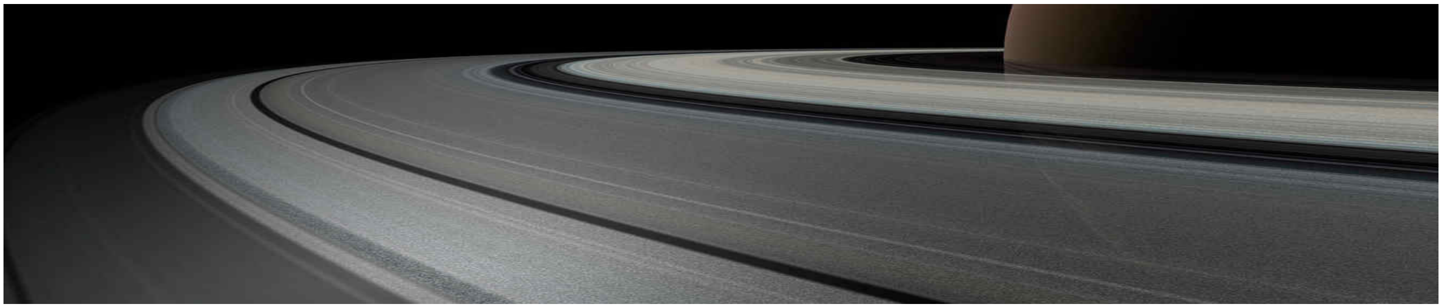

15th Dusty Plasma Workshop

May 29 – June 1, 2018
The Westin Baltimore Washington Airport – BWI
Baltimore, Maryland, USA

Program Committee

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Contents

Tuesday, May 29			Location:
3:00 PM	5:00 PM	**Free Imaging Hands-on Tutorial by Vision Research**	**Pre-function area**
4:00 PM	7:00 PM	**Registration for the 15th Dusty Plasma Workshop**	**Pre-function area**
6:00 PM	9:00 PM	**Welcoming Reception**	**Pre-function area**

Wednesday, May 30			Location:
7:00 AM	8:25 AM	**Breakfast**	***All meals and events will take place in the White Oak Room unless otherwise noted.***
7:30 AM	8:25 AM	**Registration**	
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8:35 AM	8:55 AM	8:35 am. H. Thomas. Recent Results from Complex Plasma Laboratory PK-4 on the International Space Station	
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	9:30 AM		
9:30 AM	9:50 AM	9:30 am. K. Takahashi. Structures of Coulomb Crystals in Cylindrical Discharge Plasmas under gravity and microgravity	
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	11:00 AM		
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11:25 AM	11:40 AM	11:25 am. C. Dietz. Experimental FCC-BCC Transitions in Plasma Crystals Using Machine Learning	
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12:15 PM	12:30 PM	12:15 pm. K. Sharmin Ashrafi. Variation of ion wake field inside a glass box	
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4:35 PM	4:50 PM	4:35 pm. C. Ticos. Solar Panel Cleaning on Mars With a Pulsed Plasma Jet	
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5:00 PM	5:15 PM	5:00 pm. Gurudas Ganguli. Experimental observation of cnoidal wave structures of dust acoustic waves	
5:35 PM		Board Bus/ Ride to The National Aquarium in Baltimore for Banquet	Please board one the 2 UMBC buses at the Hotel entry.
6:00 PM	6:55 PM	**Self-guided tour of the National Aquarium.** Enter through the office glass doors facing the USS Torsk submarine.	National Aquarium's address: 501 E Pratt St, Baltimore, MD 21202
7:00 PM	9:00 PM	**Banquet at Level 1 of the Aquarium** Remarks by Dr. Keith Bowan, Dean of COEIT at UMBC	
9:05 PM	9:30 PM	Board Bus/ Return to Westin by BWI	Please board one the 2 UMBC buses at the Aquarium Circle.

Thursday, May 31			Location:
7:00 AM	8:25 AM	**Breakfast**	***All meals and events will take place in the White Oak Room unless otherwise noted.***
7:30 AM	8:25 AM	**Registration**	
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	9:30 AM		
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5:35 PM	5:50 PM	Board Bus/ Ride to UMBC	Please board one the 2 UMBC buses at the Hotel entry.
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7:20 PM	7:35 PM	Board Bus/ Return to Westin by BWI	Please board one the 2 UMBC buses at the Circle facing the Fine Arts Bldg.

Friday, June 1			Location:
7:00 AM	8:25 AM	**Breakfast**	***All meals and events will take place in the White Oak Room unless otherwise noted.***
7:30 AM	8:25 AM	**Registration**	
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9:30 AM	9:50 AM	9:30:00 am. R. Marshall. Laser Induced Fluorescence (LIF) in the Caltech Water-Ice Dusty Plasma Experiment	
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Tuesday, May 29, 2018

Applying High-Speed Imaging Technology
in Dusty Plasma and Micro-Particle Studies

Join us at the 15th Annual Dusty Plasma Workshop for a free, hands-on workshop as we explore velocities, dispersion and the basic characteristics of micro-particles in dusty plasmas. You'll also have the opportunity to experience high-speed imaging in an interactive way.

The workshop takes place before the main event and will cover the following topics:

- Introduction to high-speed imaging
- Importance of high-speed imaging in micro-particle studies
- Common image-based techniques (particle image velocimetry and particle tracking velocimetry)
- Illumination techniques (pulse laser, shadowgraph and Schlieren)
- Camera, lensing and lighting considerations
- Enhanced camera features

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Join us before the Welcoming Reception:

Date: Tuesday, May 29
Time: 3-5 PM EST
Location: Near registration
Cost: Free

When it's too fast to see and too important not to.®

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Oral Presentations

Wednesday, May 30, 2018

Recent Results from Complex Plasma Laboratory PK-4 on the International Space Station

Hubertus M. Thomas[1], Mikhail Pustylnik[1], Volodymyr Nosenko[1], Mierk Schwabe[1], Surabhi Jaiswal[1], Tetyana Antonova[1], Sergey Khrapak[1], Milenko Rubin-Zuzic[1], Vladimir E. Fortov[2], Oleg. F. Petrov[2], Alexandre Usachev[2], Andrey M. Lipaev[2], Andrey V. Zobnin[2], Vladimir I. Molotkov[2], Michael Kretschmer[3], and Markus H. Thoma[3]

[1] DLR- Institut für Materialphysik im Weltraum, 82234 Wessling, Germany
[2] Russian Academy of Sciences – Joint Institute for High Temperatures, Moskau 125412, Russia
[3] Justus-Liebig-Universität Gießen, 35392 Gießen, Germany
Hubertus.Thomas@dlr.de

The PK-4 facility in the Columbus module of the International Space Station ISS allows long-term investigations of complex plasmas under microgravity conditions. PK-4 is a modular apparatus dedicated for specific experiments but also a laboratory which offers the possibility to perform a large variety of experiments with complex plasmas and to react to new developments in this field in a manner as flexible as possible.

The main interest lies in the investigation of the liquid phase and flow phenomena of complex plasmas for which PK-4 is especially suited thanks to a DC-discharge and its geometry (elongated glass tube with a large observational access). The polarity of the discharge can be switched with frequencies up to 5 kHz, so that microparticles can be trapped while the dc-character of the discharge remains. Additionally, the setup is equipped with many manipulation devices, like a strong laser for producing shear force, thermal resistors for local heating, rf-coils for exciting inductively coupled plasma and an internal additional electrode to produce shocks, waves, etc. [1]

4 science experiment campaigns have been performed since PK-4's launch in October 2014. Basic studies regarding charge on microparticles and ion drag force have been performed as well as dedicated investigations on laser induced shear forces, string formation through polarity switching, wave excitation and propagation. In this presentation we will show the most recent results and discuss the next steps in the use of PK-4 on the ISS.

Acknowledgements: We would like to acknowledge the joint ESA-ROSCOSMOS Experiment «Plasma Kristall-4» onboard the International Space Station ISS. This work is partly supported by DLR grant 50WM1441, 50WM1442 and 50WM1742.

[1] M. Y. Pustylnik, M. A. Fink, V. Nosenko et al., *"Plasmakristall-4: New complex (dusty) plasma laboratory on board the International Space Station"*, Review of Scientific Instruments 87, 093505 (2016)

Experimental Studies of Phase Separation in Dusty Plasmas under Microgravity

Stefan Schütt[1], Carsten Killer[2], and André Melzer[1]
[1] Institute of Physics, University of Greifswald, 17489 Greifswald, Germany
[2] Max Planck Institute of Plasma Physics, 17491 Greifswald, Germany
stefan.schuett@physik.uni-greifswald.de

Dusty plasmas are well suited for studying phase separation processes because they allow to access their dynamical behavior on the single particle level. To eliminate the influence of gravity on the dust particles and to be able to study three-dimensionally extended systems, previous measurements were conducted under microgravity conditions on parabolic flights. Investigations showed that binary systems consisting of two particle species exhibit phase separation even for small relative size disparities of about 3% [1]. A video microscopy technique has been developed that allows to distinguish between the two particle species despite their small size disparity by using a mixture of fluorescent and non-fluorescent particles and two cameras equipped with appropriate filters, see fig. 1. This technique has been used to determine uphill diffusion coefficients, which were much larger than the thermal self-diffusion coefficients of the same system. Also ruling out spinoidal decomposition, which occurs only for larger size disparities, the phase separation has been finally attributed to the difference in the size-dependent electric field and ion drag forces.
To gain a better understanding of the phase separation process, the behavior of three-dimensionally extended binary systems has been systematically studied during two more parabolic flight campaigns. In this contribution, first results concerning the phase separation for different size disparities as well as different absolute particle sizes are presented.
This work was supported by DLR under grant no. 50WM1638.

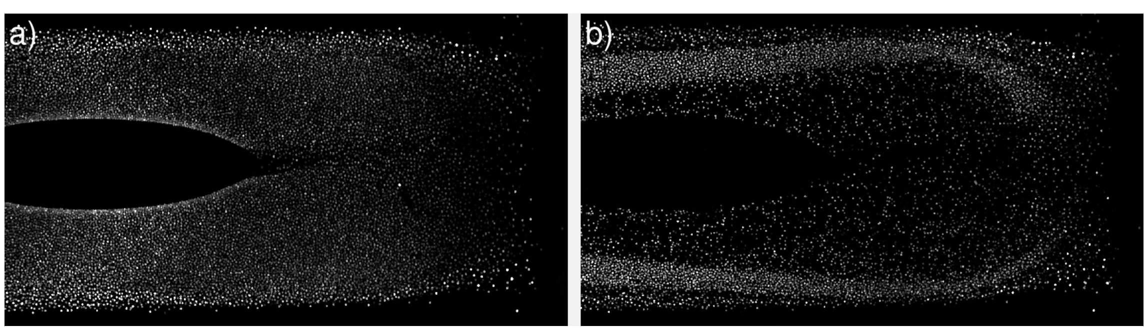

Figure 1 – Snapshot of a dust cloud consisting of two particle species with diameters of 6.78 µm and 7.02 µm, respectively. In a), all particles can be seen, while b) shows only the larger, fluorescent species. The images have been enhanced for better visibility.

[1] C. Killer, T. Bockwoldt, S. Schütt, M. Himpel, A. Melzer, and A. Piel, Phys. Rev. Lett. **116**, 115002 (2016).

Structures of Coulomb crystals in cylindrical discharge plasmas under gravity and microgravity

Kazuo Takahashi[1] and Hiroo Totsuji[2]
[1] Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan
[2] Professor Emeritus, Okayama University

takahash@kit.jp

Dynamics of dust particles in the PK-4, which has a cylindrical discharge plasma and is utilizing for microgravity experiments of dusty plasmas on the International Space Station, have been investigated on the ground and parabolic flights. Figure 1 shows the structures of Coulomb crystal in detail, which have been obtained in ground-based experiments. In a cylindrical discharge plasma (Ar, 33 Pa, 700 $V_{p\text{-}p}$ at 1 kHz), spatial distribution of dust particles formed a cylinder with cross section of ellipse. Lower part of the cylinder consists of layers including the hexagonal closed-packing structure, which clearly appears in the region of $2 < y < 4$ mm. The closed-packing structure around center of the cylinder indicates that compressive force toward to center confines the dust particles. Furthermore, outline of the cross section is not identical to potential contour of the plasma without dust particles in the cylindrical discharge, which the dust particles produce potential to confine themselves by self-consistent interaction with the plasma.

