Micro-particle charge determination using a linear Paul trap with the end electrode

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Abstract. A method for measuring the charge-to-mass ratio of micron-sized particles, using an electrodynamic linear Paul trap supplemented with the end electrode, is presented. Measurements were performed for the particle charge acquired by passing through a corona discharge.

1. Introduction
Measurement of the electrical charge of a single dust particle is important for technologies of dust removal from the air or from the industrial gas emissions, for ore enrichment using electric field, for studies of lightning and dust plasmas and for other applications.

Diverse methods of micro-particles charge-to-mass ratio measurement, i.e. the ratio of the total charge of particles to their total mass, are currently available [1]. The electrical charge on the particles can be measured by high-resistance electrometers, by the induction method or by analyzing the particle motion in an electric field. The induction method employs measuring the induction current occurring in a ring electrode when the charged particles pass through it [2].

The simplest method is determination of the charge by deviation of the particle track in an electric field. Originally this method was used in experiments of Millikan [3]. It was developed further by Laby and Hopper in Ref. [4] where they studied the motion of a charged oil droplet in a static electric field of a flat capacitor. The advantage of this method is the possibility of determining the particle size by its inhibition in the gaseous medium. This method is applicable for a constant, static electric field and for the variable field.

In a rarified medium, measurement of the ratio of charge to mass with alternating electric fields is used for the selective capture of ions and molecules. Approach based on trapping the charged particles in alternating electric fields in a gaseous medium at atmospheric pressure is suggested in [5], where particles are trapped by an alternating electric field formed by the Paul ion trap [6]. Due to the dissipation of the particle energy in a gaseous medium, the charged particle confinement range is wider than in the case of the rarified media [7, 8]. By studying the response of the particles to changes of the electric field parameters inside the trap (AC vs. DC electric fields and the frequency of the alternating electric field), it is possible to determine the ratio of the charge to the mass of the particles in this type of trap.

However, the use of the Paul ion trap for determination of the charge-to-mass ratio of the particles brings forward a number of challenges, such as those associated with long-term study of the response
of the amplitude of the particle oscillations to a change of the amplitude of the variable voltage or of the constant electrostatic potential [5].

In this paper a new method of measuring the charge-to-mass ratio of particles, using an electrodynamic linear Paul trap [6] supplemented with the end electrode, is proposed. It is shown that the charge-to-mass ratio of the particles pre-charged in a corona discharge can reach values of \(6.8 \times 10^{-6}\) C/kg.

2. Method of particle charge measurement

The schematics of the experiment is shown in Figure. 1.

The AC voltage with amplitude \(U_\omega\) is applied to the linear Paul trap electrodes (1). A charged particle in such an alternating electric field is confined to the area of the smallest amplitude of the electric field changes during the alternations. Inside the trap, this area corresponds to the central axis of the trap in the middle among the electrodes, and the particles will attract to this axis [5]. Contained in the horizontal plane, the charged particle (4) will move down along the axis of the trap under the force of gravity. To compensate the weight of the particles, the ball-shaped electrode (2) is installed on the central axis of the trap near the center of the trap on a thin rod (3). Particle repulsive potential \(U_b\) is applied to the ball-shaped electrode. Ball shape of the electrode is selected to reduce the non-uniformity of the electrostatic field that could be significant if using only the rod without the ball.

Knowing the distance between the ball-shaped electrode and the particle, one can estimate the particle charge-to-mass ratio from the balance between the gravity acting on the particle \(F_g = m_p g\) and the Coulomb repulsion force \(F_r = q_p E\), where \(m_p\) is the particle mass, \(g\) the gravity acceleration, \(q_p\) the particle charge and \(E\) the electric field.

3. Realisation of the method

Trap electrodes (1) (figure 1) were made of metal rods with a diameter of 4 mm. An alternating voltages \(U_\omega \sin(\omega t)\) and \(-U_\omega \sin(\omega t)\) were applied to the electrodes, \(U_\omega = 840\) V, \(\omega = 2\pi f, f = 50\) Hz. On the central axis of the trap, at the lower end, a metal ball-shaped electrode of the radius \(R_b = 4\) mm was installed on an 18 mm long base rod and the DC voltage \(U_b = 250, 500, 750\) or 1000 V was applied to the ball-shaped electrode.

