

Local structural properties of dusty plasma systems based on an analysis of three- and four-particle correlations

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Abstract. We present the results of an experimental study of many-body correlations (three- and four-) of three-dimensional dust formations, confined in the plasma of high-frequency capacitive discharge. The analysis of dusty plasma system, based on the reconstruction of three coordinates of dust particles using the method of binocular observation, has been made for the first time. The obtained experimental results are compared with the superposition approximation.

1. Introduction

Dusty plasma is an ionized gas, consisting of charged solid macroparticles of micron sizes. It is ubiquitous in nature (in space, in planetary atmospheres, etc.) and often appears in a number of technological processes [1]. Levitation of dust particles and the formation of ordered dusty plasma structures has been observed in the plasma of various types: thermal plasma of a flame [2, 3], nuclear-induced plasma [4], in gas discharges of various types [5–8]. Depending on the experimental conditions, such structures can be close to the homogeneous quasi-two-dimensional structures (monolayers) as well as three-dimensional systems, which can form for example several layers in the near-electrode area of rf discharge. Dust particles in contrast to atoms of real liquids and solids can be resolved as separate objects in the direct observation by naked eye, allowing to study in these imperfect systems the processes, such as phase transitions, wave propagation, the instabilities of various types, on the kinetic level, i.e. to study the behavior of individual particles. To describe the crystal structure analytically, a general formula for the lattice sites is commonly used. However, the appearance of distortion always breaks a particular symmetry, and classical approaches can become unsuitable for describing weakly correlated and non-crystalline systems [9]. In this case, one can use three- and four-body correlations to describe the structure of various disordered systems, which provide additional information about the properties of analyzed dusty plasma systems.

2. Experiment and obtained results

Figure 1 shows a schematic illustration of the experimental setup, the main element of which is a discharge chamber with optical windows needed for exposure on dusty plasma system and its visualization. There are two flat horizontally oriented electrodes, placed in the vacuum chamber



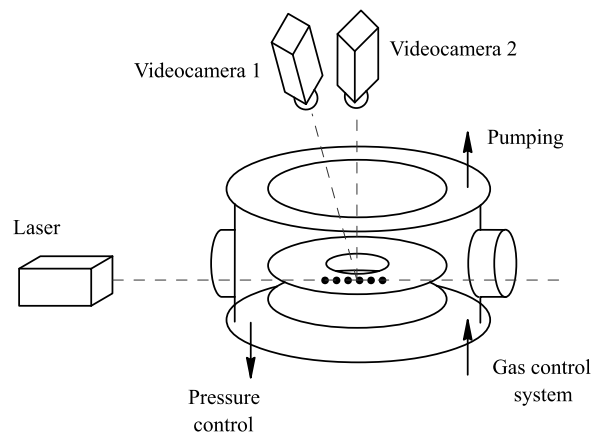


Figure 1. Scheme of the experimental setup.

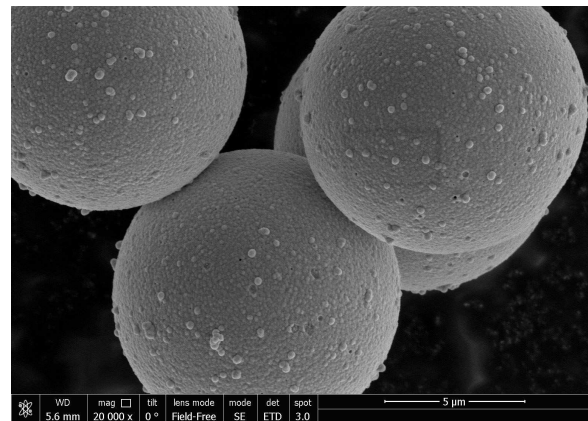


Figure 2. Photo image of macroparticles, used in the experiments, obtained from electron microscope.

for plasma generation. Through the central hole of the upper electrode, we injected dust particles (figure 2) in the discharge volume, and observed the formation of dusty plasma structures. Horizontal positioning of the electrodes has been achieved with the help of micrometer screws. In order to form the potential trap and to prevent a leaving of dust particles from the plane of view due to the mutual repulsion, we installed a metal ring with a diameter of 51 mm at the surface of the lower electrode. The electrodes via impedance-matching device has been connected with the high-frequency generator with a carrier frequency of 13.56 MHz. Applying a voltage to the electrodes resulted in generation of a radio frequency capacitive discharge in a high vacuum chamber.

