The internal energy of micron-sized particles confined in the electrodynamic trap

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Abstract. The Coulomb structure of glassy carbon particles was investigated in the linear quadrupole electrodynamic trap. The pair correlation function was constructed. The specific energy of the particles in the structure was calculated from the statistical theory of the liquid state of matter.

1. Introduction

Coulomb structures are ensembles of charged particles interacting with each other by electric forces. Strongly correlated structures of charged particles obtained in low-pressure gas discharges demonstrate such phenomena as phase transitions, waves and instabilities of various nature [1]. It is possible to confine charged particles using variable electric fields in the Paul’s electrodynamic traps [2]. One of the first experimental observations of Coulomb structures in the electrodynamic traps was carried out in the late 1950s [3]. In that work [3], a mixture of iron and aluminum particles of micron size was confined in vacuum using the classical Paul trap, which is a ring in the form of a hyperboloid of revolution with two caps with a hyperbolic surface. In 1991 the Coulomb structure of anthracene particles was confined in the classical Paul trap at atmospheric pressure [4]. In work [5], mathematical simulation of the dynamics of charged dust particles in a linear quadrupole electrodynamic trap was carried out at atmospheric pressure; the regions of stable confinement of a single particle and the maximum number of particles trapped by the trap were determined. At present, the possibility of using electrodynamic traps in air filtration systems is investigated [6]. Electrodynamic traps can be used in studies of atmospheric aerosols [7].

The aim of this paper is to study Coulomb structures in the linear electrodynamic trap using an analysis of pair correlation functions.

2. Experimental setup

In the present work, the horizontally-oriented linear quadrupole electrodynamic trap was used. The electrodes of the trap were made of steel rods 3 mm in diameter and were located at a distance of 2 cm from each other. The length of the trap was equal to 10 cm. At the ends of the trap the additional electrodes supplied with a constant electric potential of 300 V were placed. The electrodes prevented the particles from expanding in the axial direction. Spherical
particles of glassy carbon with a diameter of 10 to 20 µm were used. After charging in a corona discharge [8], the particles were injected inside the trap. The video registration of dust particles was carried out using a HiSpec 1 video camera. The shooting speed coincided with the frequency of the alternating voltage of the trap, which allowed us to weed out the micro-vibrations of the particles. The particles were illuminated by a plane laser beam with a thickness of 0.25 mm.

3. Results

Figure 1 shows the Coulomb structure of particles of glassy carbon in a horizontally-oriented linear trap: amplitude of the ac voltage $U_A$ applied to the trap was equal to 2.6 kV while frequency $f = \frac{\omega}{2\pi}$ was equal to 50 Hz.

Larger particles are concentrated in the central part of the structure and perform small oscillations near the equilibrium position, while smaller particles are arranged in the edge regions. In these regions, in addition to the micro-oscillations, the particles made chaotic motion. A pair correlation function was constructed directly for this part of the structure (limited by dashed lines in figure 1) by processing two hundred frames. The pair correlation function in figure 2 was constructed for each frame, after which each discrete value was averaged.

The pair correlation function has the first peak of a small height, which is atypical. The presence of an atypically small first peak of the pair correlation function may be due to the heterogeneity of the particle structure. The force that keeps the particles trapped decreases with the distance from the center of the trap, which leads to enlargement of interparticle distances.

Information about the pair correlation function makes it possible to calculate the thermodynamic quantities of the Coulomb system, for example, the internal energy. In work [9],

Figure 1. Coulomb structure of the glassy carbon particles with sizes from 10 to 20 µm. $U_A = 2.6$ kV, $f = 50$ Hz. The dashed lines denote the part of the structure used to plot the pair correlation function.
using mathematical modeling methods, the pair correlation function was obtained for particles confined in the linear electrodynamic trap. The internal energy of the system was calculated from the statistical theory of the liquid state of matter [10]:

\[
E = N \left( \sum_{i=1}^{N} \frac{\dot{m}_i^2}{2N} + \frac{2\pi}{S} \int_{0}^{\infty} \Phi(r)rdr \right),
\]

where the first term denotes the kinetic energy of the system, which can be neglected, \(N\) is the number of particles in a circle of radius \(R\), \(S = \pi R^2\) is the area under analysis, \(R\) is the half of the characteristic size of the region, which is bounded in figure 1 by dashed lines, \(\Phi(r)\) is the pair interaction energy.

For the experimental conditions described above, we obtain the energy per particle \(E/N = 6 \times 10^{-17}\) J.

4. Conclusion
For the structure of glassy carbon particles confined in a linear electrodynamic trap, the pair correlation function with the atypically low first peak has been obtained. Using the methods of the statistical theory of the liquid state of matter, the specific energy of the particles was calculated.

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