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Dust crystals in plasma created by a proton beam

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Abstract

In this work we present the first observations of dust crystal generated in plasma by the slowing-down proton beam. The crystal observed has a simple cubical lattice with the mean distances between particles for different gases (He, Ne, Ar, Kr, Xe) from 90 μm to 140 μm. For calculation of plasma parameters the model of kinetic processes was developed. Results of our simulation showed that anisotropic dust particles interaction can be the main physical reason for the appearance of the crystal-like structure.

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1. Introduction

Self-organization of a dust component in the plasma containing specially introduced micron-sized particles (dust) is of growing interest now [1]. This is due to unusual properties of the dusty plasma as well as due to possibilities of performing experiments in which processes leading to a formation of ordered structures of liquid or crystalline type can be observed visually and studied at the kinetic level. The dusty structures of the crystalline type have been discovered in the gas-discharge plasma [2]. These experiments gave a powerful impulse for the next studies of dusty plasmas under the Earth laboratory conditions as well as under microgravity conditions [3]. Most frequently, inert gases are used for experiments when initially a gas discharge of some kind is initiated and then dust grains are inserted into the ionized medium. At the same time the ionized medium can be created by fast charged particles incoming with the initial energy E from external source into gas. In the slowing-down process in gas, a non-equilibrium plasma is formed in the area of charged particle track with an expressed non-homogeneity in space and fast recombining in time. The medium molecule ionization results in the appearance of the first generation electrons, some parts of them having energy sufficient for ionization of other atoms. Thus the spectrum of electrons

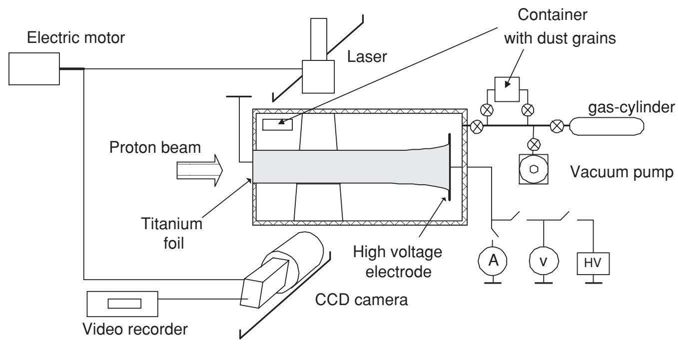

Figure 1. The experimental setup.

is formed, including electrons of all subsequent generations. This spectrum has a non-equilibrium character with a non-Maxwellian electron velocity distribution. When getting into dust particles, electrons are absorbed, as a result grains acquire negative electric charge and attract positive ions. However, because of a high mobility of electrons, dynamic equilibrium between the electron and ion flows is established at the negative charge of dust grain. This charge, at a high energy of electrons, can be large enough for the plasma to become highly non-ideal for the dust component, which forms the conditions for its crystallization. The process of dust structure formation in nuclear-induced plasma formed by fission fragments and alpha-particles flying out of radioactive source of ^{252}Cf was studied in [4–6]. It was shown that in this medium, under specific conditions, the vortex and quasi-stationary dust clouds of liquid type are formed. In this work, we present the first observations of dust crystal generated in the plasma by the slowing-down proton beam.

2. The experiment

The experiments have been performed for different gases (He, Ne, Ar, Xe, Kr). Electrostatic proton accelerator has been used for the experiments. The experimental cell had the form of a rectangular parallelepiped with a basement of 16×16 cm^2 and a height of 12 cm (figure 1). The cell's side faces were made as glass windows, the dust structure behaviour was observed by CCD camera registering the light scattered by dust particles. Horizontal proton beam with an energy of 2 MeV was passed via titanium foil and a diaphragm of 8 mm diameter. Monodisperse melamine–phenol particles with radii R of 0.505, 0.875, 1.50, 2.41 and 2:75 μm were used in the experiments. The gas–dust mixture at the required pressure was created in the cell after pumping by high vacuum pump.

3. Results of the experiments

The dust grains' behaviour proved to depend on gas pressure considerably, whereas the dependence on its type was weak. Principal results of the experiment are as follows. After pumping the gas–dust mixture into the cell, a gas pressure of about 25 Torr was established. Near the high-voltage electrode, in the paraxial area of the proton beam, a dense dust grain structure was formed with an initial density of 5×10^6–10^7 cm^{-3}. The process of dust structure formation in the proton beam takes about 2–3 s. The dust structures have a cylindrical symmetry in equilibrium with the maximum diameter 8 mm approximately coinciding with

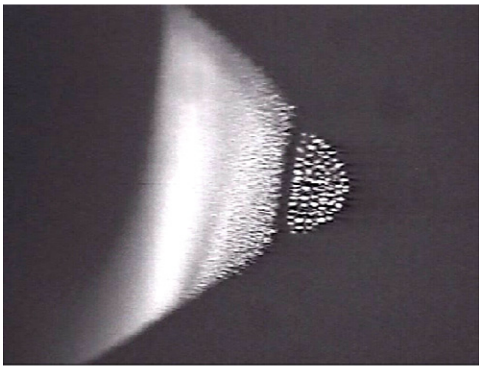

Figure 2. Crystallization of the dust structure. Gas—krypton, particles diameter—3 μm, gas pressure—1 Torr, voltage on a main electrode—140 V, beam current—3 μA.

the beam diameter. The structures can exist for 10 min or more at the same pressure. The structure is destroyed when the proton beam is closed or when the voltage applied to the high-voltage electrode is decreased or turned off.