A power of high-frequency generator producing the gas discharge was 12 W. In our experiments, we used argon as a buffer gas at a pressure of 0.1522 mbar. For this, the discharge chamber was preliminarily pumped out by the vacuum system consisting of connected in series forevacuum and turbomolecular pumps. The pressure in the chamber was monitored with the help of a capacitive sensor. In order to maintain a stable composition of the atmosphere of the discharge chamber during the experiment, argon blow was carried out at a rate of 4 SCCM.

The main elements of the diagnostic equipment of the experimental setup were two high-speed cameras, an argon laser, and a personal computer with specialized software package for particle detection, video recording and video processing. Visualization and exposure to dust particles levitating in the sheath of an RF discharge was carried out by applying the laser illumination with power varied from 0.4 W to 3.1 W. Operating wavelength of argon laser was 514 nm. Optical scheme of diagnostic equipment included plano-cylinder lens, telescope, parallel-sided plate and diaphragm, mounted on an optical table. A positive plano-cylinder lens formed a flat laser beam (so called laser “knife”), the thickness at the neck of which was from 150 to 250 microns. This expanded through a telescope light beam was passed through the diaphragm to create uniform intensity profile of the laser radiation. Parallel plate was used to control the height of the laser beam, which could be changed depending on the height of the levitating of dust particles in the near electrode region of RF discharge.

Using the video cameras, we monitored dusty plasma structures, and recorded the dynamics of the motion of individual dust particles with a frequency of shooting 200 frames per second. Cameras were placed at an angle of 22 degrees to each other producing an optical circuit for reconstruction of three coordinates of the particles based on the principle of binocular vision. The spatial resolution was 0.017 mm/pixel. The error of particle position detection was 0.01

