Experimental Approach for Obtaining a Complex (Dusty) Plasma Fluid

Egor V. Yakovlev*, Pavel V. Ovcharov¹, Dmitrii V. Dukhopelnikov¹ and Stanislav O. Yurchenko¹**

¹Bauman Moscow State Technical University, 2nd Baumanskaya street 5, 105005 Moscow, Russia
E-mail: *yakov.egor@gmail.com
E-mail: **st.yurchenko@mail.ru

Abstract. An experimental approach is proposed to obtain a complex (dusty) plasma fluid. In contrast to previously employed laser heating of a complex (dusty) plasma crystal, this approach is based on the mode-coupling instability of the crystal and does not require any additional influence. We consider a typical experiment and report results of post-processing, including the Voronoi-cell area distribution and order parameter, justifying a liquid state of the system existing for a long enough time. The results can be useful for studies of phenomena and properties of fluids at different couplings, such as excitation spectra, density–density correlations, diffusion, and relations between them.

1. Introduction
Detailed understanding of phenomena occurring in classical condensed matter is of great importance for fundamental and applied studies. One of the most powerful methods is the use of model systems to study collective phenomena at the most fundamental (kinetic) level of individual particles.

Colloidal suspensions and complex (dusty) plasma are often used as model systems [1–3]. A series of phenomena and properties such as melting and crystallization [4–7], diffusion [8–10], heat transfer [1 11–13], thermodynamics [14], plastic deformations [15–16], a role of attraction in melting and crystallization [17–20], spinodal decomposition [21–22], dynamics of dislocations [23–24], and solid-solid phase transitions [25–26] have already been studied with such systems.

Collective dynamics, thermodynamic properties, and transport phenomena have not been studied so thoroughly in complex (dusty) plasma fluids, as compared to plasma crystals. Primarily, the liquid state was intensively studied using colloidal suspensions and molecular dynamics simulations, while realization of the liquid state in complex (dusty) plasmas requires technically complicated laser heating. However, since a dusty plasma is an ionized gas (at a pressure of ≈ 0.5 – 3 Pa) containing charged (∼ 10⁴e) microparticles, the damping rate of the particle momentum due to neutral gas drag is low (because of a low pressure). This leads to the (virtually) undamped particle motion (in contrast to colloidal systems, where the individual dynamics of particles is overdamped), providing rich opportunities to study fluid dynamics with the complex (dusty) plasma.
Methods to experimentally prepare the fluid complex (dusty) plasma were previously used, for instance, addition of larger particles to the system \[27, 28\] and laser-induced heating \[29, 30\]. A dusty plasma fluid was also studied in experiments under microgravity conditions at the International Space Station \[31\]. In the present work, we propose a novel approach to prepare the plasma fluid, existing for a few seconds, with mode-coupling instability of the plasma crystal. This approach (without external influence and additional particles) is very simple and, to the best of our knowledge, is employed here for the first time.

2. Methods

The experiments were carried out in a modified GEC chamber with a capacitively coupled radio frequency (cc-rf) glow discharge at 13.56 MHz. The plasma was generated between two electrodes, one powered and the other grounded. The grounded one was on top and represented a ring and the powered electrode placed on the bottom of the GEC chamber was an aluminum disk with a diameter of \(\approx 220\) mm. The forward rf power was between 5 and 25 W. The plasma was generated in argon at a pressure between 0.4 and 3 Pa. Melamine formaldehyde microspheres with a diameter of \((9.19 \pm 0.14)\) \(\mu\text{m}\) were injected into the discharge. Because the electron temperature is higher than the ion temperature, particles acquire large negative charges in a plasma discharge. Charged particles levitated in the sheath above the bottom electrode \[1, 2\]. After the particles were hung above the electrode, the procedure of purifying the dust system from heavy agglomerates of particles was carried out, and, thus, only monodisperse particles remained in the monolayer. For this, the discharge power was reduced and heavy particles were deposited on the electrode. The procedure was to reduce the discharge power, as a result of which heavy particles were deposited on the electrode. The process was controlled by a Edmund Optics 0413M camera located on the side of the GEC chamber.

