AIP | Physics of Plasmas
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Citation: Physics of Plasmas (1994-present) **22**, 030701 (2015); doi: 10.1063/1.4914089
View online: http://dx.doi.org/10.1063/1.4914089
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/22/3?ver=pdfcov
Published by the AIP Publishing

PHYSICS OF PLASMAS 22, 030701 (2015)

Observations of imposed ordered structures in a dusty plasma at high magnetic field

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(Received 23 January 2015; accepted 23 February 2015; published online 4 March 2015)

Dusty plasmas have been studied in argon, rf glow discharge plasmas at magnetic fields up to 2 T, where the electrons and ions are strongly magnetized. In this experiment, plasmas are generated between two parallel plate electrodes where the lower, powered electrode is solid and the upper, electrically floating electrode supports a semi-transparent, titanium mesh. We report on the formation of an ordered dusty plasma, where the dust particles form a spatial structure that is aligned to the mesh. We discuss possible mechanisms that may lead to the formation of the "dust grid" and point out potential implications and applications of these observations. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4914089]

A "dusty" or "complex" plasma is a four-component plasma system consisting of electrons, ions, neutral gas, and charged microparticles. These charged microparticles, which typically range in size from tens of nanometers to a few microns in diameter, fully interact with the ambient plasma and become a third charged species in the plasma. While the origins of dusty plasma research were in astrophysical phenomena such as planetary rings[1–3] or the transport of charged grains in the solar system,[4–6] laboratory studies of dusty plasmas over the last three decades have revealed scientifically rich and exciting phenomena that have emerged as a new sub-field in plasma physics.[7,8]

Because the microparticles can acquire a large charge of several thousands of electrons under laboratory settings, among the most interesting phenomena associated with these systems is their ability to form ordered structures.[9] For example, when the dust is in the strongly coupled state characterized by large values of the Coulomb coupling parameter (ratio of the electrostatic potential energy of the particles to their thermal energy), the particles self-organize into two-dimensional plasma crystals[10–12] or three-dimensional Coulomb balls.[13] Clusters of small numbers ($N < 200$) of charged dust particles organize into concentric two-dimensional structures that are stable only for certain values of N (so-called, "magic numbers").[14] In systems containing multiple layers of particles suspended in a plasma sheath, vertical alignment of the particles due to the effect of ions streaming by the particles has been observed.[15–18] Under microgravity conditions, dusty plasmas were organized symmetrically around a central dust void region under the action of the ion drag force.[19] Self-organization, which appears to be a ubiquitous property of dusty plasmas, has been the subject of numerous experimental and theoretical studies aimed at understanding the structuring mechanisms.

A critical experimental feature of all of these systems is that the formation and spatial dimensions of these ordered structures is directly related to the size and charge of the microparticles as well as the efficiency of the plasma screening. It has been shown theoretically that in the presence of a magnetic field, the ion, and electron transport to the dust particles—and consequently the dust grain charge and plasma screening—will be modified.[20,21] Therefore, it has been unclear if ordered structures could be formed in dusty plasmas in the presence of magnetic fields. This letter reports on a type of highly ordered dusty plasma formed in a strongly magnetized plasma.

The experiments are performed using the recently commissioned Magnetized Dusty Plasma Experiment (MDPX) device. The MDPX device consists of two main components: a split-bore magnet that uses four, superconducting coils and that has a 50 cm diameter, 157 cm long open bore and a 19 cm tall, 35 cm inner diameter, octagonally-shaped aluminum vacuum chamber. A photograph of the MDPX device with the plasma chamber is shown in Fig. 1(a) and more extensive descriptions of the experimental hardware may be found elsewhere.[22,23]

Argon plasmas are generated in the experiment using a capacitively coupled, radio-frequency (rf) configuration with a fixed frequency source at $f = 13.56$ MHz at pressures ranging from 20 to 300 mTorr (3 to 40 Pa). The parallel plate configuration of the electrodes is shown in Fig. 1(b). The two electrodes are separated by a gap of 65 mm.