The particles were illuminated by a spread of the laser light and recorded by a high-speed HiSpec Fastec Imaging video camera with a maximum resolution of 1280x1024 pixels.

In the experiment, the dielectric powder particles of aluminium oxide \(\text{Al}_2\text{O}_3\) with the average radius \(r_p = 17\) microns, density \(\rho_p = 3990\) mg/cm\(^3\) and the dielectric constant \(\varepsilon = 10\) were used.
Pre-charged in a corona discharge with the field strength of \( E = 7.7 \text{ kV/cm} \), the particles were injected into the trap, where they were captured by the trap field in the horizontal plane and by the interaction with the field of the ball-shaped electrode in the vertical direction. Figure 2 shows the ensemble of the suspended particles above the ball electrode in a form of a chain. By changing the \( U_b \) potential, the particles position above the electrode was varied.

![Figure 2. Particles confined inside the linear trap with the ball-shaped electrode. 1 – the charged particles above the ball-shaped electrode, 2 – the linear trap electrodes, 3 – the end ball-shaped electrode. The voltage \( U_b = 250 \text{ V} \) forms the electric field similar to that of the point charge in the middle of the ball \( Q_b = 1.14 \cdot 10^{-10} \text{ C} \).](image1)

Trap electrodes perturb the electric field of the ball-shaped electrode. The calculation of the effect of the trap electrodes on the vertical distribution of the ball-shaped electrode field along the axis of the trap was performed using the Comsol multiphysics software in the stationary case for the time instant \( \omega t = \pi/2 \). The electric potential distribution is shown in figure 3. This potential with an increase of the distance \( r \) from the ball decreases faster than \( U(r) = q_b \cdot k / r \), where \( k = 8.98 \cdot 10^9 \text{ m/s} \), and can be approximated by a function \( U(r) = q_b \cdot k / r^{2.34} \) (figure 3).

![Figure 3. Comparison of the distribution of the electric field of the ball-shaped electrode with the trap electrode and without it. The end electrode potential \( U_b = 250 \text{ V} \).](image2)

Since in the confined structure several particles were captured and arranged in a vertical chain, the charge of the suspended particles was calculated for the top and bottom particles in the chain with the influence of the remaining particles treated under the assumption that they all have the same charge \( q_p \). For each value of \( U_b \) (250, 500, 750, 1000 V), the distances between the particles and the distances between them and the end electrode (as in figure 2 at \( U_b = 250 \)) were determined.

Then, the particle charge was calculated from the following formula:
\[ m_p \vec{g} = q_p E(r_{p-b}) + \sum_i F_{\text{int}}^i \]  

(1)

where \( F_{\text{int}}^i \) is the Coulomb interaction force between the studied particle \( p \) and particle \( i \), \( r_{p-b} \) the distance from the particle \( p \) to the center of the ball-shaped electrode and \( E(r_{p-b}) \) the field strength at the distance \( r_{p-b} \) \((E(r)=U(r)/r)\). Considering the effect from the trap electrodes on the end electrode field distribution, the equation (1) can be re-written as:

\[ m_p \vec{g} = k \frac{Q_p q_p}{r_{p-b}^{3.34}} + \sum_i k \frac{q_i^2}{r_{p-i}^{3.34}} \]  

(2)

Here \( Q_p \) is the ball-shaped electrode charge corresponding to the potential applied to the electrode \((Q_p = R_b \varphi_b / k)\) and \( r_{p-b} \), the distance between the particle \( p \) and particle \( i \).

The average charge-to-mass ratio was found to be \( q_p/m_p = 6.8 \cdot 10^{-6} \text{ C/kg} \) (\( q_p = 3 \cdot 10^4 \text{ e} \)) with the mean-square deviation \( \sigma = 1.34 \cdot 10^6 \text{ C/kg} \).

4. Conclusion
A new method is proposed for measuring the charge-to-mass ratio of the particles by their confinement in the Paul linear trap with the end electrode added and measuring the particle position over the end electrode.

Specific charge of the particles passing through the corona discharge field with the field strength \( E = 7.7 \text{ kV/cm} \) was found to be \( q_p/m_p = 6.8 \cdot 10^{-6} \text{ C/kg} \) with mean-square deviation \( \sigma = 1.34 \cdot 10^6 \text{ C/kg} \).

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