Spatial separation of particles in modified linear Paul trap

D S Lapitsky
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskayastr. 13 Bd. 2, 125412 Moscow, Russia
E-mail: dmitrucho@yandex.ru

Abstract. Paper presents theoretical investigations of spatial particle separation in modified linear Paul trap. In the simulations two upper electrodes of four of the trap were angled upwards to study particle separation at different geometries (inter-electrode distances) at the same time. To simulate particle motion the Brownian dynamics has been used. Simulations were carried out in the assumption of spherical particles and that particles charges are proportional to particle surface area. In the simulations particles occupied specific lengths according their charge-to-mass ratio.

1. Introduction
Monodisperse particles with known physical parameters are widely used in physics of low-temperature plasma [1–2], in the PIV research methods [3], in nanotechnology [4]. To produce powders of monodisperse particles several methods are used. For an example in [5] monodisperse particles are separated from polydisperse powders by organizing of required particles in standing surface acoustic waves. In [6] particle separation is provided by dielectrophoresis. Particle separation in cyclone devices is widespread and often used to separate both solid and liquid particles from gases [7] and particles with different masses. In experimental facilities RF and glow discharges were used for particle separation [8]. In mass spectroscopy ion separation in vacuum is provided by Paul traps [9]. Ion dynamics in mass-spectrometers is described by Mathieu equation. In air at atmospheric pressure due to the energy dissipation in friction of the air the range of parameters for particle and ion capturing becomes wider [10]. In previous works [11–13] the confinement of microparticles by the alternating electric fields has been studied in static gas media and in gas flows.

The aim of this work is theoretical investigations on the spatial separation of charged particles from polydisperse powder in the linear Paul trap. For that task the trap was modified: two upper electrodes were angled upward to simulate particle separation at different inter-electrode distances at the same time.

2. Mathematical model of charged particle dynamics in Paul trap
To simulate charged particle dynamics in the trap the Brownian dynamics has been used. The simulations took into account stochastic forces of random collisions with neutral particles, viscosity of air, particle interaction with electric fields of the trap, interparticle interaction and the gravitational force. Thus, the microparticle dynamics was described by the following Langevin equation [14]:

$$m_p \frac{d^2 r}{dt^2} = F_I(r) - 6\pi \eta r_p \frac{dr}{dt} + F_b + F_g + F_{int},$$

(1)
where \( m_p \) is particle mass, \( r_p \) is particle radius, \( r \) is the radius-vector of the particle, \( \eta \) is the dynamic viscosity of gas medium (18.2 \( \mu \)Pa\( \cdot \)s [15]), \( F_e(r) \) 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, \( F_{int} \) is the interparticle force of the Coulomb interaction. To solve the stochastic differential equation (1) the numerical method presented in [16] was used.

The Paul trap [17] consisted of 4 cylindrical electrodes with radius \( R_1 = 1.5 \) mm and length \( L_m = 10 \) cm, arranged in the corners of rectangle. The alternating voltage \( U_{\omega} \sin(\omega t) \) with phase shift \( \pi \) was applied to neighboring electrodes. To simulate particle separation at different trap geometries at the same time in the trap two upper electrodes of four were angled, so the vertical interparticle distance varied from \( L_b = 1.3 \) cm to 3.5 cm, while horizontal distances were constant 1.3 cm. The magnitude of alternating voltage was \( U_{\omega} = 10 \) kV and the frequency was \( f = 40 \) and 50 Hz.

3. Results of simulation of charged particle dynamics in Paul trap

In the trap 2000 particles of 9 types were injected. Particles density was 3990 kg/m\(^3\). Simulations were carried out in assumption of spherical particles and particles charges are proportional to the surface area. Next types of particles were used: 400 particles with \( r_p = 1 \mu \text{m} \) and \( q_p = 2500 \) e, other species of 200 particles with \( r_p = 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75 \) and 3 \( \mu \)m and charges correspondingly \( q_p = 3906.25, 5625, 7656.25, 10000, 12656.25, 15625, 18906.25 \) and 22500 e. Results of simulations on spatial particle separation since 30 s after injection are presented in figures 1-3. In figures 1-2 vertical sections of trapped structure 0.2 cm thickness is presented.