The lower electrode is a solid circular disk with a diameter of 28 cm. The central region of this disk has a 15 cm diameter, 0.3 cm depression that provides radial confinement for the levitated microparticles. Additionally, a 63 mm inner diameter copper gasket is placed in this depression to further aid in localizing the particles as well as providing a spatial calibration for images. The upper electrode is also a disk of 28 cm diameter, but with a 14.6 cm diameter through-hole

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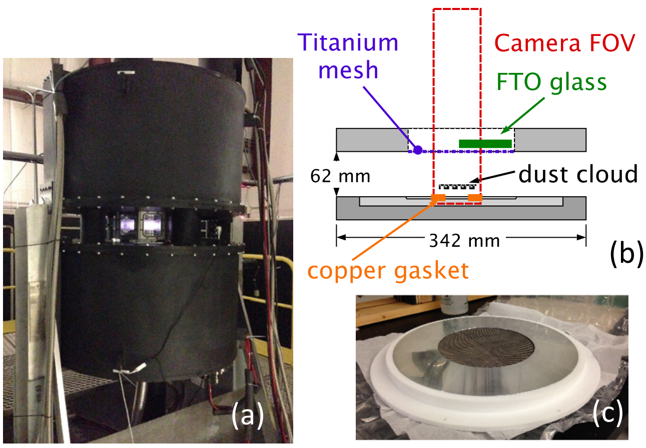

FIG. 1. (a) Photograph of the MDPX device showing the magnet cryostat (large black cylinder) and the glow from an argon plasma in the vacuum chamber. (b) Schematic drawing of the upper and lower electrodes indicating the field of view of the camera, the location of the dusty plasma, and the location of the mesh. (c) Photograph of the upper electrode showing the titanium mesh.

that allows viewing of the plasma from a window at the top of the vacuum chamber. A fine titanium mesh covers the hole with the intent of maintaining a uniform potential over the surface of the upper electrode while still allowing a view of the particles that are suspended in the plasma. The mesh is a 40 square mesh with a wire diameter of 0.25 mm and center-to-center spacing of 0.635 mm between parallel wires.

In the experiments that are described below, argon plasmas are generated using an rf power ranging from 2.5 to 4.5 W applied to the lower electrode. The upper electrode is electrically floating, and the vacuum chamber walls are grounded. At $B = 0$ T, the plasma parameters are measured using a triple probe and found to be typical for rf glow discharge plasmas: an electron density, $n_e \sim 2 \times 10^{15}$ to $8 \times 10^{15}\,\mathrm{m}^{-3}$ and electron temperatures, $T_e \sim 2$ to 5 eV, which results in an electron Debye length $\lambda_{De} \sim 0.12$ to 0.37 mm. Most importantly, at the operating pressures of these experiments, $p \sim 100$ mTorr (i.e., neutral gas density, $n_0 \sim 10^{21}\,\mathrm{m}^{-3}$), the interactions with neutral atoms is a dominating feature. The ion-neutral collision mean free path is $\lambda_{mfp\text{-}i} \sim 0.6$ mm, and the electron-neutral collision mean free path is $\lambda_{mfp\text{-}e} \sim 6$ mm.

A 300 mW, 532 nm laser expanded into a horizontal laser sheet is used to illuminate the particles. The particles are viewed through the top window of the experiment using a 4 Megapixel (2048 × 2000 pixels), Ximea XiQ camera operating at 12.5 frames per second. The spatial resolution is 0.0315 mm/pixel. Microparticles are introduced into the plasma by tapping on a moveable dust shaker that is retracted out of the plasma after the dust particles are injected. The dust particles are suspended in the plasma between the two electrodes, approximately 20 to 30 mm above the lower, powered electrode and 30–40 mm below the upper, electrically floating, electrode and the titanium mesh wire.