We reduced pressure by pumping of the cell with a low pumping velocity. Dust structures were divided into two separate areas with different dust concentrations and different characters of dust grain movement. At a gas pressure less than several Torr the dust component is crystallized at a distance of $\approx$1 cm from electrode (at the dust structure faces turned to the high-voltage electrode) (figures 1 and 2). Crystal-like structures have been obtained for all types of gases used in the experiment and for particles of different diameters. The crystal observed has a simple cubical lattice with the distance between particles from 90 μm in He to 140 μm in Kr and Xe. 3D particle positions have been measured by moving laser and CCD camera. An example of the cross section of observed crystal is shown in figure 2. Charge fluctuations of the dust grains as well as collisions of plasma particles with grains and buffer gas friction stabilize the energy of the dust subsystem but may not be on the lowest level. Focusing action of the negative dust grains on the ion fluxes directed to the negative high-voltage electrode results in anisotropy of dust particle interaction. The gravity and interaction with the dust particles space trap created by high-voltage electrode and positive space charge within the proton beam as well as the physical factors mentioned above may be the reasons for the appearance of cubic crystal with no minimum energy configuration. For practical purposes most of the experiments were done for structures created in Kr (figure 2). The 2D radial distribution function (figure 3(*b*)) obtained by treatment of 15 slides has some maxima. The first maximum corresponds to the average distance between particles = 140 μm, the second one corresponds to the distance $\sqrt{2}a$. The third maximum was a result of overlap picks for mean distances $2a$ and $\sqrt{5}a$, the fourth maximum was a result of overlap picks for mean distances $\sqrt{8}a$, $3a$, $\sqrt{10a}$ and the fifth one corresponds to the mean distance $\sqrt{13}a$. Such distribution attributes to simple quadrate lattice. The total particle number in the crystal (figure 3) is equal to 460. The relative distance fluctuations were equal to 0.08 in agreement with the Lindemann criterion.

4. Mathematical simulation

A kinetic model has been developed accounting for dust particle charging by proton beam [7]. The self-consistent calculated density of atoms, molecular ions and excited atoms as well as

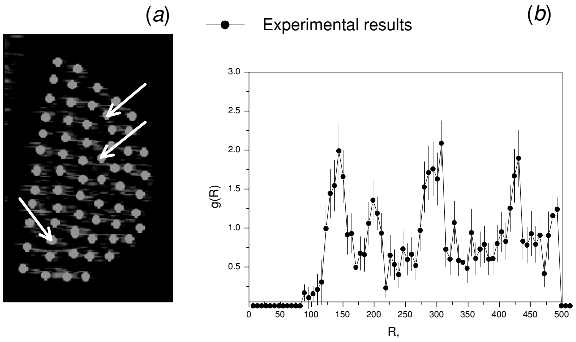

Figure 3. (*a*) The computer image of the dust crystal (figure 2). The arrows show particles inculcated into the lattice. The crystal size is 1.7×0.83 mm^2. The average distance between the particles is 140 μm. (*b*) 2D radial distribution function—particle number at some distance from the selected particle.

the electron energy distribution function allows one to estimate such significant dusty plasma parameters as the charges of dust particles Z_d, screen length λ_D and coupling parameter Γ. Under typical experimental conditions for different gases Z_d was in the interval 500–1000 elementary charge units, λ_D was in the interval 100–250 μm and Γ lies between 200 and 500. For example, the crystal (figures 2 and 3) have $Z_d = 970$, $\lambda_D = 210$ μm and $\Gamma = 390$.

A mathematical model has been developed to take into account the dust grain screening by plasma particles, the dependence of dust grain's charge on its space position and anisotropy of dust grains' interaction associated with the drift ion flux focusing. To simulate the crystallization of the dust particle system we invoke the 3D Brownian dynamic method (for details see [7]).

5. Conclusion

In this work we present the first observations of dust crystal generated in plasma by the slowing-down proton beam. General results of the experiment are as follows. By reducing the gas pressure in the experimental cell to less than several Torr the dust component is crystallized at a distance of ≈1 cm from the electrode at the dust structure faces turned to the high-voltage electrode. The process of dust structure formation has a weak dependence on the gas sort. The crystal observed has a simple cubical lattice with the mean distance between particles of 90 μm in helium and 140 μm in krypton and xenon. Crystal structures have been obtained for all types of gases used in the experiment and for particles of different diameters.

A mathematical model for the proton beam plasma with dust particles has been developed. Results of our simulation showed that the anisotropic dust particles interaction might be the main physical reason for the appearance of the crystal-like structure. The results of calculation of dust grains charging demonstrate creation of non-ideal plasmas due to strong interaction between dust grains. Coupling parameter Γ achieves up to some hundreds.

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