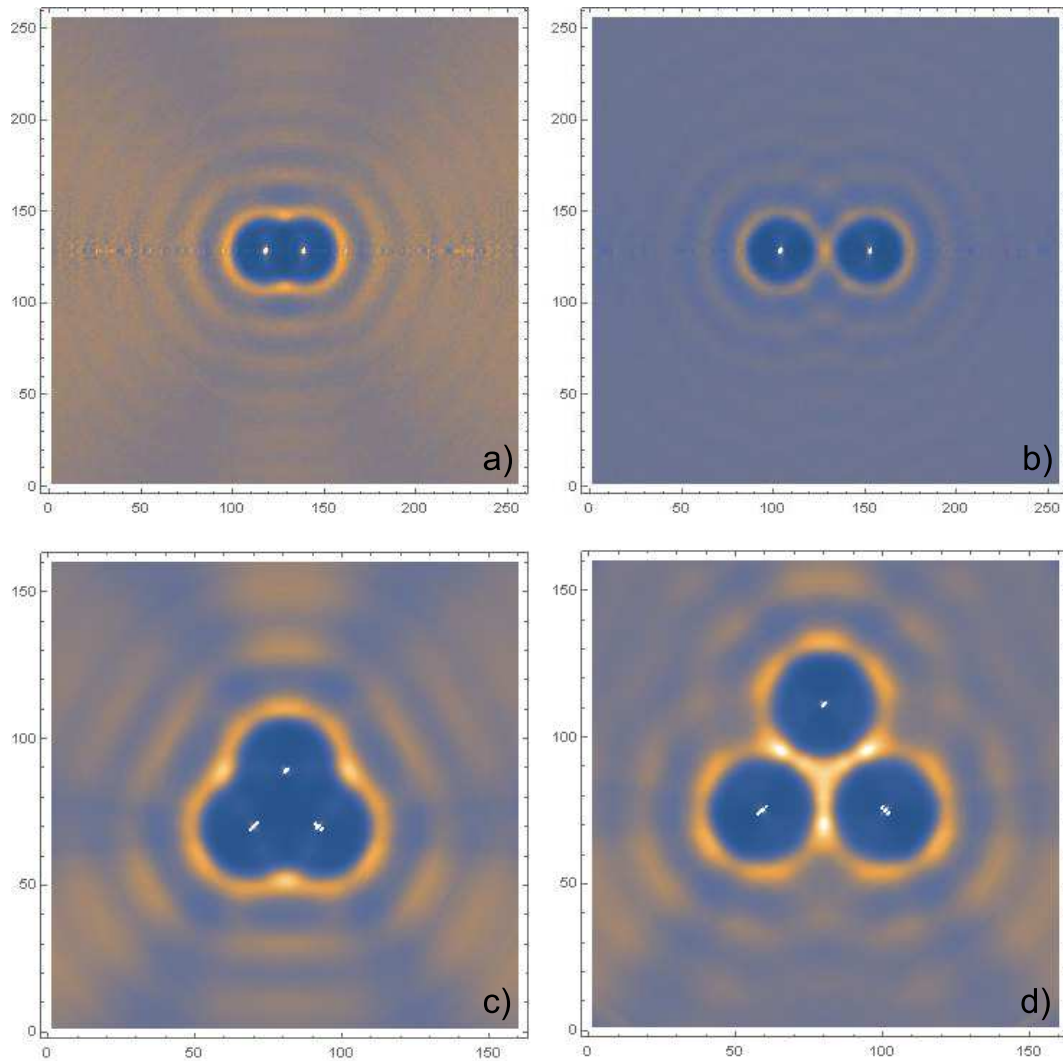


Figure 3. a, b—graphic images of the three-particle correlation function with a fixed distance between two particles, corresponding to the mean interparticle spacing in the dust structure l_p and $2l_p$, respectively. c, d—graphic images of the four-particle correlation function with a fixed distance between three particles, corresponding to the mean interparticle spacing in the dust structure l_p and $2l_p$, respectively.

mm for the horizontal plane and 0.03 mm for vertical one.

Proper reconstruction of trajectories of dust particles and their velocities is impossible without an accurate method of determining the coordinates of the particles. In the present study, we used a specially developed algorithm based on Fourier filtering method which allows to determine the coordinates of particles with sub-pixel accuracy, as well as to improve the accuracy of determining the displacement of particles by several times, and completely eliminate the so-called effect of pixel locking (i.e. systematic error of detection typical for recognition methods with sub-pixel accuracy, at which the reconstructed particle coordinate is shifted compared with the true value to the nearest integer value).

Firstly, the video was divided into separate frames for the purpose of a consequent processing of images of dust particles and identifying their positions on the video frame. Further

preprocessing was carried out to eliminate motion backlight and various noises (so-called “background subtraction”) caused by induced external alternating electric fields, statistical fluctuations, dispersion of parameters of photosensitive CCD elements, etc., which lead to specific distortions of the observed patterns. Then particle detection on video frame was carried out, by varying the threshold of the brightness, contrast, and the factors that determine the form of the Fourier-functions to maximize the correspondence between the coordinates of the dust particles, determined by eye, and those ones, determined with the help of various program search algorithms. In each case, the set of the parameters of the particle search (contrast, brightness threshold, the function profile for the Fourier filtering, etc.) was selected individually depending on the nature of the detecting noise and experimental parameters.

Based on analysis of the information about the coordinates of the particles, we built many-body correlation of the position of dust particles. For a determination of the local structure of a polycrystalline or liquid system, it is not enough to have only the information, derived from a triple distribution function, as it is rather indirect data (figure 3 a, b). For a complete description of local order, it is necessary to consider the four-particle distribution function (figure 3 c, d).

The experimental results are in good agreement with three- and four-particle approximation, obtained from superposition approach. Deviations of the results for many-body correlations of the analyzed system from those of the superposition approximation do not exceed 20%.

3. Conclusions

In our work, we present the results of an experimental study of many-body correlations (three- and four-) of three-dimensional dust formations, confined in the plasma of high-frequency capacitive discharge. The analysis of dusty plasma system, based on the reconstruction of three coordinates of dust particles, using the method of binocular observation, has been made for the first time. The obtained experimental results are compared with the superposition approximation.

Acknowledgments

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