Shown in Figure 2 are two observations of microparticles in the MDPX device. The figures show pixel-based, intensity maxima for a sequence of 100, 8-bit (256 grayscale levels) images, which allow us to view the trajectory of the microparticles over approximately 8 s. In the observations shown in Fig. 2, measurements were performed using 2-μm diameter silica microspheres at a constant rf power of 2.5 W.

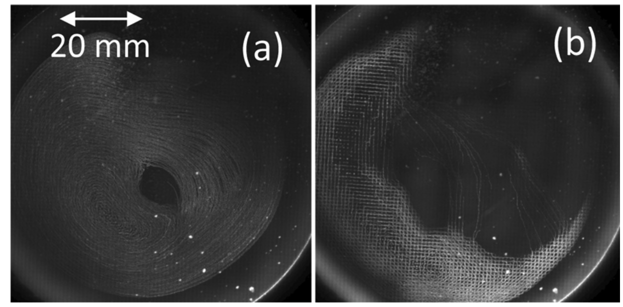

FIG. 2. Dusty plasmas of 2-μm diameter, silica microspheres over different magnetic fields, and pressures at a fixed rf power of 2.5 W. Each figure is the sum of the maximum intensity of a sequence of 100, 8-bit (256 grayscale levels) images. (a) $p = 145$ mTorr, $B = 1.0$ T; (b) $p = 145$ mTorr, $B = 2.0$ T. These images show the formation of a grid of suspended dust particles for the higher magnetic fields.

Figure 2(a) shows a measurement of particle trajectories for a neutral gas pressure of $p = 145$ mTorr (19.3 Pa) and a magnetic field of $B = 1.0$ T. The circular pattern of the particle motion shows a continuous flow of particles that is believed to be due to ion $\vec{E} \times \vec{B}$ flows as reported in earlier works.[24–28] By contrast, in Fig. 2(b), the gas pressure is the same, but the magnetic field is increased to $B = 2$ T. There remains some remnant of the flowing structure, but the most prominent feature of this image is the grid structure that appears in the suspended microparticles.

The presence of the wire mesh as part of the top electrode raises three important questions: (1) Is the grid pattern observed in the suspended dust grains reflecting the structure of the titanium mesh used for the top electrode? (2) Can the grid pattern be removed, altered, or controlled? (3) If the observed grid pattern is due to the mesh, what is the mechanism that causes the dust grains to become confined to the magnetic flux tubes that map directly to the mesh wires and not to spread to the regions between the mesh wires?

To address question (1), consider the enhanced view of the grid features in the dusty plasma shown in Fig. 3. Figure 3(a) shows a view of 2-μm diameter particles at rf power of 2.5 W, $B = 2.0$ T, and $p = 145$ mTorr (19.3 Pa) [e.g., from

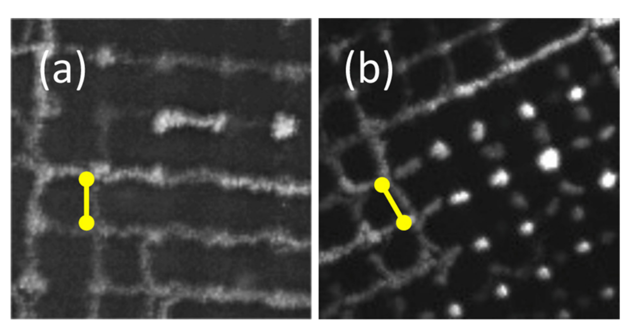

FIG. 3. Close-up of dust grid showing the scale (yellow bars) of the titanium grid relative to the dust particle spacing. The field of view is 125 pixels × 125 pixels (3.94 mm × 3.94 mm). (a) Expansion of an image of 2-μm diameter particles at $p = 145$ mTorr, $B = 2.0$ T. (b) Expansion of an image of 0.5-μm diameter particles at $p = 53$ mTorr, $B = 1.5$ T.