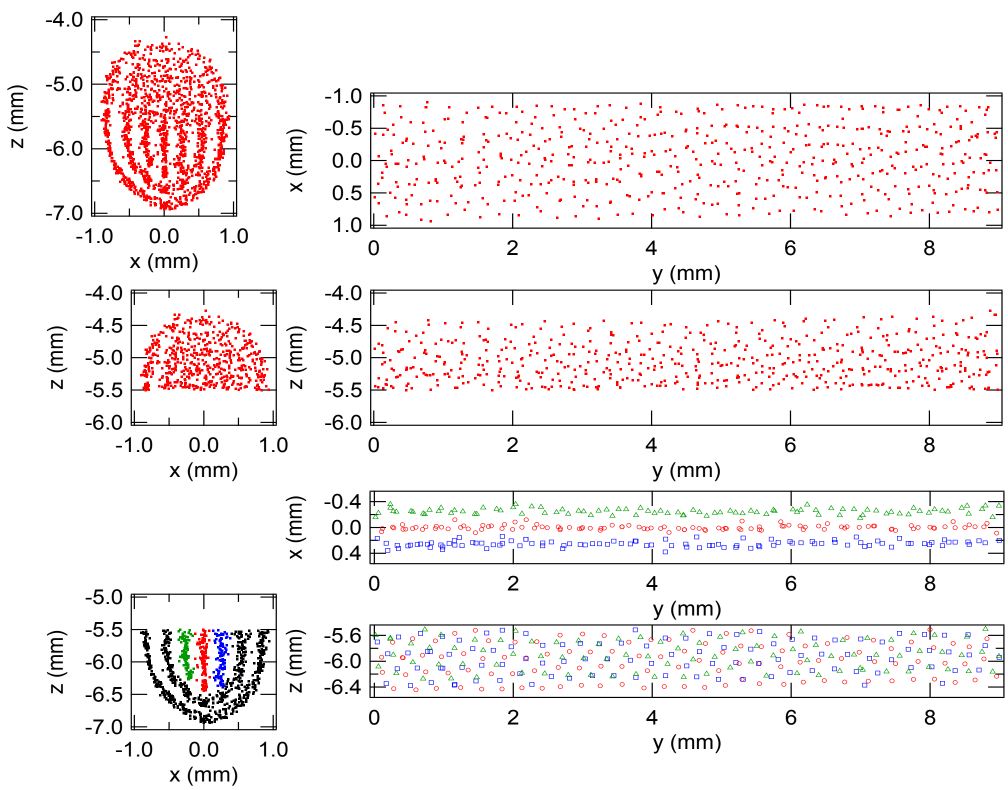

Figure 1 – Coordinates of dust particles in a cylindrical discharge plasma.

Complex Plasmas under Compression – Capabilities of the Next Generation Complex Plasma Space Experiment "Ekoplasma"

U. Konopka,[1] C. A. Knapek,[3] P. Huber,[3] E. Thomas, Jr.,[1] J. Williams,[2] and H. M. Thomas[3].
[1] Physics Department, Auburn University, Auburn, AL, USA
[2] Physics Department, Wittenberg University, Springfield, OH, USA
[3]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Oberpfaffenhofen, Germany
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The ordering state of a substance is characterized by its macroscopic properties such as temperature, compressibility and particle density. Expressed in terms of properties on the microscopic/atomic scaling length this quantities are related to the random kinetic energy and the average inter-particle potential energy of each member in the system. The ratio of the average kinetic to potential energy is referred to as the coupling parameter of a system and its value governs at least qualitatively the state of the ordering of the substance under investigation. As such it is clear, that a transition from a gas phase over a liquid to a solid phase can be initiated, increasing the coupling in the system, by either reducing the substance's temperature or by increasing the particle interaction for example by compressing the system.

In this paper we present recent results related to triggering a phase transition in a Complex Plasma based on actively compressing a large particle cloud, a feature that is available with the newly designed "Ekoplasma" alias "PlasmaLab" discharge chamber at the German Aerospace Center (DLR). The cooperative experiments between Auburn University and DLR demonstrate using PlasmaLab that volumetric large dust ensembles can be realized even on ground as we will demonstrate, (on ground however introducing substantial anisotropies to the system as a side effect). PlasmaLab also allows to actively shrink the experiment volume by moving the electrodes and thus compress the confined particle cloud ultimately leading to a crystallization of the system. Some examples will be shown.

We would like to acknowledge the PlasmaLab development activities of DLR. This work is supported by funding from the NASA/Jet Propulsion Laboratory (JPL-RSA 1571699) and DLR/BMWi under contract 50WM1441. Additional support is provided by the National Science Foundation EPSCoR program (OIA-1655280).

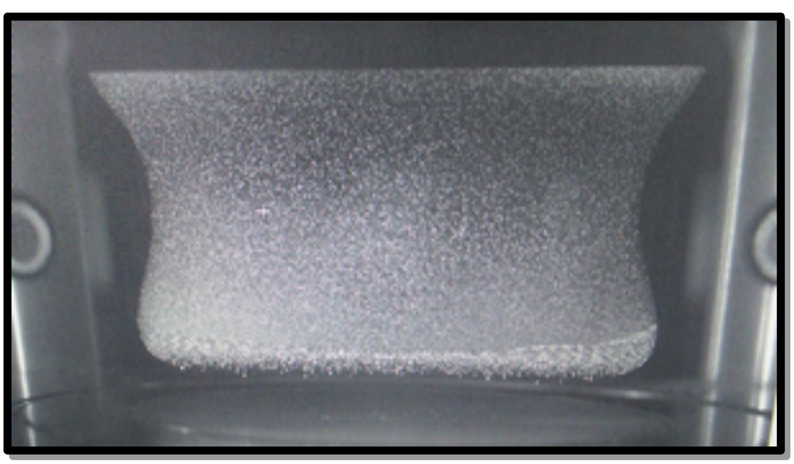

Figure 1 – Realizing substantial extended dust clouds in the "Zyflex" chamber, a prototype for the next generation complex plasma space experiment "PlasmaLab" alias "Ekoplasma". The cloud presented here has a vertical extend of about 60 mm in this ground based experiment.

2D Complex Plasma Crystal Experiments in the Large Chamber

John Meyer[1], Vladimir Nosenko[1], Ingo Laut[1], Sergey Zhdanov, and Hubertus Thomas[1]
[1] Institute for Materials Physics in Space, German Aerospace Center,
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John.Meyer@dlr.de

Two-dimensional plasma crystals are an important area of research in complex plasmas with many aspects outstanding. A major one being crystal size, we use a large-diameter capacatively coupled radio-frequency chamber to examine large 2D complex plasma crystals. Working up to a full electrode diameter of 77.5 cm, currently the observed crystal diameter is limited by a 55 cm inner diameter ring placed on the electrode. The dust used is 9.19 µm diameter melamine formaldehyde spheres in argon plasma at neutral gas pressures between 0.10 Pa and 1.00 Pa. In performing these experiments, we also observed mode coupling of the vertical and longitudinal wave modes without crossing. We present experiments and analysis of large complex plasma crystals and recent results in mode coupling.

Field-Aligned Chains within the PK-4 Environment

Truell W. Hyde[1], Lorin Matthews[1], Peter Hartmann[1,2], Marlene Rosenberg[3], Oleg Petrov[1,4], Vladimir Nosenko[1,5], Jie Kong[1], Ke Qiao[1], Eva Kostadinov[1] and Jorge Carmona-Reyes[1]

[1]Center for Astrophysics, Space Physics and Engineering Research (CASPER), Baylor University, Waco, Texas, USA, [2]Wigner Research Centre for Physics, Budapest, Hungary, [3]University of California at San Diego, [4]Joint Institute for High Temperatures, Russian Academy of Sciences, DLR Institute of Materials Physics in Space, Wessling, Germany

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Complex plasmas have proven a versatile analog for the study of soft matter systems, particularly those whose global behavior is determined by the combined effect of the particles' low temperature / kinetic energy, interparticle / interchain interactions, global and/or local confinement and the streaming ion flow. The streaming ion flow plays a major role in interparticle interactions and particle alignment but is in general much weaker than other system forces. As such, its effects are often masked by gravity for terrestrial experiments. The PK-4 system currently in operation on the International Space Station (ISS) provides a microgravity environment which avoids this issue. The PK-4 utilizes a DC discharge within a glass tube 400 mm in length and having an inner diameter of 30 mm. [1]

This talk will discuss possible mechanisms behind extended particle chain formation in microgravity environments such as those found within a PK-4 system. Experimental observations will be compared to plasma discharge simulations as well as dust charging and interaction simulations. Data for the dust-dust and dust-plasma interaction will be compared and the relationship between the phenomenon generally known as striations and dust particle behavior will be examined.

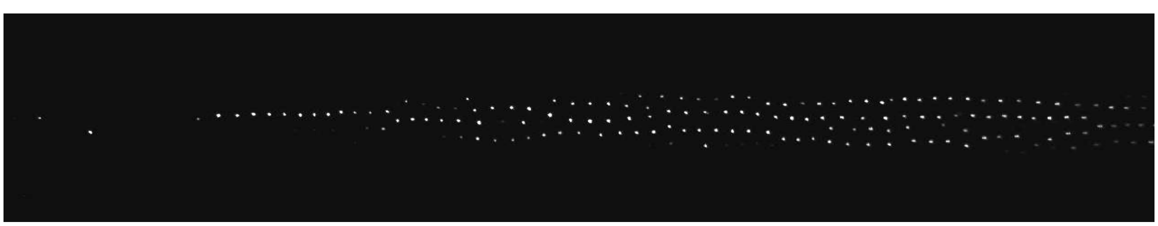

Figure 1 – ISS Data (First Campaign)

[1] M. Y. Pustylnik, et. al. *Review of Scientific Instruments* 87 (2016) 093505.

Support from NASA Grant number 1571701, NSF / DOE Grant numbers 1414523, 1707215 and NSF Grant Number 174023 is gratefully acknowledged.

Experimental FCC-BCC Transitions in Plasma Crystals visualized using Machine Learning

Christopher Dietz[1], Roman Bergert[1], and Markus Thoma[1]
[1] I. Physikalisches Institut, Justus-Liebig-Universität, Gießen, Germany
christopher.dietz@physik.uni-giessen.de

Plasma crystals are known to behave like Yukawa systems. Consequently, plasma crystals possess a phase transition not only between solid and disordered phases, but also between the crystal structures fcc and bcc. However, experimental investigations of this transition are missing. We resolve the three-dimensional particle positions of a plasma crystal in time during the crystallization process with a fast scanning camera. Then we analyze the crystallization with a crystal structure analysis algorithm based on machine learning. This contribution reports that the fcc-bcc phase transition can be visualized by robust phase diagrams based on machine learning. The phase transition of the extensive crystal is at a screening parameter of $\kappa = 2.66$ for a gas pressure of 30 Pa (figure 1). As a consequence, the kinetic dust temperature at the phase transition $T = 486$ K is roughly estimated by comparison with the theoretical phase diagram of Yukawa systems. In future investigations, this comparison can be used to directly estimate the coulomb coupling parameter Γ if the kinetic dust temperature is measured.

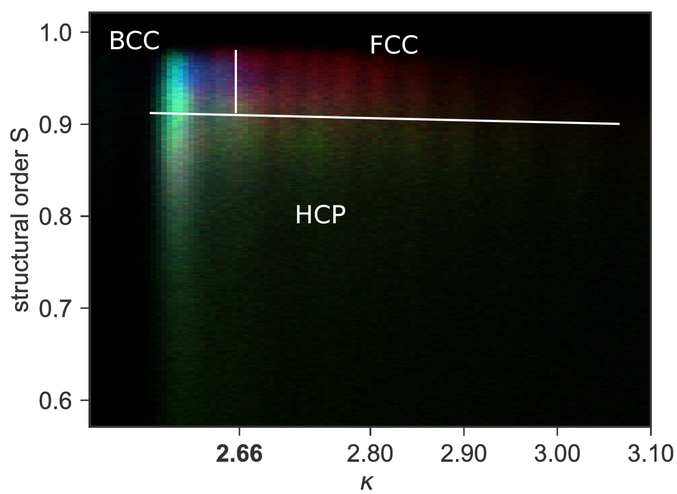

Figure 1 – Phase diagram of the crystallization process of a plasma crystal at 30 Pa neutral gas pressure. The colors indicate the probability for the respective crystal structure (blue: bcc, red: fcc, and green: hcp). The structural order S is derived from bond orientational order parameters. It is 1 for undisturbed crystal structures and 0 for the disordered case. The screening parameter is denoted as κ.

High precision operando size measurement of microparticles

Niklas Kohlmann, Oguz-Han Asnaz, Frank Wieben, Franko Greiner, and Dietmar Block
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Besides structural and dynamic processes in complex plasmas, the particles themselves are recently more and more in focus of research. Important parameters are the particle size, shape and surface topology. However, non-invasive in-situ or even operando methods to determine the named parameters during plasma operation are missing. Angular resolved mie scattering measurements can fill this gap and provide particle sizes with high precision. An out-of-focus imaging technique similar to Interferometric Laser Imaging for Droplet Sizing (ILIDS) is used to obtain the angular-dependent scattering intensities. Correlating the so called phase function to the data provided by the Lorenz-Mie theory for spherical objects the particle size and refractive index can be obtained. It is shown that the method allows to measure the particle size with an accuracy of a few nanometer if the polarisation state of the laser illumination is taken into account. The particle size measurements are validated with complimentary measurements using a long distance microscope. It is found that the sizes are in good agreement for both methods. Further applications, like the detection of changes of particle surface topology due to plasma-particle interaction or the decrease in particle size due to prolonged plasma exposure, are discussed for different particle materials.

