’s smaller dynamical viscosity, the dissipation of the kinetic energy of the dust particles will be smaller and, therefore, the particle’s velocity and kinetic energy will be greater due to the action of the trap’s electrical field on the particle. At higher velocities of the particles, the boundary frequency should be higher in order to prevent the escape of particles from the trap at the half-cycle of the electric field oscillations. It follows from the results of the calculations presented in figure 2 that by using the quadrupole dynamic trap, it is possible to confine particles with greater masses and dimensions compared to the low pressure plasmas with an rf or dc glow discharge.

Figure 3 presents regions for confining the maximum number of particles (dynamical trap capacity) at the given value of frequency and different $Q/m$ at atmospheric pressure. The region for confining the maximum number of particles is within the curve for the given frequency. The range of $Q/m$ changes for the given value of the maximum number of confined particles is determined by boundary points of the intersection of the straight line conducted through a point representing the given quantity of particles with the curve obtained in the simulation. By increasing the number of particles in a dusty structure, the region of confinement reduces that appears in the behavior of the continuous lines in figure 3. To determine the maximum number of particles that could be confined by the trap, a large amount of particles were injected into it. After that we defined the quantity confined in the inner region of the trap.
By increasing the frequency, the region of confining a fixed number of particles increases. The maximum number of particles corresponds to the maximum of the curve in figure 3. The extreme number of particles confined in the trap is attained only at a single value of the charge-to-mass ratio $Q/m$.

3. Experimental setup

The scheme of the experimental installation with the linear quadrupole trap for capturing and confining charged dust particles is presented in figure 4. The retaining and closing electrodes of the dynamic trap were made of copper rods 3 mm in diameter and 12 cm in length. The distance between the axes of the retaining rods was 1.3 cm. The closing end electrodes were placed at the trap axis. The distance between the faces of the closing electrodes was 65 mm. The retaining electrodes served for capturing the charged particles and the closing electrodes bounded the motion of particles along the axial line of the trap. An alternating voltage with an amplitude from 0 to 2000 V was applied at the retaining electrodes. The voltage frequency was changed with the help of a generator. A direct current voltage of 900 V was applied at the closing electrodes. To reduce the action of external electric fields, the trap was placed on a grounded metal table and the power supply wires were placed at a safe distance, so that their electric field did not influence the electrodynamic trap field. The wires were installed on the metal table surface. The particles were detected by a high speed video camera HiSpec with a maximum resolution of $1280 \times 1024$ pixels. For stable registration of particles with sizes of $10–150 \mu m$, a diode laser ($\lambda = 550$ nm) with power changing from 10 up to 100 mW was used. Particles were illuminated by a cylindrical laser beam as well as by a laser sheet with a thickness of $150 \mu m$. The trap was placed inside a transparent box to exclude the influence of air flows on the particles’ motion.
4. Observations

For our experiments we used polydispersional particles of Al$_2$O$_3$ with sizes from 10 to 80 µm and hollow borosilicate glass spheres with diameters of 30–100 µm. As follows from the simulations, the quadrupole trap exhibits selectivity in respect to the mass and charge of particles. Due to this, the trap will confine only those particles which satisfy the confinement conditions. To obtain particles with charges necessary to form a stable ordered structure, a special source of charged particles has been produced. The charging of micro-particles was achieved with the help of the streamer discharge in the plane capacitor field. The source allowed us to charge particles positively to 10$^5$–10$^6$e and give them an initial velocity of 0.5–2 m s$^{-1}$. The details of the special source for charging particles will be published elsewhere. The selection of particles with the given charge-to-mass ratio was achieved in the electric field of the plane capacitor where the flow of charged particles was directed. The capacitor plates were arranged in the horizontal plane. The distance between plates was 10 cm. The positive potential from the dc voltage source was applied to the bottom capacitor plate. The voltage was changed in such a way as to balance the gravity force for the particles possessing the charge-to-mass ratio necessary for confinement by the trap; the particles satisfying this condition went along the capacitor plates and got into the trap. To provide a stable confinement of particles by the trap it was necessary to decrease the velocity of particles. The braking of particles was achieved by the neutral drag force in air at the disconnecting of the capacitor electric field. The particles moved through the quadrupole trap where low-velocity particles with a suitable charge-to-mass ratio were captured. For determining the charge of the captured particles we used the following procedure. The voltage at the trap was switched off causing the particles to fall down due to gravity and...
Figure 5. (a) Photo of the trap and ordered structure of aluminum oxide particles with 10–15 µm sizes. $U = 2000$ V, $f = 80$ Hz and $U = 900$ V. (b) Magnified image of the ordered Coulomb structure. Size of the field of view is $17 \times 9.5$ mm$^2$. The inter-particle distance between particles of similar sizes is 400–800 µm, the distance between a big particle and smaller ones is 1800–2000 µm.

