Localization of active particles in chain structures in a direct current discharge under external influence

E A Kononov\textsuperscript{1,2}, M M Vasiliev\textsuperscript{1,2} and O F Petrov\textsuperscript{1,2}

\textsuperscript{1} Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
\textsuperscript{2} Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141701, Russia
E-mail: gadvin@yandex.ru

Abstract. We present the results of the analysis of the trajectories, dynamic entropy, and root-mean-square displacement of moving copper particles in a cluster of chain structures when exposed to laser radiation. We have revealed that the dynamics of the particle motion in the cluster corresponds to three modes: motion in a localized area, Brownian motion, and combined directional chaotic motion. The results of the analysis of linear displacement along and across the direction of motion of dust particles at various values of the laser radiation power are presented. It has been shown experimentally that copper particles are active Brownian particles and their activity grows with increasing laser radiation power, leading to a structural phase transition with the exchange of chain fragments within the cluster.

1. Introduction

Today, the study of dusty plasma systems is an actively developing interdisciplinary field of science related to plasma physics and astrophysics, fluid mechanics and material science, theories of open systems and active matter, which is confirmed by numerous experimental and theoretical studies [1, 2]. Dusty plasma is a thermodynamically open, dissipative system that can exist in various states, including liquid and crystal ones, as well as form anisotropic three-dimensional (including quasi-one-dimensional and quasi-two-dimensional) structures [3].

Under the influence of laser radiation, the metal surface of the particles is heated and the radiometric force begins to act on the particles [4]. In work [5], it was shown that microparticles with a metal cover, being in gas discharge plasma under the action of a radiometric force induced by laser radiation, are active. Moreover, the efficiency of converting energy from the external resource into kinetic energy of translational and rotational Brownian particle motion is controlled by the power of laser radiation [6]. This most important result opens a new direction in the study of dusty plasma systems related to phase transitions in active particle systems. To analyze phase transitions, an approach based on calculating the dynamic entropy of an open dissipative system of interacting particles can be used [7]. To calculate the dynamic entropy, a simple approximation is used, which can be easily used for the analysis of experiments and numerical simulation [8].

Thus, the study of the localization of metal particles in chain structures in a direct current discharge, depending on the intensity of the external action, is of undoubted interest.
2. Experimental details

The experiments on the localization of particles in chain structures were carried out in a gas discharge glass tube with a length \( l = 450 \text{ mm} \) and an inner diameter \( d = 40 \text{ mm} \). The lower end of the tube was sealed and the cathode was located in it, the upper part of the tube was connected to a continuous pumping system and the anode was located there. The tube was pumped out and filled with inert gas neon to a working pressure of \( P = 16.67 \text{ Pa} \), which was supported by a continuous supply of working gas at a speed of 0.4 standard \( \text{cm}^3/\text{min} \), after which a direct current discharge was generated between the anode and cathode at the following parameters: voltage \( U = 1.178 \text{ kV} \) and current \( I = 0.4 \text{ mA} \). During the experiment, a cluster of chain structures was formed in one of the strata of the positive discharge column, consisting of polydisperse copper particles with an average diameter of 2.5 \( \mu \text{m} \) (figure 1), and the maximum chain length was 16 particles.

To visualize and influence the formed cluster of chain structures, we used a uniform expanded beam of a solid-state laser with a diameter of 30 mm passing through the glass bottom of the tube. During the experiment, the laser radiation intensity gradually increased (in the range from 79 to 980 mW), which led to the kinetic heating of dust particles. In this case, the vertical arrangement of particles in the structure was not violated, which was evident when observing the structure.

The movement of dust particles was recorded in the vertical plane using a high-speed video camera with a video recording frequency of 200 fps and a spatial resolution of 13.2 \( \mu \text{m/pixel} \). The resulting video images were processed using special computer programs, which enabled us to determine the coordinates of the particles for each moment of time, their trajectory and speed, the mean square displacement and dynamic entropy for each dust particle in the structure, as well as linear displacement along and across the direction of movement of dust particles.

Using well-known thermodynamic functions in terms of description of the phase state for small systems is not relevant. Therefore, to analyze the degree of system chaotization, we used the dependences of dynamic entropy on the coarsening parameter.

In this work, a simple approximation—a simple approximation of Kolmogorov–Sinai entropy is considered, which can be easily used for analysis of experiments and numerical simulation—“mean first-passage time” (MFPT) dynamic entropy [9]. Provided that the spatial scale (coarsening parameter) is not too small, the dynamic entropy can be approximately calculated as following: at time \( t = 0 \) we circle around the particle a sphere of radius equal to the coarsening parameter centered at the particle’s location and then determine the time moment \( \tau \), in which the particle trajectory first reaches a predetermined threshold value. The inverse “time of the first intersection” will be equal to the MFPT dynamic entropy \( S(\varepsilon^*) \equiv 1/\tau(\varepsilon^*) \). Thus, the dynamic entropy \( S(\varepsilon^*) \) is a measure of the average “runaway velocity” of a particle from its initial position [10]. It should be noted that this value can be calculated for each individual particle of the system but it requires a sufficient spatial and temporal resolution of the video recording equipment, as well as sufficient shooting time.

3. Experimental results

Figure 2 illustrates a typical example of obtained the trajectories of dust particles in a cluster of chain structures at different values of power of a heating laser.