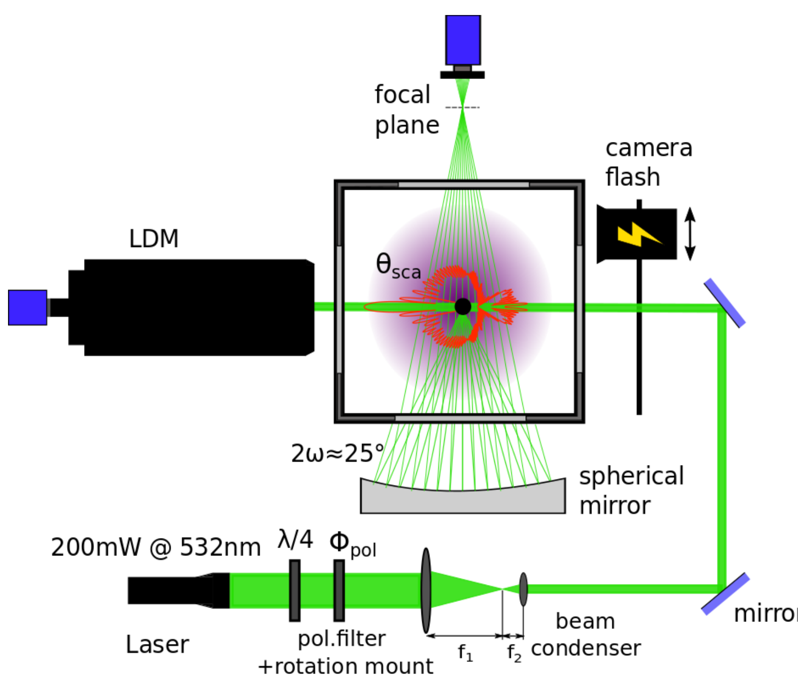

Figure 1 – Experimental setup for the out of focus detection of angular resolved scattering intensity measurements.

Variation of ion wake field inside a glass box

Khandaker Sharmin Ashrafi, Dustin Sanford, Lorin Matthews, and Truell Hyde
CASPER, Baylor University, One Bear Place 97310, Waco, Texas USA

Khandaker_Ashrafi@baylor.edu

To get a complete understanding of the data obtained from dusty plasma experiments, it is important to understand the interactions between grains. The perturbation of ion flow by the electric field of charged dust grains creates a wake field downstream of the dust grains. The difference in local ion density caused by the wake field changes the equilibrium dust charge and shielding distance of the dust grains, and thus affects the interaction between grains. Here we use a molecular dynamics simulation of ion flow past stationary dust grains to investigate the interaction between the dust particles and ions. We consider a long vertical chain of particles confined within a glass box placed on the lower electrode of a GEC cell. Ions stream from the bulk plasma at the top of the box to the negative lower electrode. We investigate the modification of dust charge, shielding length, and wake field potential along the length of the chain with the variation of ion flow speed.

Support from NSF / DOE Grant numbers 1414523 and 1707215 is gratefully acknowledged.

Fluctuation Theorem Confirmed in a Dusty Plasma*

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As an area of research, statistical physics has fewer experiments, and more theory, than is typical in other areas of physics. One reason for the lack of experiments is the difficulty of making experimental observations of individual molecules as they move within a substance. Dusty plasmas, however, allow observing and even tracking individual dust particles. Moreover, dusty plasmas can prepared so that the particle motion is strongly coupled, and the collection of dust particles act as an analogue for molecules in a liquid. For these reasons, it is attractive to use dusty plasmas for the experimental exploration of statistical physics concepts in liquids.

Our group has recently used experimental data to carry out several tests of statistical physics theories that previously had not been tested or demonstrated in any substance. In this talk we present one of these, which was reported recently.[1]

Fluctuation theorems describe so-called violations of the Second Law of Thermodynamics, in small systems. The original such fluctuation theorem was the 1993 theory of Evans, Cohen and Morriss (ECM), which described the entropy production rate in the nonequilibrium steady-state of a laminar shear flow.[2] A shear flow is a hydrodynamic configuration where the flow velocity has a gradient. The ECM theory predicts that for a small observation sample, the entropy production rate will sometimes violate the Second Law of Thermodynamics by fluctuating to a negative value, and that the probability of these violations can be predicted. The original ECM paper has been cited over 1500 times, but until our recent publication[1] there had been no experimental test in a shear flow of this theory.

We analyzed data from an experiment with a laser-heated liquid-like two-dimensional dusty plasma. Two laser beams were used to drive a shear flow. In the gradient region between the two laser beams we analyzed the particle motion. The entropy production rate was calculated by tracking particle motion and computing the time series for shear stress in a small sample region.

We observed negative entropy production events, and these events had a probability that obeyed the fluctuation theorem. This result confirms, for the first time, that fluctuation theorems apply to a strongly coupled dusty plasma.

*Work was supported by Department of Energy and NASA/ JPL Agreement No. 1573108. The results reported here are based on data from an experiment that was performed previously by Zach Haralson.

[1] Chun-Shang Wong, J. Goree, Zach Haralson, and Bin Liu, "Strongly coupled plasmas obey the fluctuation theorem for entropy production," Nature Physics, 14, 21-24 (2018).
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Ion Wake Influence on Dust Chain Formation

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In many environments, positive ions in the plasma have a directed flow with respect to the negatively charged dust grains. The resulting interaction between the dust and flowing plasma creates an ion wakefield downstream from the dust particles, with the positive space-charge region modifying the interaction between the charged grains and contributing to the observed dynamics and particle structure. Since the force exerted by the ion wakefield is weak, the effects are usually masked by gravity for terrestrial experiments. The PK-4 experiment on board the International Space Station allows experiments to be conducted in microgravity, and thus the underlying physics behind self-ordering of interacting complex plasma dust particles in field-aligned chains can be investigated.

Here we report preliminary results of numerical models of the plasma discharge, wakefield and particle interactions in the PK-4 environment. An axisymmetric PIC/MCC and hybrid discharge simulation is adapted to model the discharge conditions in the PK-4 and a ground-based DC glow discharge and determine grain equilibrium positions. The local plasma parameters are then used as boundary conditions for an N-body code which models the dynamics of the ions and their interaction with the charged dust grains. Charging and dynamics of the grains are coupled self-consistently and derived from the ion-dust interactions. Pair correlation functions obtained from the grain dynamics will enable exploration of dusty plasma phenomena in the strongly coupled liquid phase.

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Anomalous diffusion in 1D dusty plasma structures: A fractional Laplacian model for strong correlations

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In the normal diffusion regime, the mean square displacement (MSD) of an ensemble of moving particles increases linearly in time, i.e. $\langle x^2 \rangle \sim t^s$ where $s = 1$. However, exponents $s \neq 1$ are also possible, yielding two distinct examples of anomalous transport: subdiffusion when $s > 1$ and superdiffusion when $s < 1$. Here we present a study of anomalous diffusion using the spectral approach to transport problems characterized by Anderson-type Hamiltonians with fractional Laplacian operators $(-\Delta)^s$, $s \in (0,2)$. The proposed model is applied to 1D dusty plasma systems, where strong interactions, structural defects, and collective effects are present.

It is expected that for $s > 1$ the wave propagation in the medium slows down due to negative correlations, while for $s < 1$, transport is enhanced due to positive correlations. In the spectral method we use, one calculates the mathematical distance D from a vector in the space to an infinite-dimensional sequence representing the time evolution of the wave propagation. It can be shown that if D approaches a nonzero value as time goes to infinity, the wave delocalized from the origin to the exterior of the medium. Below we present preliminary results from a toy-model code, which confirm that, in a 1D disordered system, $s > 1$ enhances localization effects, while $s < 1$ facilitates transport.

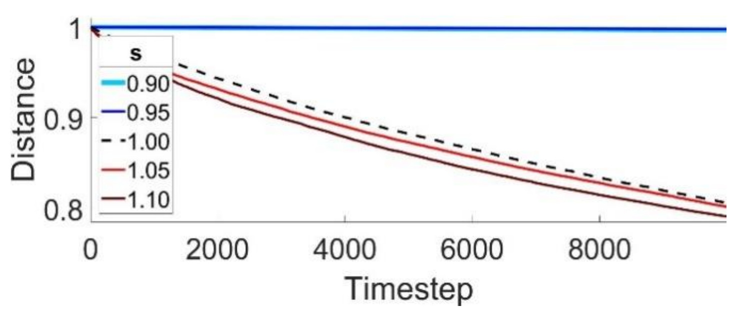

Figure 1 – In the normal diffusion and subdiffusion regimes ($s = 1, 1.05, 1.10$, shown as black dashed, light red, and dark red lines, respectively) the values of D tend to 0 as the number of timesteps increases. In agreement with theory, this corresponds to localized behavior. In the superdiffusion case ($s = 0.90, 0.95$, shown as light blue and dark blue lines, respectively), the values of D show negligible drop, indicating the existence of extended states.

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Solar panel cleaning on Mars with a pulsed plasma jet

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Fine dust particles are ubiquitous on Mars [1]. Storms or light winds can blow dust up in the atmosphere and carry it over large distances. When the lifting force of the wind ceases the dust particles settle down and deposit as a fine layer. The dust presence and its accumulation can decrease the power production of solar panels by blocking the Sun rays at a rate ~0.3% per day. The Martian dust is highly adherent to surfaces due to a combination of factors such as electrification (due to a high flux of UV radiation and low content of water vapors in the atmosphere or due to high electric fields during storms) and chemical composition (e.g. dust with a high ferric content is easily magnetized). A type of regolith with a similar chemical composition and made of volcanic ash with particle sizes up to 1 mm known as JSC Mars-1A can simulate the Martian dust.

We propose a robust cleaning technique which seems to be very effective for a wide range of particle diameters (from microns to mm) and much more rapid compared to known methods. The removal of dust is based on a pulsed plasma jet as shown in Fig. 1 a) [2]. A proof-of-principles demonstration is presented by cleaning an array of photovoltaic (PV) cells shown in Fig. 1 b) heavily covered with dust and sand immersed in CO_2 at low pressure [3].

The plasma is created in a discharge with two electrodes having a coaxial geometry in a miniature configuration of a few centimeters in size, at the pressure of the Martian atmosphere of 5 torr. Among the obvious advantages of this new method is the efficient cleaning of any type of surfaces with different morphology including those of solar cells, only after a few shots. The gun is operated at voltages only between 1 and 2 kV in order to minimize the required energy per pulse and to avoid damaging the PV cells.

Fig. 1: a) Image of plasma jet in CO_2 at 5 torr; b) cleaned PV after 20 shots at 1 kV.

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Experimental observation of cnoidal wave structures of dust acoustic waves*

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Self-excited dust acoustic waves (DAWs), generated in a ground-based experiment [1], are characterized using a method based on fitting exact nonlinear solutions of the Korteweg-de Vries (KdV) equation. The observed periodic waves, which have peaked crests and very flat troughs, display an excellent fit to cnoidal wave solutions of the KdV over a range of parameter space of the experiment. Our results will aid in the interpretation of future driven DAW experiments to be carried out on the PK-4 device under microgravity conditions. In particular, the analytical representation will help in understanding frequency synchronization when an external modulation is imposed.

*Work supported by NASA/ JPL Agreement No. 1573108 and NRL Base Funds

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Dust charging and heating models: high magnetic fields and strong electron emission

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The orbital-motion-limited (OML) theory provides a complete kinetic description of plasma response to the presence of a spherical absorbing body. Its simplicity and adaptability to a great variety of plasma-surface interactions make it a cornerstone of dust charging and heating models. However, OML formulas are only valid for collisionless, unmagnetized plasmas with weak shielding, implying that their applicability is limited to dust particles which are smaller than all mean-free-paths, Larmor radii and Debye lengths associated to the plasma species.

Among the numerous physical mechanisms susceptible to violate OML assumptions, the presence of high magnetic fields and strong electron emission currents are of particular interest to the study of dust and droplets in fusion plasmas:

- When background electrons are magnetized at the dust scale, the suppression of cross-field transport leads to the formation of a depleted flux tube which extends over distances exceeding the Coulomb mean-free-path [1]. A potential hill then arises in this region to maintain quasi-neutrality, eventually leading to a drastic reduction of the electron current to the dust, by up to two orders of magnitude [2,3].

- When electron emission is strong enough to compensate the incoming electron current, dust becomes positively charged and traps the emitted electrons in its vicinity. As a result, a potential well appears which acts as an effective shield against background electrons and significantly reduces dust heating [4,5].

Although a complete self-consistent description of the plasma response in the aforementioned cases is a formidable task, the essential physics at play can be captured by semi-analytic models, which have been recently developed for predictive studies of dust survivability in ITER [6].

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Emergent Bistability and Switching in a Nonequilibrium, Dusty Plasma Crystal

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Multistability is an inseparable feature of many physical, chemical, and biological systems which are driven far from equilibrium. In these nonequilibrium systems, stochastic dynamics often induces switching between distinct states on emergent time scales; for example, bistable switching is a natural feature of noisy, spatially extended systems that consist of bistable elements. Nevertheless, here we present experimental evidence that bistable elements are not required for the global bistability of a system. We observe temporal switching between a crystalline, condensed state and a gas-like, excited state in a strongy-coupled dusty plasma at low pressures (P < 1 Pa) and low bias voltages (|V| < 10 V). The melting of the crystal is initiated by well-known spontaneous vertical oscillations of particles at low pressures, and crucially depends on the polydispersity of the particles. Accompanying numerical simulations show that conservative forces, damping, and stochastic noise are sufficient to prevent steady-state equilibrium, leading to switching between the two states over a range of time scales, from seconds to hours.