Fig. 2(b)], where it is possible to measure the approximate spacing between the grid lines. Figure 3(b) shows the result for a similar experiment performed using 0.5–μm diameter particles at rf power of 2.5 W, $B = 1.5$ T, and $p = 53$ mTorr (7 Pa). The measurements of the particle spacing correspond to approximately 0.65 mm +/− 0.1 mm for the 2 μm dust and 0.69 mm +/− 0.09 mm for the 0.5 μm dust. In both cases, the dust grid spacing is essentially identical to the spacing of the mesh wires. Additionally, the width of the dust grid structures formed by the μm-sized dust particles is $w = 0.25$ mm, which corresponds to the diameter of the 40 wire mesh. This result is reproducible over a range of experimental conditions, as long as $B \geq 1.0$ T. Therefore, it appears that the dust grid structure "maps" to the spatial dimensions of the wire mesh. Because the magnetic field is very uniform in this region of the experiment, ~0.2% ripple,[29] variations in the grid structure are likely due to imperfections in the wire mesh or non-uniformities in the plasma.

To address question (2), a 10 cm long × 5 cm wide rectangular, FTO (fluorine-doped tin oxide)-coated transparent, conducting, glass plate was placed directly on top of the mesh as indicated in Fig. 1(b). It is oriented so as to cover approximately ½ of the viewing area as shown in Fig. 4(a). The objective was to "short-circuit" the mesh and create a solid conducting surface that would suppress the formation of the grid. It is important to note the titanium wire mesh and the FTO-coated glass do not have the same conductivity and that the glass plate was placed on the mesh to try to maximize the contact between the two surfaces, but there were certainly ripples in the wire mesh that prevented a perfect contact between the two pieces. A series of experiments were performed using 2-μm diameter microparticles at an rf power of 4 W, $B = 1.5$ T, and over a pressure range between 95 and 170 mTorr (12.7 to 22.7 Pa). Fig. 4 shows pixel-based, intensity maxima for a sequence of 100, 8-bit (256 grayscale levels) images.

Fig. 4(a) shows the formation of the grid pattern at a pressure $p = 128$ mTorr (17.1 Pa) in the region without the FTO-coated glass, but a greatly suppressed grid in the region with the FTO-glass. The measurement of the particle spacing in the gridded regions (i.e., without the FTO-glass) corresponds to 0.64 mm ± 0.1 mm. Fig. 4(b) shows a measurement at a pressure, $p = 167$ mTorr (22.3 Pa), where the particles are now circulating freely between the two regions. These results demonstrate that the grid pattern that appears in the dusty plasma is strongly connected to the mesh.

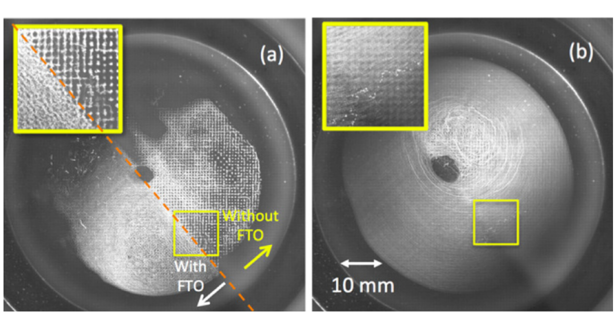

FIG. 4. Dusty plasmas of 2-μm diameter silica microspheres when a FTO-coated, conducting glass plate is placed on one-half of the titanium mesh for an rf power of 4 W and a magnetic field of $B = 1.5$ T. (a) $p = 128$ mTorr. This figure also indicates that the lower left side is the region with the FTO-coated glass and the upper right side is the region without the FTO-coated glass. The grid pattern in the dusty plasma is seen in the region without the FTO-coated glass and is greatly suppressed in the region with the FTO-coated glass. (b) $p = 167$ mTorr. Particles are freely circulating in the plasma. The inset in both images is an expanded view of the boundary region between the two regions in the experiment.