When only monodisperse particles remained in the system, a 2D plasma crystal with a diameter of about 100 mm was formed. A monolayer of particles was illuminated by a horizontal laser sheet, the thickness of which was approximately constant throughout the crystal. A Photron FASTCAM S6 camera was used for videomicroscopy of particles, which were imaged through a window at the top of the chamber. The camera operated at a speed of 250 fps.

Figure 1. Snapshot of the experiment with the complex (dusty) plasma fluid: (a) the monolayer plasma crystal before melting; (b) the melted system, where microparticles are located in the monolayer, but do not form a crystal.
To obtain a complex (dusty) plasma fluid, the two-dimensional plasma crystal with a diameter of about 50 mm and the distance between the nearest particles 330 ± 20 µm was first formed at a forward power of 25 W and a pressure of about 2 Pa. At the second step, the argon pressure was smoothly decreased, which induced melting of the plasma crystal by heating due to the mode coupling instability (MCI) [32, 33]. The melting of the crystal at the temperature \( T_m \approx 9 \) eV was observed at 1.15 Pa. In such a manner, we obtained the complex (dusty) plasma fluid, which existed in a steady state at \( T \approx 18 \) eV (between the values of 9 and 50 eV corresponding to the melting of the crystal and activation of fluid MCI, respectively [34]) for 1.5 s.

The post-processing of experimental videos of plasma crystals was carried out in two steps. At the first step, the particles were recognized at each frame and the correspondence between the particles in the neighboring frames was established. Thus, we identified tracks and velocities of particles in the entire time of the video. The horizontal coordinates and velocities of particle were then extracted with sub-pixel resolution in each frame. At the second step of processing, Voronoi tessellation was carried out. The cells of the Voronoi diagram were colored according to different parameters, for example, cell area, number of vertices, bond-orientational order parameter, thermal or hydrodynamic component of the kinetic energy of particles, etc. Such diagram of color-coded cells is convenient for analysis of the structure of the dusty plasma monolayer and study of various processes and phenomena occurring in this system.

3. Results

Figure 1 shows experimental snapshots of the system at two different times. The frame in Fig. 1a shows the dusty plasma crystal (see Methods for details on obtaining the plasma crystal). This state of the system was formed at a forward discharge power of 25 W and a pressure of 2 Pa. The interparticle distance in the plasma crystal monolayer was approximately (330 ± 20) µm. Figure 1b illustrates the complex (dusty) plasma fluid, according to disordered locations of particles in the monolayer.
Figure 2 presents the results of post-processing of the snapshot in Fig. 1b corresponding to the dusty plasma fluid. The Voronoi diagrams for the complex (dusty) plasma systems are presented in Fig. 2, where the Voronoi cells are color-coded in accordance with (a) their area in Fig. 2a and (b) the bond-orientational order parameter $\Psi_6$ of the cell. One can see in Figure 2 that the central region of the system has transited from the crystalline to liquid state, since the order is broken.

The mechanism for obtaining the liquid state of a dust system can be simply explained as follows. First, at the system parameters 1.15 Pa and 25 W, the crystalline MCI starts, transforming the energy from the plasma flow to the kinetic energy of the microparticle subsystem, heats the crystal and melts it. After that, the system continues to be heated by the fluid MCI, occurring in the fluid. Therefore, we used such combination of pressure and discharge power (or damping and vertical confinement) that the crystalline MCI melted the crystal, but the energy release provided by the fluid MCI was insufficient to rapidly heat the dusty liquid monolayer. After melting, the liquid dusty plasma system existed for a few seconds in a steady state, before the onset of the intense fluid MCI.

4. Conclusions
In this work, we have described an approach to obtain the dusty plasma fluid existing in a steady state for a long enough time without laser heating and any another external influences. This work provides a simple approach for the experimental study of complex plasma fluids and generic phenomena in them.

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