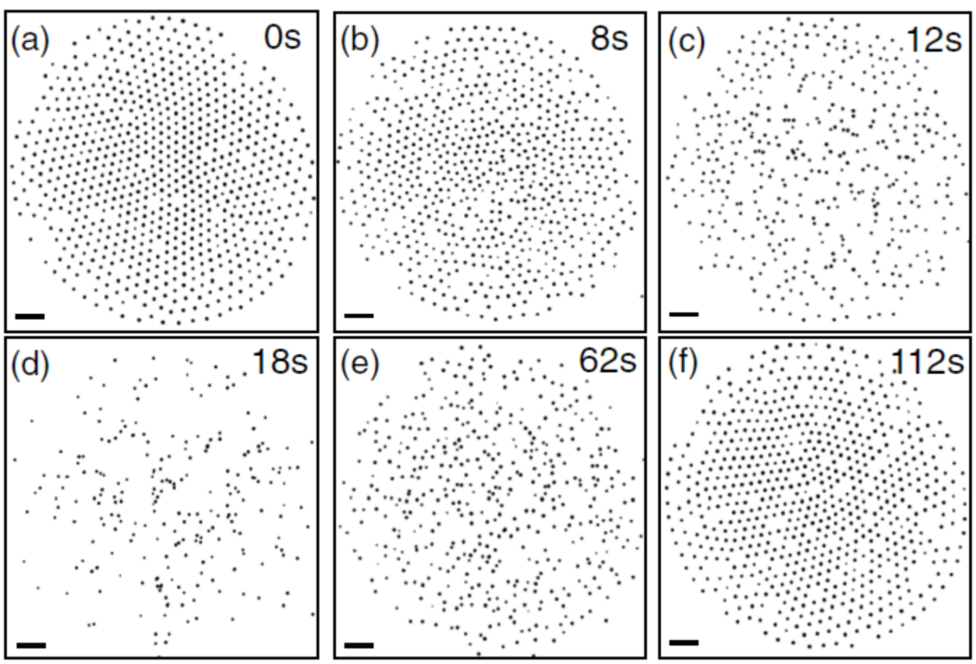

Figure 1 – Sequence of images showing the melting and subsequent re-crystallization of the dust particles at low pressure and bias voltages (taken from Gogia et al., Phys. Rev. Lett. 119, 178004 (2017). The scale bar is 5 mm.

Nanodusty plasma - the real dusty plasma

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Traditionally 'dusty plasma research' is the investigation of noble gas plasmas at low pressure containing a few, micrometer sized 'dust' particles. The interaction of the dust particles with the plasma is weak, i.e. the plasma mainly acts as agent that provides the charge and confinement of the dust particles. Three dimensional, stress free particle ensembles (dust clouds) of micrometer sized dust particles can only be created under micro gravity conditions due to the simple fact that gravitation scales with the cubed particle radius $\propto a^3$. Fig.1 shows dust clouds created under different conditions. In contrast to the cloud of micrometer sized dust under micro gravity (Fig.1(a)) and the nanoparticle cloud ((Fig.1(b)), the 'thermophoretic stressed' cloud (Fig.1(b)) shows no self exited dust density waves. Remarkably, the clouds under

Figure 1: *Three dimensional dust clouds, created (a) with micrometer sized dust under microgravity conditions, (b) using thermopheretic levitation, and (c) using nanoparticles in a ground based lab.*

micro gravity and the nanodust cloud look quit the same. However, the dust density of the nanodust clouds is much higher ($\approx 5 \cdot 10^{13}$m^{-3}). This leads to a strong electron depletion in the surrounding argon plasma. The electron depletion is quantified in terms of the so called Havnes Parameter $P = 4\pi\varepsilon_0 a \frac{k_B T_e}{e^2} \frac{n_d}{n_i}$. In plasmas with low dust density ($P < 1$) the plasma parameters are not strongly affected by the presence of the dust. In nanodusty plasmas, the Havnes parameter exceeds unity ($P > 1$) indicating that nearly all electrons reside on the dust and the free electrons are depleted. At very dense dust clouds ($P \gg 1$) essentially no free electrons are left.

We present different techniques, which are used to fully characterize the nanodust [1] and the nanodusty plasma [2]. Nanodusty plasma can easily reach states with a Havnes parameter of $P = 50$.

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Two dimensional dust density wave diagnostics (DDW-D) for the full characterization of a nanodusty plasma

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When the dust density in a dusty plasma reaches sufficiently high values, interesting phenomena occur. The presence of a large number of nanoparticles leads to a strong electron depletion in the surrounding plasma. In the limiting case this results in a pure two-component dust-ion plasma. This contribution describes a diagnostic method to non-invasively determine a large set of plasma parameters on a full two-dimensional cross-section by analyzing the self-excited dust density waves (DDW) of the nanoparticle cloud, which is a naturally occurring phenomenon driven by the ion flow.

Central to the analysis of the DDW are the wavevector and wave frequency of the wave field, which can be obtained by illuminating a plane through the nanodust cloud and using high-speed imaging at several thousand frames per second. By applying a hybrid fluid-kinetic model for the plasma-dust system, the underlying plasma parameters can be determined. This gives a full characterization of the plasma with spatially resolved information about ion and electron densities, dust charge, and the plasma potential. This contribution expands on Ref. 1 and presents the DDW diagnostics (DDW-D) for the complete characterization of a two-dimensional cross-section of the plasma.

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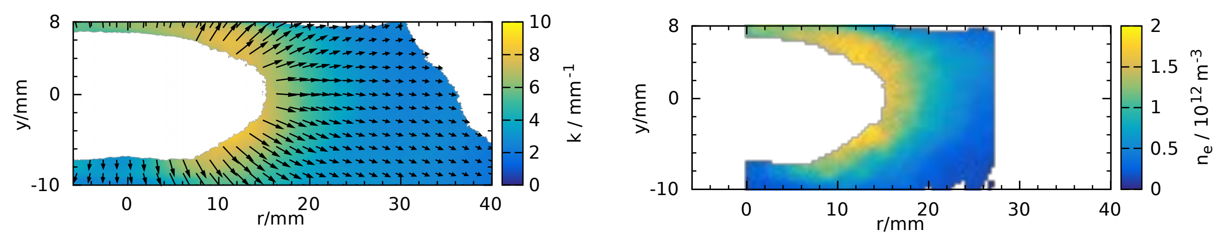

Figure 1 – Left: Color-coded map of the wave vector on a central plane through the nanodust cloud. Right: Color-coded map of the electron density as measured with the DDW-D.

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Nonlinear responses of a strongly coupled dust particle pair under the influence of an ion wake

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In order to observe and then examine nonlinear particle-particle interactions within a complex plasma, the amplitude-frequency response of a strongly coupled, vertically aligned, dust particle pair structure was measured experimentally by driving the lower electrode sinusoidally. Secondary responses were observed in both the sloshing and the breathing modes providing a signature for quadratic nonlinearity. These were compared to the theoretical amplitude-frequency responses derived from the equations of motion assuming two coupled oscillators and employing a multiple scale method. Fitting the experimentally measured response curves to the theoretical derived curves, the coefficients of the particle-particle interactions were calculated to the second order (k1’ and k2’), while the coefficients to the first order (k1 and k2) were calculated from the mode spectrum. These results identify a large downstream nonlinear scale parameter β, defined as the ratio between the coefficients for the first and second order terms in the interaction force expansion, indicating a more linear downstream interaction than upstream due to the influence of the ion wake.

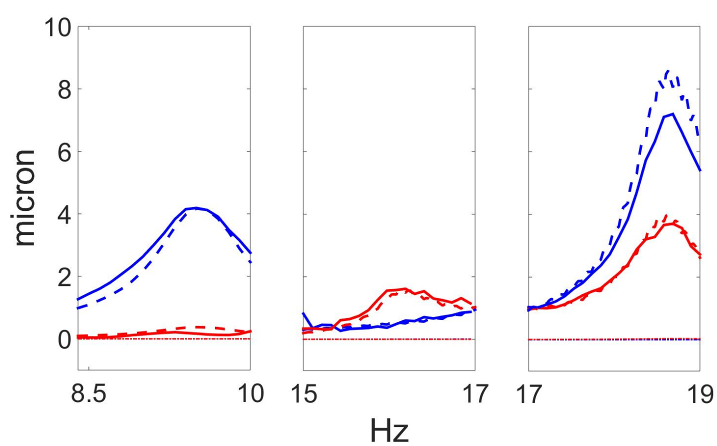

Figure 1. Solid and dashed curves represent the experimentally measured and simulated secondary responses. The red curve illustrates the breathing coordinate while the blue curve shows the sloshing coordinate. From left to right, the superharmonic sloshing region (around 9.5Hz), superharmonic breathing region (around 16Hz) and primary sloshing region (around 18.5Hz) can be observed. Simulated responses without nonlinearity (i.e., k1’= k2’= 0) are shown as dashed-dotted curves indicating no excitation.

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Measurements of Thermal Effects in the Dispersion Relation of the Dust Acoustic Wave

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The dust acoustic wave (also known as the dust density wave) is low-frequency, longitudinal mode that propagates through the dust component of the dusty plasma system and is self-excited by the free energy from the ion streaming through the dust component. Over the past twenty years, the dust acoustic wave has been a subject of intense study and recent studies have shown that thermal effects can, in some cases, have a significant role in the measured dispersion relation. In this talk, we report on the results of an experimental study of the dispersion relation of this wave mode over a range of neutral gas pressures in a weakly-coupled dusty plasma system in an rf discharge plasma. The experimental dispersion relation are modeled using a theoretical dispersion relation that includes thermal effects and the effects of dust correlations that arise from the confinement of dusty plasmas in the plasma volume. (K. Avinash, Phys. Plasmas, 22, 033701, 2015)

This work is supported by National Science Foundation Grant Number PHY- 1615420.

Non-linear effect of a vertical dust chain confined in a glass box

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The stochastic motion of dust particles confined in a glass box placed on the lower electrode of a GEC reference cell is investigated using MSD and position probability distribution function techniques. These techniques are used to measure the interaction potential between a pair of vertical dust particles as a function of their separation distance. The resulting experimental data shows that for large separation distances ($\Delta h > 0.4$ mm) the interaction potential is almost parabolic while for separation distances between 0.2 mm $< \Delta h < 0.4$ mm the resulting mathematical expression for the potential requires the addition of a cubic term having a negative signed coefficient. Finally, at $\Delta h < 0.2$ mm the sign on the cubic coefficient changes to a positive sign. It will be argued that this behavior is related to the positive to negative sign change observed in the linear thermal expansion coefficient for particle pair structures.

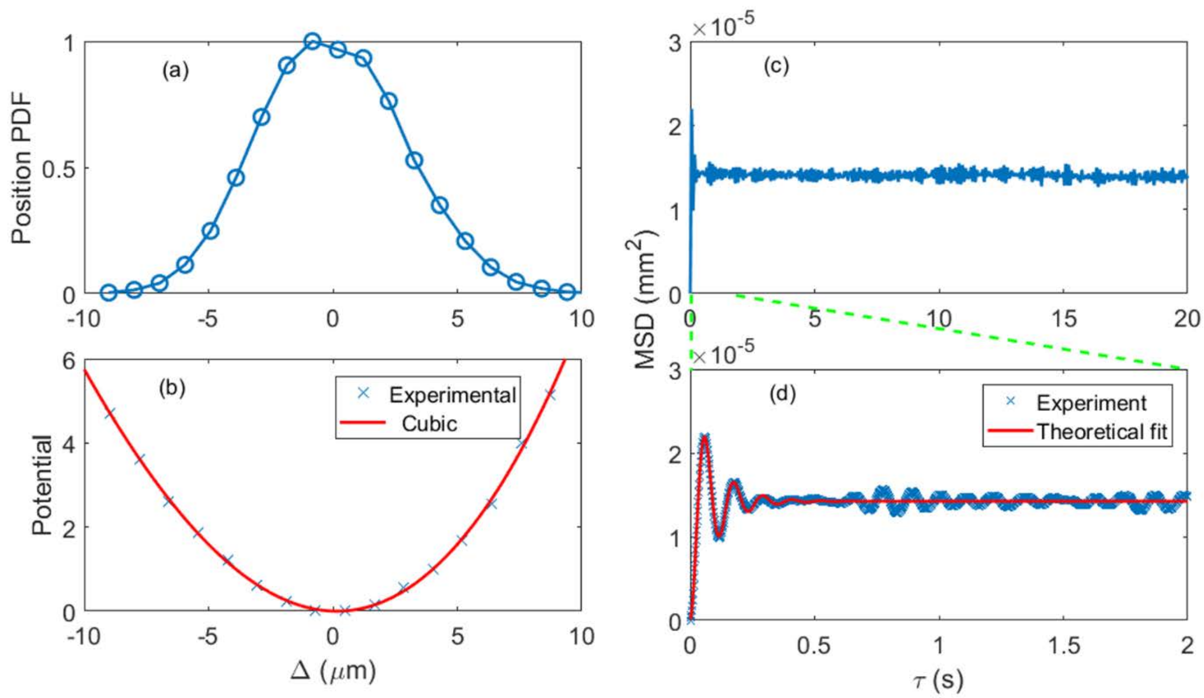

Fig 1. (a) Experimental relative position probabilty distribution function. (b) Confinement potential derived from (a). (c) Corresponding MSD. (d) Expanded view of (c).