To address question (3), we have considered a number of possibilities. Given the presence of a strong magnetic field, it is reasonable to consider the formation of an extended pre-sheath or "shadow" that extends into the plasma from the mesh as described in earlier works related to probes in magnetized plasmas.[30–33] However, the mechanisms described in these works are generally based upon highly ionized plasmas with a small neutral atom population. By contrast, as is typical for the vast majority laboratory dusty plasmas, the experiments reported here are highly neutral-dominated. In the absence of a magnetic field, at these operating pressures, the maximum ion-neutral collision mean free path $\lambda_{mfp\text{-}i} \sim 0.6$ mm and the maximum electron-neutral collision mean free path is $\lambda_{mfp\text{-}e} \sim 8$ mm. The effect of the magnetic field will be to shorten these distances. However, with a distance of 30 to 40 mm between the mesh wire and the dust, it is clear that collisional effects are important. Furthermore, the experimental data presented in Figs. 2 through 4 that show the formation of the grid structure at a higher magnetic field and the loss of the grid structure with the increase in neutral pressure, clearly illustrate that these aforementioned effects will be modified by the magnetic field and the role of ion-neutral and electron-neutral collisions. And, it should be pointed out that the dust grid phenomenon described in this paper becomes less effective with the increase in neutral gas pressure; this is the exact *opposite* of the process for the formation of dusty plasma crystals, where increasing gas pressure leads to the formation of highly ordered structures.[34,35]

From numerous studies, it is known that the suspension of the dust grains is due to a balance between gravitational, electrostatic, ion drag, and neutral drag forces in the plasma.[10–19,36] A complex, self-consistent interplay between a number of physical mechanisms must ultimately give rise to these forces. Among the physical processes we have considered are: the relative diffusion rates of ions and electrons parallel and perpendicular to the magnetic field, the global ionization of neutral atoms, the possible differences in ion and electron densities and plasma potential between the mesh wires and the holes, and the effective electrical circuit between the plasma and mesh. Further experimental and theoretical work is needed to determine the dominant physical processes that are responsible for the structuring.

It is also noted that in previous studies of complex plasmas at high magnetic fields, a phenomenon called plasma filamentation was observed.[37,38] Here, the plasma becomes structured into stationary or mobile vertical columns depending upon the operating conditions. The previous figures in this paper were all performed under conditions that minimized filamentation. Our experimental measurements show that the grid pattern persists in the plasma even in the presence of filamentation—with the filaments having a typical scale size of 2 to 3 mm in diameter—considerably larger than the scale length of the dust grid.

As the focus of this letter has been on the experimental description of a new type of dusty plasma ordering phenomenon, the development of a self-consistent model for the ordering is beyond the scope of this work. However, we fully anticipate that these observations will motivate experimental and theoretical efforts to fully evaluate the parameter space in which the dust grid forms, to understand the two- and three-dimensional structure of this system, and to gain detailed insights about the physical processes that are at work.

These initial results potentially open several new directions for dusty plasma research. In studies of dusty plasma self-organization, the local spatial ordering is generally determined with limited control of the experimenter. The experimental configuration reported here shows that it may be possible to design ordered structures in dusty plasmas of arbitrary size and shape without being constrained to certain ranges of particle sizes. It may also be possible to create systems with multiple gridded structures with different sizes to study interface effects and structural deformation at the particle scale. Additionally, the semi-discrete motion of the particles between the grid points may suggest a new type of organized behavior within this driven, ordered state. The electrode structuring technique observed here may offer a new approach to control the growth and deposition of microparticles and nanoparticles with known spatial structures in plasmas.

In summary, this paper reports on the observation of an imprinted ordered structure in a dusty plasma at high magnetic field. It is shown that the ordered state has the same spatial structure as the grid that covers the central portion of the upper electrode. When a conducting, transparent electrode covers the mesh, the grid pattern in the dusty plasma is suppressed. Although the short collisional mean free paths and the small spatial scale of the suspended dust structure complicate diagnostics and interpretation, the potential impact of these observations is the realization that, through the use of a magnetized plasma, the spatial structuring of a dusty plasma may be externally controlled.

This work was supported by funding from the U.S. Department of Energy (DE - SC0010485) and the National Science Foundation (PHY-1301881, PHY-1126067, and PHY-1301856).

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