Compression and stretching of Coulomb structures in a linear electrodynamic trap by an electric field

R A Syrovatka, L V Deputatova, V S Filinov, D S Lapitsky, V Ya Pecherkin, L M Vasilyak and V I Vladimirov
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: syrovatkara@gmail.com

Abstract. A method of the controlled effect by the electric fields on Coulomb structures in the linear electrodynamic trap for the controlled compression and stretching of these structures was proposed. The obtained images of the Coulomb structures at various frequencies of effect by rectangular pulses of the electric field are presented. Such effects can be used to obtain the thermodynamic properties of the Coulomb structures by the statistical method.

1. Introduction
The electrode systems generating a quadrupole electric field allow hanging the charged particles in a well-defined region of space without contact with the wall of a container. These kinds of devices are known as electrodynamic traps. Electrodynamic traps a commonly used to measure the detailed properties of individual charged particles in the 100 nm to 100 µm size range. The process of freezing of supercooled water droplets was studied in [1]. Fluorescent emission from a single aerosol particle was measured in [2]. Mass spectra of ensembles of polystyrene microspheres and diamond nanocrystals were obtained in [3]. Electrodynamic particle confinement has been used in biology for studying the properties of microorganisms and individual cells [4]. Electrodynamic traps can be used to creating Coulomb structures of aerosol particles at atmospheric pressure [5]. The charges and the masses of single Al₂O₃ particles confined in the linear electrodynamic trap were measured. In [6] Coulomb structure consisted of about three thousand Al₂O₃ particles was confined in the linear electrodynamic trap at the atmospheric pressure.

The trapped particles with the same sign can form strongly correlated Coulomb systems. In such systems potential energy of interparticle interaction exceeds average kinetic energy of the particles. The study of the properties of these systems is an actual problem for improving the efficiency of capturing and confining of the Coulomb systems in the electrodynamic traps. Different Coulomb systems, e.g. dusty plasma, colloidal fluids, soft matter, and others, are actively investigated at various conditions. Their energy states, thermodynamic properties, interactions, waves, oscillations, reactions to external electric and magnetic fields, laser radiation and temperature gradients are being studied. A number of such studies of various effects were performed in dusty plasmas. Coulomb structures in the electrodynamic trap are the systems of the charged particles with the same charge sign without a plasma. Studies of the effects on such structures have not been done enough. In [7] an ensemble of the charged particles in the linear...
quadrupole trap was effected by the sound waves. Authors measured frequency of the sound waves and oscillations of the particles. Moreover, the natural frequencies of the Coulomb system were determined. Investigations of the effect of electric fields at the Coulomb structures in the electrodynamics trap are interesting, due to there is no neutralizing plasma background as in the dusty plasma. It is possible to compress or stretch the Coulomb structures, and then, using Brownian dynamics and the statistical theory of the liquid state, calculate the thermodynamic quantities of a strongly nonideal Coulomb structure trapped in a linear Paul trap in air at atmospheric pressure. In this way, one can study the dynamics of the internal energy of the Coulomb system, its pressure on the trap, and calculate the nonideality parameter.

The purpose of this work was to create a method for controlled electric field effect to Coulomb structures in a linear quadrupole trap and to investigate the possibility of compression or stretching of such structures.

2. Experimental setup

The electrodynamic trap consisted of four cylindrical horizontally oriented electrodes placed in vertices of a square with a side of 2 cm. The electrodes length was equal to 10 cm and the diameter was equal to 4 mm. The sinusoidal voltage in opposite phase between adjacent electrodes was applied on the electrodes. The voltage amplitude usually was equal to 4.5 kV and the frequency was equal to 50 Hz. Figure 1 shows schematic diagram of the power supply of the electrodynamic trap.

The oscillations were excited by rectangular electric pulses applied to the additional electrodes, which were located at the ends of the trap. The distance between these electrodes was equal to 5 cm. The pulses amplitude was varied from 10 to 320 V. The pulses frequency was varied from 1 to 20 Hz. Relative pulse duration could be adjusted from 0.01 to 0.99. The scheme of the trap is presented on figure 2.

A generator of rectangular pulses was made especially for this work. The collectors of the two transistors working in a switch mode were used as outputs. Transistor switches were controlled by symmetrical trigger. Switching was performed by applying a signal from a master oscillator. Control signals to transistor switches could be supplied in phase or antiphase. Figure 3 shows scheme of the pulse generator.

Polydisperse Al₂O₃ particles were used in this work. The charging of the particles was carried out by the induction method. The particles were placed on the flat electrode. The electrode was moved to the electrodynamic trap. Then, a positive electric potential was applied to the electrode. When the potential was more than 5 kV, the particles flew up and were drawn into the trap.
Figure 2. Scheme of the linear electrodynamic trap: 1—trap electrodes; 2—dust particles; 3—generator of rectangular pulses.

Figure 3. Scheme of the pulse generator.

The motion of the particles was recorded using a charge-coupled-device camera HiSpec1 With a maximum resolution of 1240 × 1024 pixels. The camera allowed us to record video at up to 524 frames per second at the maximum resolution. Illumination of the particles was performed by a flat horizontally oriented laser beam with a thickness of 1 mm. We used a laser with a wavelength of 532 nm and output power up to 150 mW.

3. Experimental results
Figure 4 shows compression and stretching of the Coulomb structure in the linear electrodynamic trap for different values of pulse frequency. The trap voltage was equal to 4.5 kV. The amplitude of the pulses was equal to 320 V. The relative pulse duration was equal to 0.5. The pulses were in phase. With increasing frequency, the amplitude of the oscillations was reduced down to almost undetectable at 20 Hz; the oscillations cease to affect the middle region of the structure. At a frequency of 1 Hz, the structure at the moment of maximum compression corresponds to the structure at a constant potential at the additional electrodes.
Figure 4. Coulomb structure of Al₂O₃ particles of 20 to 40 µm in size in the linear electrodynamic trap at the moments of greatest compression (b, d, f) and stretching (a, c, e): (a, b) pulses frequency was equal to 1 Hz; (c, d) pulses frequency was equal to 5 Hz; (e, f) pulses frequency was equal to 9 Hz.

4. Conclusion
The proposed method of electric field effect on Coulomb structures in the linear quadrupole trap turned out to be effective for controlled effects on the structures. Data on dynamic compression and stretching have been obtained for the first time. This method perhaps will allows one to investigate the thermodynamic quantities of the Coulomb structures in the linear traps.

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