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Interaction between a dust particle pair and the ion flow modified potential in complex plasma

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The manner in which the electric field potential around a dust particle is modified by an ion flow is an important topic in complex (dusty) plasma physics. In this research, a non-intrusive method to measure the particle-particle interaction strength and the *in-situ* confinement for a vertically aligned dust particle pair is introduced. The method uses only the thermal motion of the particles and allows the above-mentioned quantities in both the vertical and horizontal directions to be determined simultaneously. By comparing the interaction strengths in the vertical and horizontal directions for various rf powers, the ion flow modified potential around a dust particle can be studied in both the upstream and downstream directions. The particles are found to be in a subsonic ion flow region for lower powers, due to the different screening lengths measured in the upstream and lateral direction. A decrease in the magnitude and an increase in the length scale for the downstream wake potential is observed in this subsonic region. These characteristics of the ion wake potential have been predicted both theoretically and numerically but to our knowledge, this is the first time they have been observed experimentally.

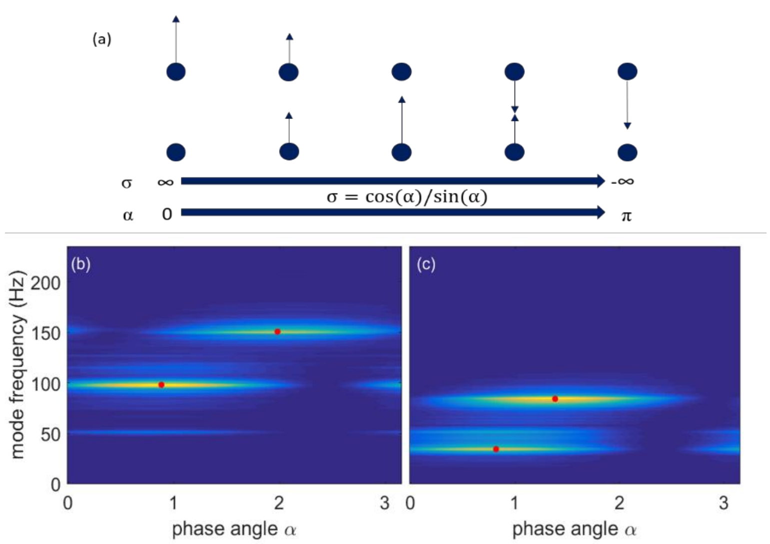

Fig. 1. Eigenvector space scanned and spectra obtained from the vertical and horizontal velocity.

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Overlapped Plasma Sheath in Narrow Space

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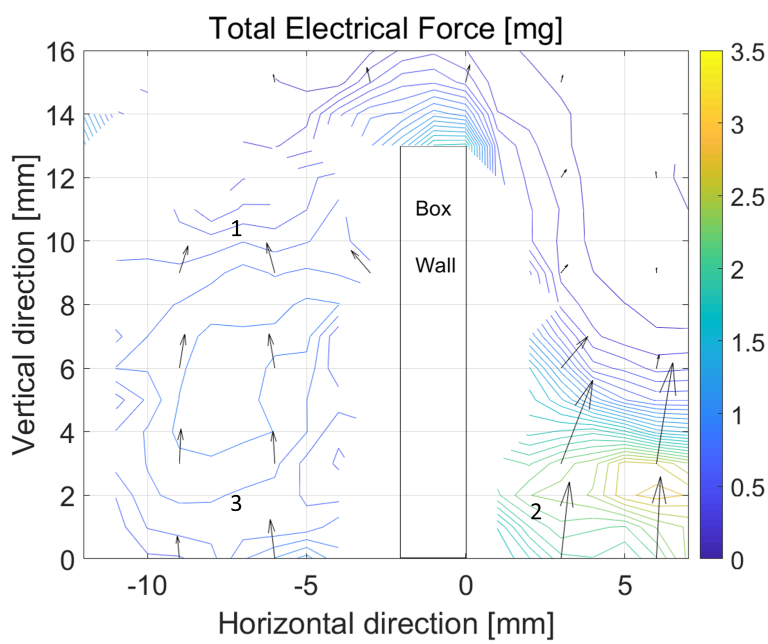
The fundamental properties of the plasma sheath have proven difficult to measure. As a result, most studies focus on sheaths formed around planes, cylinders and spheres and often assume them to be one dimensional. Additionally, recent experimental investigations have attempted to examine sheaths formed inside narrow spaces. In these cases, the sheaths created by the various surfaces involved often overlap one another in a manner not easily described by current sheath models. Given this occurs in industrial applications like those found in semiconductor manufacturing or medical plasmas, such investigations are sorely needed. In this talk, a dust particle will be employed as a probe to measure the sheath formed inside several glass boxes of differing sizes and placed on the lower electrode of a GEC rf reference cell. Employing the experimentally measured motion of the dust particle, the distribution of the electric field force inside these boxes will be mapped. It will be shown that comparison of this motion for sheaths formed within different environments allows several effects of sheath overlap to be observed.



Force map in different regions with different overlapped sheath. Region 1: sheath of the walls of the glass box overlapped; Region 2: the sheath of the single wall and the sheath of the electrode overlapped. Region 3: sheath of the walls of the box and the sheath of the electrode overlapped.

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Status and future of the Magnetized Dusty Plasma Experiment (MDPX)

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For over a decade, it has been postulated that the addition of a magnetic field can have a profound influence on the properties of a complex/dusty plasma. A number of experimental devices have been built around the world to explore the physics of dusty plasmas in strongly magnetized plasmas. In 2014, the Magnetized Dusty Plasma Experiment (MDPX) device at Auburn University became the latest facility commissioned to study the properties of dusty plasmas at high magnetic field ($B \geq 1$ T). The MDPX device is a flexible, high magnetic field research instrument with a mission to serve as an open access, multi-user facility for the dusty plasma and basic plasma research communities. In a strong magnetic field, the transport of ions and electrons in the plasma will be modified. This changes how the microparticles become charged and modifies the Debye screening of the microparticles by the surrounding plasma, thus altering the inter-particle interactions within the plasma. Experiments on the MDPX device have given us new insights into particle charging, self- and imposed-ordering, particle transport, particle growth, and plasma and dust instabilities in strongly magnetized plasmas. This talk will highlight a few of these new observations but will focus on using these observations to motivate the next generation of experiments on the MDPX device.

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Quantitative analysis of laser forces in binary complex plasmas

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Lasers have been widely used in complex plasma experiments to excite particle oscillations and waves, trap particles and increase the kinetic temperature of particles levitating in the plasma sheath. The latter allows for e.g. the investigation of phase transitions, heat transport and diffusion processes. All above mentioned methods utilize that momentum is transferred to the particles via radiation pressure. A second mechanism, the radiometric force, has been discussed, that is related to a photophoretic process [1]. If and to what extent the second mechanism plays a role is unknown since it is difficult to obtain this information from experiments. Since the magnitude of the radiation pressure depends on the particle cross section using differently sized particles provides an opportunity to investigate the mechanism for momentum transfer in detail. Binary mixtures, systems composed of two particle species with different radii, can form two-dimensional systems under certain conditions [2]. Thus, these two component systems are ideal to investigate whether other mechanisms substantially contribute to e.g. the kinetic temperature particles assume in the thermal reservoir generated by the laser heating setup. In this contribution results of laser heating experiments with binary mixtures are presented. The kinetic temperatures of both particle species are analyzed in terms of neutral gas pressure dependency and compared to a model. Especially the contributions of radiation pressure and a radiometric force are discussed.

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Methods for the characterization of imposed, ordered structures in MDPX

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Recently a new type of dusty plasma structure was discovered in the Magnetized Dusty Plasma Experiment (MDPX) at Auburn University. These structures were termed imposed, ordered structures due to the dust particles acquiring the same spatial pattern as a conducting wire mesh in the experiment at high magnetic fields. While early studies of this phenomena focused primarily on the initial observations and particle dynamics within this new structure, little work was done to systematically determine under what experimental conditions these imposed, ordered structures were formed. This work will establish a pair of parameters to categorize the experimental conditions. The first parameter, the normalized mean grey value (NMG value), quantifies the average amount of the observational area within the experimental region of interest through which the particles are flowing. The second parameter, the local bond order parameter Ψ_4, describes the relative inter-particle orientation. By using these measurements, in conjunction with the ion Hall parameter, a correlation between ion magnetization and confinement to the imposed, ordered structure can be shown.

This work is supported by funding from the US Dept. of Energy, Grant Number DE-SC0016330 and by the National Science Foundation, Grant Number PHY-1613087. Additional support is provided by the NSF EPSCoR program (OIA-1655280).

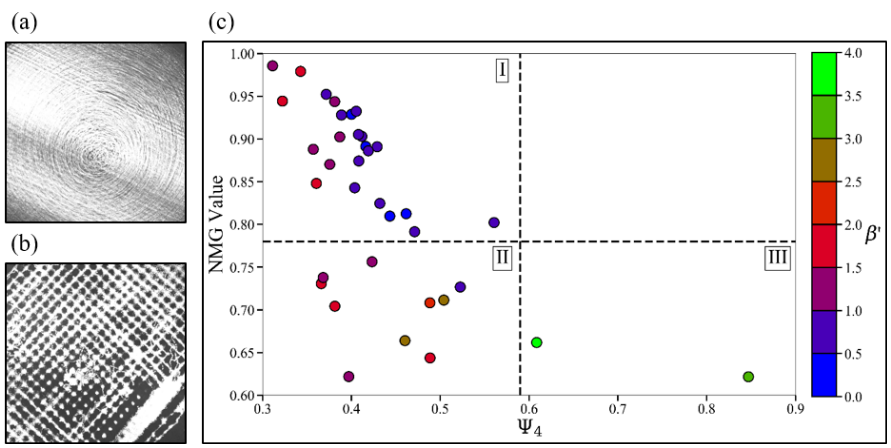

Figure 1 – (a) A sum image of 600 video frames at B = 0.49 T and P = 120 mTorr with a NMG value of ~1 due to the white particle streaks filling a high percentage of the region. (b) A sum image at B = 1.22 T and P = 40 mTorr with a low NMG value from high confinement to the imposed, ordered structure. (c) NMG value versus Ψ_4 colored according to the modified Hall parameter $\beta' = \frac{\lambda_{mfp}^{in}}{2\pi r_l}$ where λ_{mfp}^{in} is the ion-neutral mean free path, and r_l is the ion Larmor radius. Region I represents cases with very low confinement to the imposed, ordered structure and low interparticle organization. Region II has higher confinement to the imposed ordered structure, but still low interparticle organization. Region III has both high confinement and high interparticle organization, and correlates to magnetized ions within the plasma.

Friday, June 1, 2018

Non-invasive impedance measurements of electron density in a complex plasma

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A plasma discharge can be modeled electrically as a combination of capacitors, resistors, and inductors. The plasma, much like an RLC circuit, will have resonances at particular frequencies. The location in frequency space of these resonances provides information about the plasma parameters, the electron density in particular. These resonances can be detected using impedance measurements, where the AC impedance of the plasma is measured by sweeping the frequency of an AC voltage applied to a sensor and determining the magnitude and phase of the measured current.

Diagnostic measurements in a dusty plasma present a significant challenge due to dust grain interaction with the physical probe or non-invasive probing mechanism. The novelty of this method is that insertion of a physical probe that perturbs the charged dust grains is not necessary. In this work, an electrode serves dual purposes, being used to probe the dusty plasma while also sustaining the glow.

This non-invasive impedance probing method is used to measure the electron density in a complex plasma discharge. Comparison of non-dusty and dusty plasma experimental results will be presented. Particular attention will be focused on the dust particle impact on the measured free electron density in the discharge. Potential applications of this diagnostic method and regimes over which this measurement method is valid will also be discussed.

Particle Orbits in Combined E and B Fields

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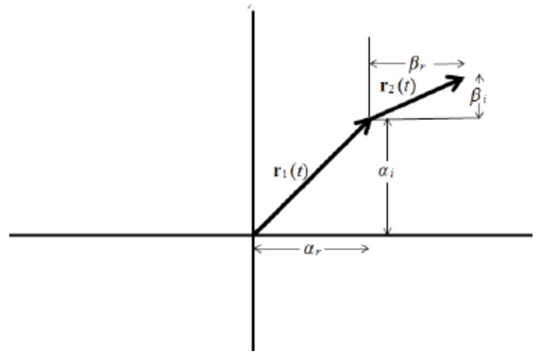

Figure 1 Sum of two individually rotating vectors.

Analytic solutions are presented [1] for the orbit of a charged particle in the combination of a uniform axial magnetic field and a parabolic electrostatic potential. As shown in Fig. 1 the orbit trajectory consists of the sum of two individually rotating vectors with one vector rotating at a constant fast frequency and the other rotating in the same sense but with a constant slow frequency [1,2]. This can be visualized as being like a double pendulum where both arms (vectors) make complete and continuous rotations about their point of support; the particle is located at the tip of the arm having the moving point of support (i.e., particle is located at the tip of the outer arrow in Fig.1). If the lengths of the two rotating vectors are identical, the particle has zero canonical angular momentum in which case the particle orbit passes through the origin.