In figures 1-2 one can see that particles are spatial separated into layers that correspond to the specific type of particles that can be described by the ratio \( \tau = q_p/m_p \). In all figures the bigger \( \tau \) the higher layer is situated inside the trap. Increasing the interelectrode distance the phenomenon of compartmentation becomes clearer. In figures 1-2 one can see that even particles with the same \( \tau \) arrange in different layers (red dots, \( \tau = 10^{17} \) C/kg). The vertical 2 cm cross section of layers in the center of the trap is presented in figure 3.

![Figure 1](image1.png)

**Figure 1.** Side view of the trap. Spatial particle separation in modified Paul trap, \( f = 40\)Hz, \( L_b = 3.5\)cm.

![Figure 2](image2.png)

**Figure 2.** Side view of the trap. Spatial particle separation in modified Paul trap, \( f = 50\)Hz, \( L_b = 3.5\)cm.
Figure 3. End view of the trap. 2 cm cross sections of particle layers, $f = 40\text{Hz}$, $L_b = 3.5\text{cm}$.

4. Conclusion

Paper presents theoretical investigations of particle separation in modified linear Paul trap. In assumption of spherical particles and that their charges are proportional to the particle surface area it was shown that particles organize in layers subject to their charge-to-mass ratio: the bigger $\tau$, the higher particles are. The linear dependence of particle charge to its surface area can be achieved by particle charging in the corona discharge [18].

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References

[1] Vishnyakov V I and Dragan G S 2003 Condens. Matter Phys. 6 687
[2] Fortov V E, Khrapak A G, Khrapak S A, Molotkov V I and Petrov O F 2004 UFN 174(5) 495
[3] Glushniova A V, Savelieva A S, Son E E and Tereshonok D V 2014 High Temperature 52 N2 221
[4] PriymanV 2002 Mat. Res. Soc. Symp. Proc. T3.3577-585
[5] Rasim Guldiken, Myeong Chan Jo, Nathan D Gallant, Utkan Demirci and Jiang Zhe 2012 Sensors 12(1) 905
[6] Peter R C Gascoyne and Jody Vykoukal 2002 Electrophoresis 23(13)1973
[7] Brouwers J J H1996 Chem. Eng. Technol. 19(1) 1
[8] Pestrikov V V, Grigoriev D A, Vasiliev M M, Petrov O F and Fortov V E 2013 Granada, Spain: 31st ICPiG PS2-081
[9] Mihalcea B M, Visan G T, Giurgiu L C and Radan S 2008 J. Optoelec. Adv. Mater. 10(8) 1994
[10] Lapitsky D S, Filinov V S, Deputatova L V, Vasilyak L M, Vladimirov V I and Pecherkin V Ya 2015 High Temperature 53(1) 1
[11] Lapitsky D S, Filinov V S, Deputatova L V, Vasilyak L M, Vladimirov V I and Pecherkin V Ya 2015 EPL 110 15001
[12] Deputatova L V, Filinov V S, Lapitsky D S, Pecherkin V Ya, Syrovatka R A, Vasilyak L M and Vladimirov V I 2015 J. Phys.: Conf. Ser. 653 012131
[13] Vasilyak L M, Vladimirov V I, Deputatova L V, Lapitsky D S, Molotkov V I, Pecherkin V Ya, Filinov V S and Fortov V E 2013 New J. Phys. 15 043047
[14] Filinov V S, Lapitsky D S, Deputatova L V, Vasilyak L M, Vladimirov V I and Sinkevich O A 2012 Contrib. Plasma Phys. 52(1) 66
[15] Tsilingiris P T 2008 Energy Conversion and Management 49 1098
[16] Skeel R D and Izaguirre J A 2002 Mol. Phys. 100 3885
[17] Paul W 1990 Reviews of Modern Physics 62 531
[18] Syrovatka R A, Deputatova L V, Filinov V S, Lapitsky D S, Pecherkin V Ya, Vasilyak L M, and Vladimirov V I 2016 Contrib. Plasma Phys. 56 419