Figure 6. Snapshot of a part of the ordered Coulomb structure of hollow glass spheres 30–50 µm in diameter. $U_{ac} = 2000$ V, $f = 80$ Hz and $U_{dc} = 900$ V. Size of the field of view is $11 \times 7.5$ mm$^2$. The distances between particles are 1300 and 1800 µm.

precipitate at the substrate. With the help of an optical microscope, the sizes of the precipitated particles were measured. The weight of the particle was calculated in the assumption that the particle was a sphere. The particle charge was determined from the condition that the gravity force in the plane capacitor gap was balanced by the electric field force.

The examples of the obtained ordered Coulomb structures of aluminum oxide particles with sizes from 10 up to 80 µm at frequency $f = 80$ Hz are shown in figure 5. The number of particles observed in the structure was equal to 50–100 and depended on the frequency and amplitude of the alternating voltage applied to the dynamic electrodes of the trap.

Figure 6 presents the structure formed by hollow glass microspheres 30–100 µm in diameter. The maximum number of particles in the ordered structure in this case was not greater
than 50. Due to the great friction force, the chaotic movement of particles was negligible. Most of the particles oscillated with small amplitudes in synchronism with the alternating electric field. The particles nearest to the axis had the lowest displacements and only several peripheral particles oscillated with a noticeable amplitude; it seems likely that these particles were at a stability boundary.

The formed ordered Coulomb structure did not change for a long time (it was observed for about 12 h). It was observed that the Coulomb interaction was strong and the mean interparticle distances were approximately the same. We estimated the charges on particles captured by the trap using the procedure mentioned above and obtained values of $10^5$–$10^6$e. It is worth noting that in contrast to dusty structures in plasma, the charged micro-particles in the trap form a Coulomb system without a neutralizing plasma background. Since the trap confines particles with equal charge-to-mass ratios, the ordered structures can contain particles of different sizes. An example of such a structure is shown in figure 6(b) where in the bottom part of the dusty structure one can see a big particle. The inter-particle distance between particles of the same size is equal to 400–800 µm but the distance between the big particle and small ones is 1800–2000 µm; that is the last distance 2.5–3 times above the former value. Considering that the confining force of the trap is proportional to the space shift and the repulsive force between particles is a Coulomb one, which is the second power on the distance we obtain, the big particle charge is six to nine times greater than the other particles’ charge.

**Figure 7.** Photo of the trap and the ordered Coulomb structure of aluminum oxide particles with sizes 10–15 µm. $U_{ac} = 2000$ V and $f = 80$ Hz. (a) $U_{dc} = 900$ V and (b) $U_{dc} = 750$ V.
When the amplitude of the alternating voltage decreased, an ensemble of particles went down under the action of gravity force. Nevertheless, particles in the ensemble did not change their location. By further decreasing the voltage, a number of particles left the trap. But a change of the positions of particles inside the ordered structure did not happen. The first particles to leave the trap were those located at the outer boundary of the structure. When the frequency decreased below 30 Hz or increased above 180 Hz, particles began to rearrange inside the structure and also to leave the trap. Nevertheless, we did not observe a chaotic motion of all the particles in the trap. When the dc voltage at the closing electrodes was decreased, the linear structure size increased (see figures 7(a) and (b)).

By further decreasing the closing voltage, particles reached the closing end electrodes and then left the trap moving along the closing electrodes. When the number of particles in the trap decreased, up to ten or less particles, they aligned along the trap axis forming a linear chain.

It should be mentioned that the length of the rods used in the experiments was 12 cm, which differed to the 15 cm rods used in the simulation. In the simulations we found that changing the length of the rods in this range could lead to a small change of the electric field in the peripheral region near the ends of the rods; however, particles are not present in this region (see figures 5 and 7). The same note also concerns a small difference in the distance \( L_h \) used in the experiments and simulation.

5. Conclusion

In conclusion, we demonstrated by mathematical simulation the possibility to confine in the quadrupole dynamic trap an ensemble of charged dust particles with a strong Coulomb interaction and found regions of stable confinement. It has been shown that an increase of gas density expanded the capturing region of particles and decreased the particles’ oscillation amplitude around an equilibrium state. As a result, ordered Coulomb structures could be obtained. It was revealed that a trap with fixed parameters may confine a limited number of charged particles.

We have presented the first observations of ordered Coulomb structures of charged dust particles obtained in the quadrupole trap in air at atmospheric pressure. The structures consisted of positively charged oxide aluminum particles 10–15 µm in size and hollow glass microspheres 30–50 µm in diameter. The ordered structure could contain particles of different sizes and charges. The trap could confine a limited number of charged particles.

The ordered structures of the charged micro-particles obtained in the experiments can be used to study Coulomb systems without neutralizing the plasma background and the action of ion and electron flows, which are always present in non-homogeneous plasma. For example, an investigation of the influence of the pulsed electric field on ordered Coulomb structures in plasma is always difficult due to the plasma screening the electric field. Its influence on the charged particles will depend on the plasma density and the particles’ disposition. The parameters of the plasma itself will also change in the applied field and the parameters of the plasma trap would change as a result [5–7]. It becomes difficult to separate the ordered structure response on the external action from the structure rebuilding in the changed trap. In contrast to this case, external electric fields in the trap without plasma act directly on the charged particles; the electric field distribution in this system could be readily calculated.
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