When the electric field is small, the particle motion is a sum of **E** x **B** drifts and cyclotron motion; this limit corresponds to the guiding center approximation. Non-axis-encircling orbits occur when the length of the vector associated with the fast frequency is shorter than the vector associated with the slow frequency. Axis-encircling orbits occur when the fast vector is longer than the slow vector.

If the radial electric field is repulsive relative to the origin and has a value exceeding a specific threshold, the particle no longer makes periodic orbits but instead has its radial separation from the origin increase exponentially with time; this corresponds to stochastic motion.

If the potential is not parabolic but instead has an inverse dependence on distance from the origin and is large and attractive, a zero-canonical momentum particle (equal length vectors) spirals into the origin [2].

By changing the charge to mass ratio of a dust grain in the combination of a uniform axial magnetic field and a radial electric field, the various types of orbits described here could be demonstrated.

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Laser Induced Fluorescence (LIF) in the Caltech Water-Ice Dusty Plasma Experiment

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The Caltech Water-Ice Dusty Plasma Experiment creates an astrophysically relevant water-ice dusty plasma in the laboratory [1]. Background gas on the order of 100s of mTorr enters into a small vacuum chamber where it is ionized into plasma by 1-3 W of 13.56MHz RF across two parallel circular electrodes. The electrodes are cryogenically cooled with liquid nitrogen to ~150K which causes water vapor to spontaneously freeze into ice grains in the plasma. Past studies have shown that the maximum size attained by the ice grains depends heavily on background gas species, background gas pressure, and by addition of a magnetic field [2]. It is also concluded that grain growth is dominated by accretion [1].

A LIF diagnostic is under development for the Caltech Water-Ice Dusty Plasma Experiment. This diagnostic uses a tunable ultra-narrow-band diode laser, a photomultiplier, and a lock-in amplifier. Two separate laser heads can be operated one at a time to perform LIF on either neutral argon or singly ionized argon. Neutral argon measurements yield signal to noise ratios greater than 100. This LIF signal can be observed without any signal averaging but with a greatly reduced signal to noise ratio. The Lamb Dip has been observed [3]. Work is underway to create a more accurate and precise system to measure temperature as well as a motorized 5-axis stage to allow temperature measurement as a function of position. Argon ion LIF investigations will begin shortly.

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Blast waves experiments in a 2D dusty plasma

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Using a 2D layer of microspheres levitated in RF plasma, a nonlinear compressional pulse was launched by moving a wire. The experimental setup was similar to that of Samsonov *et al.* [1] except that our wire moved and was allowed to float electrically. We found that moving the wire inward, toward the center of the cloud of microspheres, caused a compressional pulse to be launched as in Figure 1. Because this pulse propagated at a supersonic speed and its density profile had a sharp gradient, we describe the pulse as a shock. In particular, the shock was of a type called a "blast wave" because the motion of the wire that excited the shock was abruptly stopped, yet the shock continued onward without further energy input from the wire.

During the time that the energy input from the wire had already stopped, we found that the pulse amplitude did not decay exponentially with time, as one might expect due to gas drag. Energy input from ion flow may explain this sustained pulse amplitude, since unlike the wire's motion, ion flow was sustained throughout the experimental run.

Work supported by the U.S. Department of Energy and NASA-JPL.

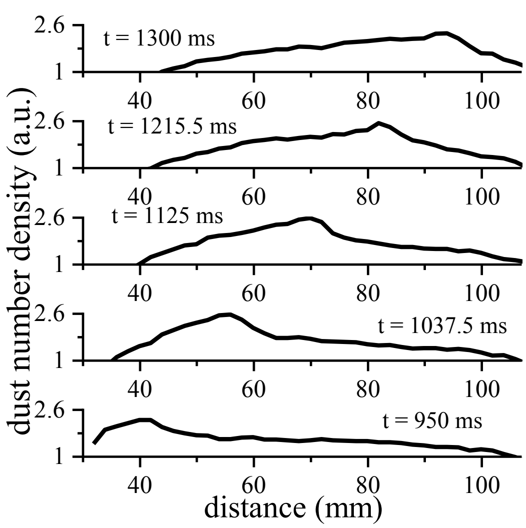

Figure 1 – Evolution of the pulse waveform. The distance shown here was measured in the direction of the wire's motion.

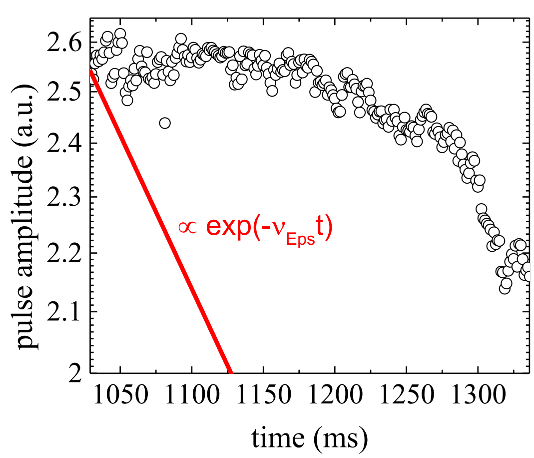

Figure 2 – Pulse amplitude vs time. The wire's motion stopped at t = 900 ms, before the earliest time shown here.

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Interaction of a supersonic particle with a three-dimensional complex plasma

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The Ekoplasma setup is developed as next generation plasma chamber for future investigation of complex plasmas on the International Space Station. In this contribution the setup is used during the 29th DLR parabolic flight campaign to study the influence of a supersonic projectile on a three-dimensional complex plasma. Micron sized particles formed a large undisturbed system in the "Zyflex" chamber during microgravity conditions. A Mach cone with a double Mach cone structure was excited by a supersonic probe particle with Mach number $M \approx 1.5 - 2$ in the large weakly damped particle cloud. The sound speed is measured with different methods and particle charge estimations are compared to the calculations from standard theories. High image resolution enabled the study of the Mach cone on the single particle level and gives insight to the dynamics. We discovered a heating of the microparticles behind the supersonic projectile but not in the flanks of the Mach cone. The heating is connected to different waves of the double Mach cone structure.

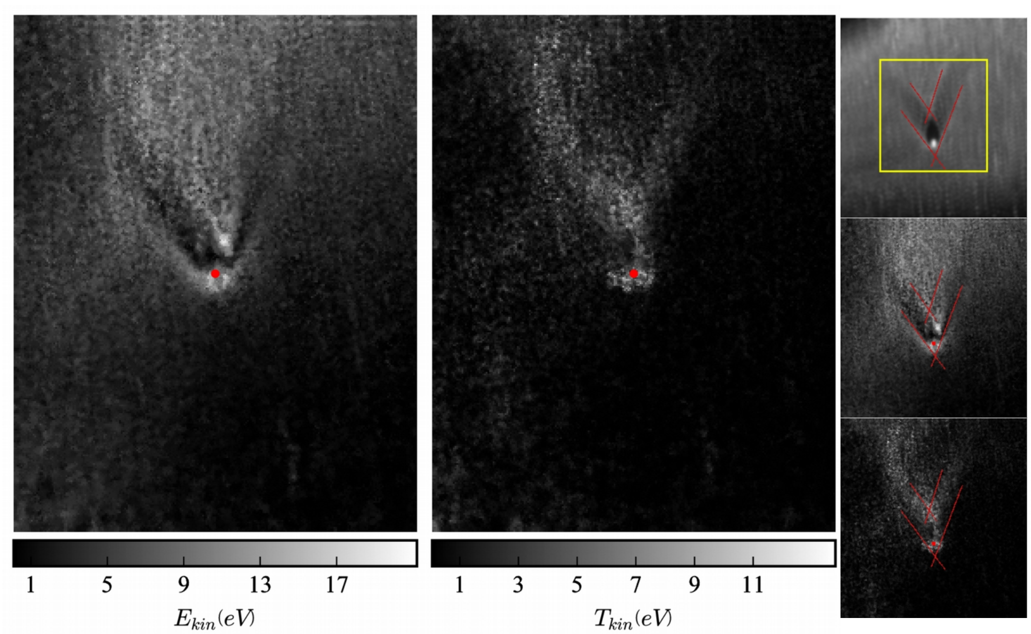

Figure 1 – Effect of the supersonic particle on the kinetic energy (left) and kinetic temperature distributions (middle) in the microparticle cloud. (right) The double Mach cone structure is indicated by red lines and the position of the probe particle by a red dot for blurred overlay (top), energy (middle) and temperature (bottom). Note that the heating occurs mainly behind the supersonic particle and not in the waveshock fronts of the first Mach cone.

This work and some of the authors are funded by DLR/BMWi (FKZ 50WM1441).

Inductively Coupled Discharges to Sustain and Rotate Dusty Plasmas at High Magnetic Fields

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Recent dusty plasma experiments at fields ranging from 0 to 3.25 T at the MDPX superconducting magnet at Auburn University[1] demonstrate that it is possible to sustain stable and filament-free dusty plasmas. Argon gas with fill pressures ranging from 35 to 150 mTorr, were used to sustain inductively coupled plasmas (ICP) and levitate silica hollow microspheres with a diameter of 50 µm. Our experimental setup included a metal tray in which the dust normally rests (no dust shaker was used for these experiments), and an upper electrode immersed in an argon plasma that is normally at floating potential. The upper electrode is only connected to a DC power supply (enabled concurrently to the RF discharge) to purposely create filaments and arcing to the bottom tray, leading to dust particles being 'kicked up' and then being levitated by the resistive plasma sheath as they fall back down. Once enough particles are captured at the plasma sheath, the DC voltage is turned off and levitation is only sustained by the ICP. The RF frequency range 22 – 30 kHz is cutoff by the plasma close to the chamber's cylindrical wall, leading to a plasma density gradient that peaks at the wall and is minimum at the chamber's axis. We conjecture that such density gradients cause pressure gradients that are in turn responsible for dust rotation (Fig.1) through ion momentum transfer in the $\nabla P \times B$ direction, initially proposed as an explanation for previously reported experiments[2,3]. However, rotation is an order of magnitude higher and with particles that are a lot more massive than in these previous experiments. Here, we discuss the leading hypotheses and parameters that may explain the observed fast rotation, and comparisons with molecular dynamics simulation as well as a new magnetized dusty plasma setup at UMBC with fields up to 0.08 T.

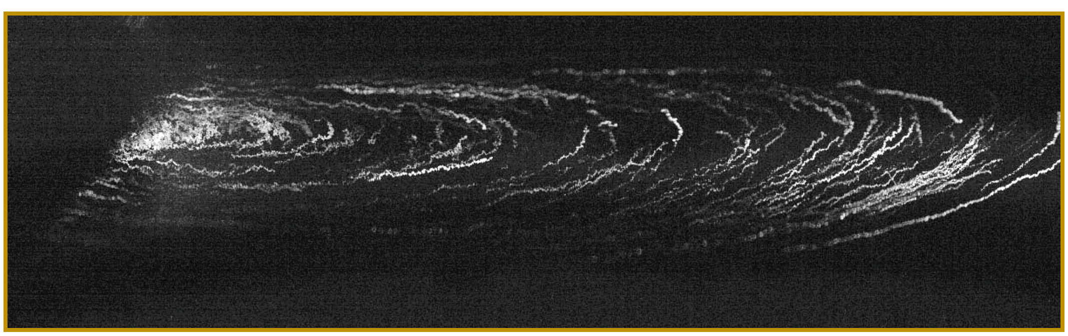

Fig. 1 Tracks of 50 µm particles rotating in a 0.062 T field, 103 mTorr argon prefill.

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[2] P.K. Kaw, K. Nishikawa, N. Sato, *Phys. Plasmas* **9**, 387 (2002).
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Modeling the growth of chondrule dust rims under different plasma conditions in protoplanetary disks

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Chondrules, the formerly molten, quasi-spherical, (sub)millimeter-sized silicate grains that are the primary constituents of chondritic meteorites, are commonly surrounded by fine-grained dust rims (FGRs). These rims, which can be observed in the laboratory, encase valuable information regarding early processes in our solar system. Such rims are generally considered to have been acquired by collisions between free-floating chondrules and dust particles in the nebular gas. As cosmic dust becomes charged in the radiative plasma environment, their trajectories and orientations while moving toward the chondrule can be altered by the electrostatic force acting between them. The deflection and deceleration can cause the dust particles to miss the chondrule, affecting the coagulation probability. In addition, the charge also impacts the porosity of the rim as the decreased relative velocity can reduce restructuring.

This study compares the growth of fine-grained chondrule rims through the collection of micron-sized dust grains in protoplanetary disks with different turbulence strengths and different plasma conditions. A Monte Carlo algorithm is used to select incoming dust particles and determine the elapsed time between collisions, with the collision outcome modeled by an N-body code, Aggregate_Builder (AB). The distribution of charge on the aggregate surface is calculated by the Orbital Motion Limited Line of Sight (OML-LOS) method, where the monomer surfaces in the aggregate are divided into patches and the electric currents due to incoming electrons and ions are calculated for each patch.

Dust grains with a greater charge cause dust rims to grow more slowly and be composed of larger monomers. The decreased relative velocity between charged grains causes small grains to be repelled from the chondrule in regions of weak turbulence, while in regions with strong turbulence, the main effect is a reduction of the restructuring.