With a laser radiation power of up to 225 mW, the dynamic entropy of a chain cluster consists of two “beams” corresponding to the upper part where the particles are solitary and the lower part containing several chains. In this case, the “beams” of dynamic entropy are scattered, and the chain structures in the cluster are stable and the particles move slowly in the vicinity of their equilibrium positions [figure 3(a)]. As the laser power increases to 380 mW, the particles leave their potential wells and begin to move inside the shells of the chain structures, and the “beams” of dynamic entropy begin to merge into one [figure 3(b)]. With a further increase in
Figure 1. Illustration of a video image of a cluster of chain structures formed in one of the strats of the positive column of a direct current discharge in neon at a pressure of 16.67 Pa, a voltage of 1.78 kV and a current of 0.4 mA.

Figure 2. Trajectories of dust particles in a cluster of chain structures during 10 s at different values of laser radiation power: $W_{\text{las}} \approx 156$ (a), 380 (b) and 950 mW (c).

The intensity of laser radiation to 980 mW, the chains begin to “exchange” particles, and the “beam” of dynamic entropy, with values of the coarsening parameter from 0.01 to 0.1, has an inflection, and the section after the inflection becomes uniform again and corresponds to the diffusion regime of particle motion [figure 3(c)].

To analyze the dynamic characteristics of the dust system, we calculated mean square displacement of moving dust particles in a cluster of chain structures depending on time at different values of laser radiation power (figure 4).
Figure 3. Dynamic entropy of each dust particle in a cluster of chain structures at different values of laser radiation power: $W_{\text{las}} \approx 156$ (a), 380 (b) and 950 mW (c).
Figure 4. Mean square displacement \( \langle r^2 \rangle \) of macroparticles in a cluster of chain structures as a function of time for various values of the laser radiation power: \( W_{\text{las}} \approx 156 \) (a), 380 (b) and 950 mW (c).
Figure 5. Linear displacement $L$ during Brownian motion of particles with a modified surface along and across the direction of motion for various values of the laser radiation power $W_{\text{las}}$: circles—linear displacement along the direction of movement; squares—linear displacement across the direction of movement.

At low power of the laser radiation ($< 225$ mW), there is a limited movement of dust particles over a long period of time [$t > 0.1$ s, figure 4(a)], which means the confining of macroparticles in potential traps. An increase in the intensity of the laser radiation ($> 380$ mW) leads to a growth of the mean square displacement of the moving dust particles, which means a decrease in the coupling between charged dust particles in the chain structures. Moreover, the diffusion of dust particles in chain structures at short time scales [figure 4, $t < 3$ (b) and 7 s (c)] is abnormally high $\langle r^2 \rangle = 2Dt \propto t^2$ and $\propto t^{3/2}$, which corresponds to ballistic and transitional modes of anomalous diffusion. But for large time scales [figure 4, $t > 3$ (b) and 7 s (c)], the experimental data are consistent with normal diffusion $\langle r^2 \rangle = 2Dt \propto t$, which means that time spent by dust particles in this mode decreases with increasing laser radiation power.

So, the dynamics of particle motion in a cluster of chain structures depends on laser radiation power and exhibits three patterns of behavior: confining in a potential well, Brownian motion and combined directional chaotic motion consisting of laser-induced (photophoresis) and Brownian motion, which is consistent with the results of dynamic entropy analysis.

To analyze the nature of the Brownian motion of particles in a cluster of chain structures, we constructed a linear displacement along and across the direction of motion for various values of the laser radiation power $W_{\text{las}}$ (figure 5).

It has been found that with an increase in the power of the acting laser radiation, the linear displacement along the direction of motion of the macroparticles grows and has a maximum at 380 mW, which can indicate an increase in activity with increasing laser radiation power. However, when the laser radiation power exceeds 380 mW, the linear displacement along the direction of motion of the particles decreases to the initial values and reaches a plateau, which can be explained by the energy expenses of the particles to break the potential barrier and jumps between the chain structures inside the cluster. At the same time, the linear displacement perpendicular to the particle velocity vector remains constant and is close to 0 within the error. Thus, we can conclude [11] that copper particles in a cluster of chain structures are active.
Brownian particles, their activity grows with increasing the power of laser radiation, leading to a structural phase transition with the exchange of chain fragments within the cluster.

4. Conclusion
In this work, we observed a change in localization and an increase in the activity of copper dust particles in a cluster of chain structures with power increase of the heating laser radiation. The analysis of the trajectories, dynamic entropy, and mean square displacement of the particles in the cluster reflects a change in the dynamics of particle motion with increasing laser radiation power: at values of laser radiation power less than 225 mW, the chain structures were stable, and the particles within chains moved slowly while being confined; at values of laser radiation power from 225 to 380 mW, the particles left their potential wells and began to move inside the shells of chain structures; with a further increase in the power of the acting laser radiation to 980 mW, the chains began to “exchange” particles. So, the dynamics of particle motion in a cluster of chain structures changes depending on the magnitude of the laser radiation power, and it corresponds to three modes: motion in a potential well, Brownian motion and combined directional chaotic motion consisting of laser-induced (photophoresis) and Brownian motion. An analysis of the linear displacement along and across the direction of motion of the particles at different values of the laser radiation power showed that a change in the dynamics of particle motion and a structural phase transition with the exchange of chain fragments inside the cluster became possible due to the mechanism of conversion of optical radiation energy into particle motion energy, i.e., due to the activity of copper particles.

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