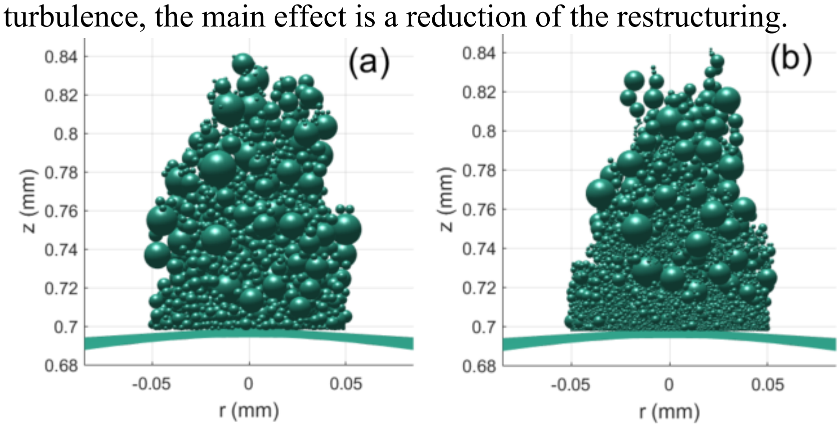

Figure 1 – Rim growth on a 100 μm-diameter patch on the surface of a chondrule with a radius of 700 μm, formed from a) charged dust grains and b) neutral dust grains.

Support from NSF / DOE Grant numbers 1414523 is gratefully acknowledged.

Poster Presentations

Poster Session 1

Wednesday, May 30, 2018

An overview of modifying the spatial structure in a complex plasma

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Complex plasmas are four-component, low temperature plasma systems composed of electrons, ions, neutral atoms, and micron-sized, charged particles (dust). Because the dust particles are charged, they interact with the background plasma. In the presence of gravity, the dust particles are compressed to thin layers, but under microgravity conditions, the particles fill the plasma volume which enables the study of small-scale forces. One important question is the determination of how the thermodynamic properties of a complex plasma evolve when the inter-particle potential (screened Coulomb potential) is modified from a non-reciprocal to a reciprocal structure.

In the Plasmakristall-4 (PK-4) microgravity laboratory on the International Space Station, particles are injected into a dc glow discharge plasma and flow along an axial electric field. Upon the application of “polarity switching” (a periodic oscillation of the electric field), it is observed that there is change in the spatial ordering and the thermal state of the particles. It is believed that this change is due to a modification of the ion screening around the dust particles that arises from the oscillating electric field which modifies the spatial structure of the Debye screening around the dust particles. This presentation will present preliminary results on this structure effect seen in the PK-4 flight and ground-based experiments.

This presentation will also present initial results from molecular dynamics simulations which has been motivated by the polarity-switching experiments on PK-4. Using the DEMON simulation code, the screening potential around the dust particles is modified to investigate the effect on the spatial ordering and thermal properties of a dusty plasma.

We would like to acknowledge the joint ESA-ROSCOSMOS Experiment «Plasma Kristall-4» on-board the International Space Station. This work is supported by funding from NASA/JPL (JPL-RSA 1571699) and DLR/BMWi under contract 50WM1441. Additional support is provided by the NSF EPSCoR program (OIA-1655280).

Exploration and Comparison of ISS PK4 Data to Ground- and Numerical-based Models

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The study of dusty plasma phenomena such as dust acoustic waves and field aligined dust particle chains are of interest due to their impact across various fields of basic physics and industrial applications. Data recently provided by the Plasmakristall-4 (PK-4) device located on the International Space Station (ISS) is providing important clues about the physics underlying the behavior of the aforementioned phenomena. For all of these experiments it is critical researchers can properly read the video data that the PK-4 device provides in order to ensure that under analysis it is appropriately synchronized with the electronic data. In this work, we will present analysis and translation of selected data sets from the first three flight campaigns of the PK-4. The algorithms used to translate the PK-4 CAN-BUS hexadecimal data and the process applied for stitiching the data from the two particle imaging cameras will be presented. Additinally, the process whereby timestamps for both the CAN-BUS PK-4 housekeeping data and the data from the cameras are used to synchronize the PK-4 experimental results will be discussed (see figure 1). These translation and stithching results are critical not only for providing a proper understanding of previous campaign experiments but also for planning future experiments. Finally, this work has proven to be essential to the construction process of the Baylor PK-4 ground unit (fig. 2) and this will also be dicussed.

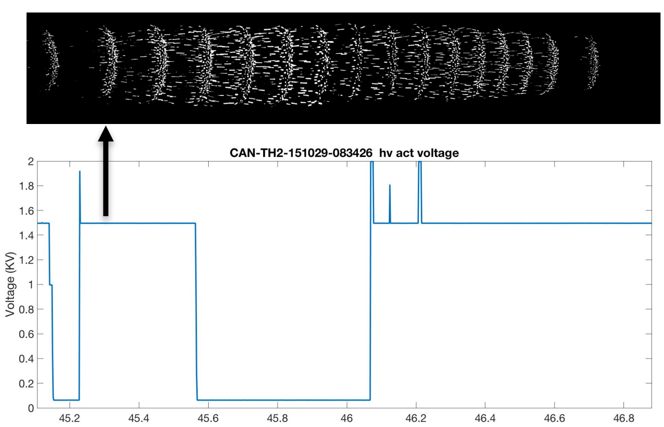

Figure 1. Alignment of the the housekeeping data with the video data

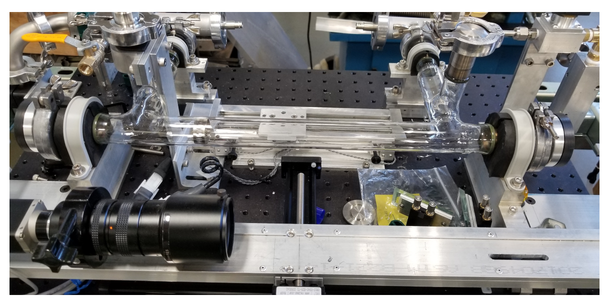

Figure 2. Baylor's PK-4 ground unit.

Support from NASA Grant number 1571701, NSF / DOE Grant numbers 1414523, 1707215 and NSF Grant Number 174023 is gratefully acknowledged.

Interpretation of dust impact signals detected by RPWS and BMSW instruments

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We present the analysis of laboratory investigations of dust impacts into two instruments, RPWS (Radio Plasma Wave Science) and BMSW (Bright Monitor of the Solar Wind). In the case of RPWS, the reduced size model of the Cassini spacecraft equipped with three antennas, similar to RPWS was developed. The aim of the laboratory simulation measurements is to clarify the physical processes of a signal generation, to investigate instrumental effects which can affect production of these signals and to find posissible consequences for dust signals detected by spacecraft in our solar system.

The antennas of RPWS can be configured either in a dipole or monopole modes. Both the antennas and spacecraft body can be biased up to ±50 V with respect to the interaction chamber. Small tungsten plates were attached to the impact spots of antennas and the spacecraft body to increase an impact charge yield. On the other hand, the configuration of the Faraday cups of BMSW allows a fast separation of the impact cloud due to high homogenous electric field between a suppressor grid and collector. The spacecraft model and Faraday cup were bombarded with submicron-sized iron grains in the velocity range of 1–40 km/s using the 3 MV dust accelerator operated at the LASP facility of University of Colorado.

The RPWS experimental results support the suggestion that dust events (Fig. 1 – left) recorded in the dipole mode are due to antenna hits. On the other hand, impacts onto the High Gain Antenna generate signals on the monopole antenna only. The recollection of the impact charge and the induced charging are the main processes responsible for production of antenna signals. The amplitudes and polarities of the detected signals depend both on the impact location (antenna vs. spacecraft) and the polarities of the spacecraft and antenna biases. The BMSW instrument results indicate an influence of the charge carried by the grain on generation of dust signals (Fig. 1 – right).

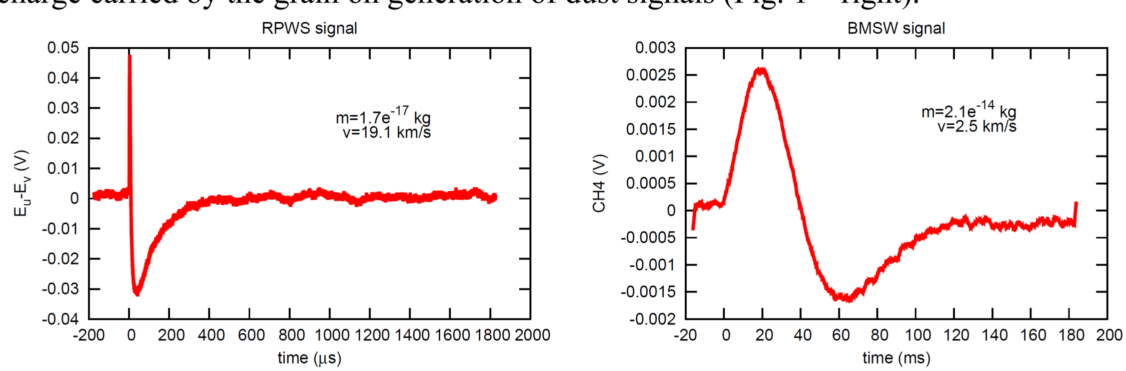

Fig. 1 – Example of detected dust signals by the Cassini spacecraft model (left) and by BMSW instrument (right).

Emergent Bistable Switching in Nonequilibrium Crystal

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In nonequilibrium systems made of bistable elements, global bistability is a common feature, so that the entire system switches behavior. Nevertheless, our recent work has shown experimentally that bistable elements are not required for the global bistability of a collective system [1]. We observed temporal switching between a crystalline, condensed state and a gas-like, excited state in a quasi-two-dimensional dusty plasma. The switching occurs over a broad range of time scales, from seconds to hours. We confirmed our results using molecular dynamics simulations, which showed that conservative forces, damping, and stochastic noise are sufficient to induce switching in systems with small particle polydispersity. Building on this work, here we generalize these results by examining the harmonic vibrational modes of the system. We find that an intermediate number of vibrational modes with low participation ratios are responsible for emergent switching. The importance of inertia is a distinguishing feature of this class of switching. In addition, by increasing the number of particles in both the experiment and simulation, we find more complex, avalanche-like dynamics - only part of the system switches from the crystalline to the gas-like phase, and the size of the melted region varies with each avalanche event.

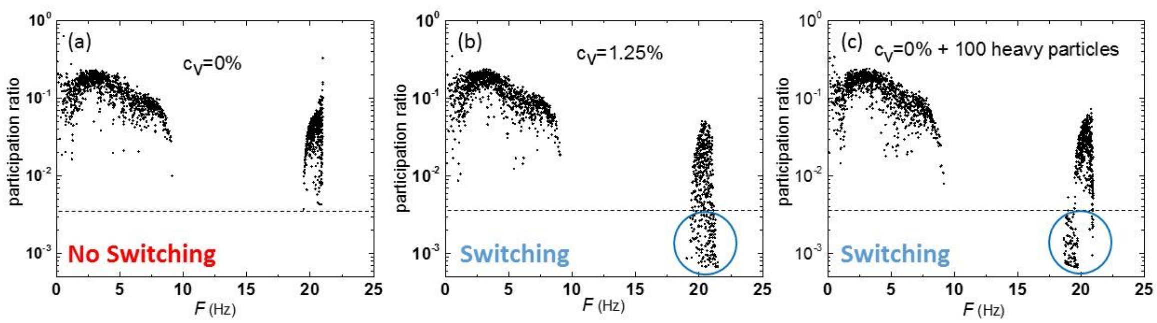

Figure 1 – Investigation of the vibrational modes of the 2D dusty plasma crystalline layer from numerical simulations. Each layer consists of 500 particles and is characterized with two bands – one centered around ~20Hz corresponding to the vertical modes and the other one, ranging from 0 to 10 Hz, corresponding to horizontal modes. Participation ratios of the system are shown for three different particle size distributions as a function of frequency. Particle size distributions are characterized via the coefficient of variation (standard deviation divided by the mean of particle sizes). (a) Perfectly monodisperse sample that never switches – it remians crystalline and oscillates like a rigid body. (b) A sample with continuous particle size distributions, $c_V = 1.25\%$. This system switches continuously between crystalline and melted states. (c) Monodisperse system of 400 particles with an additional 100 heavier particles (with radius 1.06 times larger than the radius of monodisperse particles). This system also switches between crystalline and gas-like states. In both (b) and (c), there are eigenvectors with low participation ratios. These modes are responsible for the transfer of vertical oscillation energy to the horizontal directions, and the eventual nucleation of melting.

1. G. Gogia and J. C. Burton, Physical Review Letters **119**, (2017).

In-situ nanoparticles characterization by Small Angles X ray Scattering (SAXS) during their growth in a dusty plasma

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In the wide areas of technological development there is a very important lack of risk management related to nanoparticles. For example, in the case of so-called passive nanostructrures (nanopowders for example), the knowledge concerning their new properties and functionalities, their morphology, their toxicity and the levels of exposure to these entities are very low. It is well known that there is no in-situ control system for nanoparticles suspended in open air, especially at manufacturing sites and workplaces in industrial environments. There is therefore an urgent and vital need for development of detection, metrology and characterization tools in this size range that can respond to the diversity of situations. In addition, and at the industrial level, this need becomes extremely urgent for microelectronics technologies. Indeed since the early 90's it has been shown that plasmas themselves are very important sources of growth of nanoparticles from the used reactive gases, the products of etching and spraying. They constitute an important source of contamination of the devices being manufactured despite all the precautions taken such as working in clean rooms where the ambient air is in principle strongly filtered.
In this contribution we report on nanoparticles characterization by means of small angles X rays scattering (SAXS). The main results concern their mean size, morphology and porosity during the earlier growth phase.

Study of particles de-agglomeration in non-equilibrium low-pressure radiofrequency plasma

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This contribution describes an interesting phenomenon concerning the interaction between a non-equilibrium low-pressure radiofrequency plasma and aggregated particles injected into it. This phenomenon is related to the particle de-agglomeration when they are injected in a plasma. In order to develop nanoparticle metrology diagnostics in "dry environment", a unique experimental device has been developed, composed of a low-pressure radiofrequency plasma reactor and a nanoparticle injector allowing the characterization of nanoparticles by non-intrusive metrology diagnostics. The particles injected into the plasma gas phase are trapped and levitate within the chamber. The average size of the nanoparticles obtained by the developed methods are in general smaller than the average size given by the manufacturer, but in quite good agreement with those (in the reactor) given by transmission electron microscopy. The injection of the particles is regarded by mean of a fast camera. We observed that during the injection, the particles de-agglomeration ration reaches up to 90%). The analysis of particles by metrology methods in plasma makes it possible not to analyze the aggregates, but the primary particles. This phenomenon opens many ways in particular for toxicity control and presence of so-called nanoparticles (less than 100nm) in ingredients from, for example, the pharmaceutical or cosmetic industry. Moreover it allows the study of the interactions between plasma and aggregated particles.

Plasma-dust structures in the DC discharge

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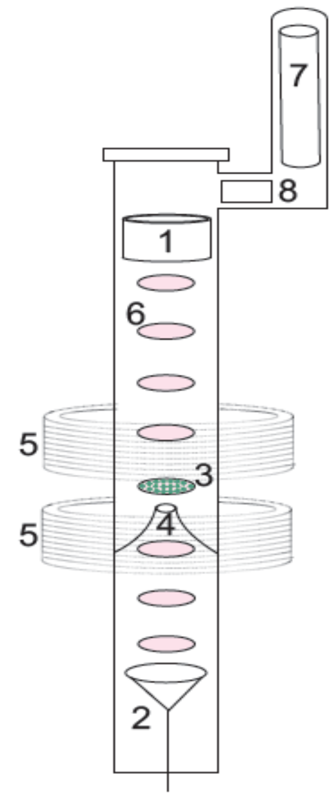
At present, there are several theoretical assumptions that the rotation of the plasma-dust structures in the striation in a magnetic field can be caused by the presence of a number of irregularities such as the inversion of the radial ion flux, which is related either to the local reversal of the field, or to the onset of recombination on the dust structure; the effect of edge effects [1-2]. In this work, the influence of a tapered current channel (the diaphragm in the form of a cone) on the properties of plasma-dust structures in a stratium of the glow discharge is experimentally investigated. The experimental setup is shown in Fig. 1.

The rotation of the structure of dust particles was investigated . It was observed that with increasing magnetic field induction, the number of particles levitated in the striation decreases. Additionally, the changes in the gas discharge due to presence of an external uniform magnetic field were studied.

The results were obtained in the experimental setup for studying the properties of dusty plasma and plasma-dust structures in a glow discharge plasma (Fig 1). Experimental condition: gas-argon, pressure P = 0.1-0.25 Torr, discharge current i = 0.5-1.5 mA, induction of external magnetic field B = 0-400 mT. As dust particles, polydisperse aluminum with a characteristic size of 1 to 10 μm was used [3]



1-anode; 2-cathode;3-plasma-dust structures; 4- tapered current channel; 5-system of coil; 6-stratium; 7- sensor pressure; 8-dust container;
Figure 1. The experimental setup

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Experimental investigation of the properties of plasma-dust formations on pulsed plasma accelerator

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Plasma with dust particles was detected in the divertor region of the ITER, furthermore it was revealed that it strongly affects to the main parameters of the plasma pinch [1].
In this paper the results on the investigation of the properties of a dusty plasma formed in a pulsed plasma accelerator by the interaction of a pulsed plasma with a candidate material of the first wall of ITER-like device have been presented.
The experiments were carried out at the setup of pulsed plasma accelerator IPU-30 [2].The interaction of the pulsed plasma with the surface of the carbon plates is accompanied by instantaneous heating (Figure 1b) and ejection and subsequent scattering of particles from the surface of the plates (Figure 1c), where the ejected particles follow the plasma, creating a moving plasma-dust cloud (Figure 1c).

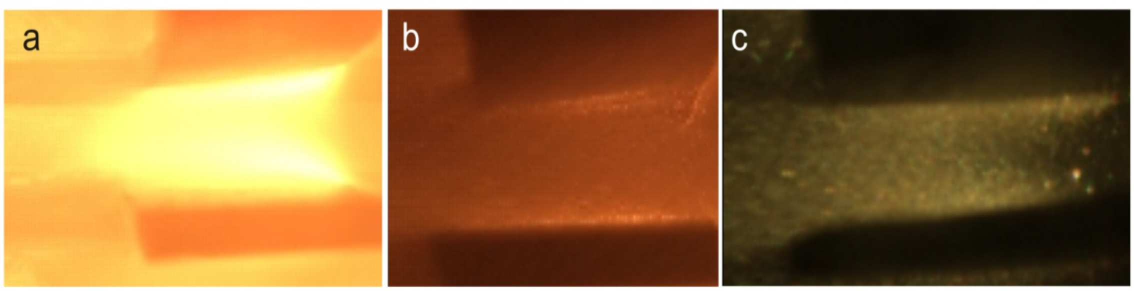

Figure 1 – Flow past the pulsed plasma through graphite plates (a), heating the surface of the plates due to the friction (b) and ejections of the particles (c).

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Simulation of Dust Dynamics for Various Materials of the Edge Fusion Plasma

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Recently, the problem of controlling the edge dusty plasma has attracted increasing interest as one of the most important problems in fusion devices. It is mainly caused by safety reasons because dust can increase the risk of explosion with accidental air, coolant or tritium leakage. At present, in various fusion devices different materials are used as plasma facing components. Different materials and combinations of materials are studied in order to reduce the rate of destruction of plasma surfaces and plasma contamination by heavy impurities. The choice of material in fusion devices is usually determined by specific thermochemical characteristics and differences on material properties[1-4].

In this work we consider the dynamics and lifetime of dust particles made of different fusion-related materials (Be, Ni, Mo, W) formed on the wall surface of fusion reactor. To describe the dynamics of the dust particle, the equations of motion, the equations of mass and energy balance, and the equations for charging the dust particle are solved. Calculations were made taking into account the parameters describing the material functions, such as molar enthalpy, vapor pressure, complex phenomena in the interaction of dust particle with plasma leading to mass loss and properties of electron emission and radiation. The dependence of the dust particle charge and energy fluxes on the dust temperature has been obtained. The time dependence of temperature and radius of the dust particle has been calculated. On the basis of these calculations, estimates of the dust lifetime have been obtained. The dependencies of the characteristic lifetime of dust particles on plasma parameters for various materials are compared.

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The Effect of External Magnetic Field on Dust Particles Charging Processes

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Investigation of the dust particle charging processes is necessary for constructing the dusty plasma theory, which can describe formation, existence, evolution and destruction of the ordered plasma-dust structures and can be used to describe the dynamic phenomena in plasma[1]. A complete description of plasma-dust structures allows us to obtain exact information about the fundamental properties of solids, phase transitions and self-organized objects. An important problem is the study of the process of dust particle charging. The solution to this problem makes it possible to calculate the charge of dust particles and the potential for their interaction, which is the key to the study of ordered structures.

Recently, the authors [2] conducted the experiments where the processes of dust particle charging in the magnetized plasma were studied [2]. In the presence of the strong magnetic field it was shown that the absolute value of the dust particle charge is much lower than the estimations of the OML theoretical model. Therefore, the purpose of this work was to study the influence of magnetic field on the dust particle charge in the gas-discharge plasma. The influence of magnetic field on the dust particle charge, on charge fluctuation and on charging time was studied. The dust particle charge was calculated using the particle-in-cell method, and ion collisions with atoms were taken into account using the Monte Carlo collision procedure [3, 4]. The time dependence of the dust particle charge as well as its charging time was obtained at different values of the magnetic field. It was found that the strong magnetic field reduces the absolute value of the dust particle charge and increases the charging time.

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Obtaining hydrophobic and hydrophilic surfaces in low-temperature atmospheric pressure plasma

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Hydrophobic and superhydrophobic surfaces, playing important role in fundamental research of functional materials, have a number of unique functional properties – water resistance, resistance to corrosion, resistance to bio-fouling. Therefore, this research area attracts more and more attention of researchers from all over the world [1-2].

The most simple but effective way of obtaining hydrophobic and hydrophilic surfaces is the method of plasma treatment at atmospheric pressure, in which deposition occurs at atmospheric pressure, i.e. no complicated vacuum and electronic equipment is required. This technology has a number of advantages over other methods, such as high synthesis speed, simplicity and low equipment cost [3,4].

This paper presents experimental results on the synthesis of hydrophobic and hydrophilic surfaces in the plasma of the HF discharge. An experimental setup was developed for obtaining hydrophobic and hydrophilic surfaces in a low-temperature atmospheric pressure plasma. Optimum plasma parameters were determined for the synthesis of hydrophobic surfaces, the contact angle with water of which is greater than 100^0. Previous work describes the process of synthesis of carbon nanoparticles at low pressures (up to 1 Torr) and sputtering them on different surfaces, resulting in hydrophobic surfaces with a contact angle of more than 120^0 [5,6].

A series of experiments was carried out for silicon, aluminum and polymer substrates. Surfaces were treated with the plasma torch. The duration of deposition ranged from 10 to 20 seconds, the power of the HF discharge varied within 10-40 W in steps of 5 W. Sputtering was carried out in a flow of working gas Ar and Ar+CH4 at atmospheric pressure, the gas flow was 1-5 L/min.

The obtained samples were examined with the help of SEM, SPM, Raman scattering and optical microscopy, the analysis of which indicates the surface roughness.

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Coulomb Crystal of Micro-organisms in an RF Plasma

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Levitation of charged micro-organisms is an interesting phenomenon from the perspective of understanding nature and its applications. The occurrences of charged-up micro-organisms in the earth's upper atmosphere have been reported [1]. One of interesting applications of the levitation of charged-up micro-organism is the biomolecular mass spectrometry [2]. Another application is plasma photonic crystal with dusty plasma [3]. Coulomb crystal of micro-organisms can be deal as crystal of functional dust due to chirality of them. Levitation of micro-organisms in a radio-frequency (RF) plasma has been reported [4].

As shown in below figure, experimental results clearly demonstrate the levitation and crystallization of micro-organisms, *Klebsiella pneumoniae*, in a horizontally-parallel-plate RF plasma. The *Klebsiella pneumoniae* is categorized in bacillus like as spheroidal shape, and has typical size of a few microns. The figure shows they form a quasi-ordered configuration like as two-dimensional Coulomb crystal. Each particle vibrates or turns around its equilibrium position. Initial results of crystallization of micro-organisms will be reported.

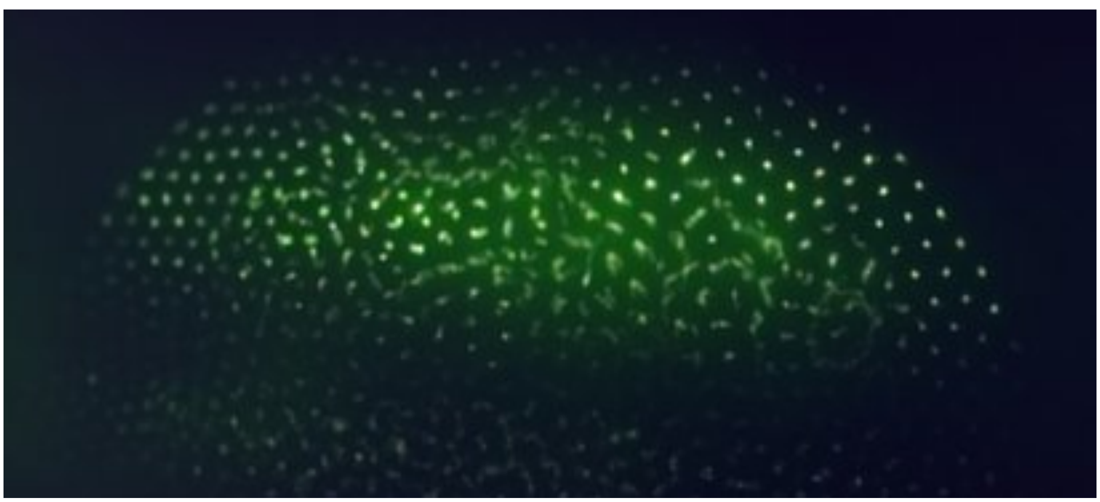

Figure 1 – Coulomb crystal of *Klebsiella pneumoniae*. (Top view. Integrated over 1.6s time interval)

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Shear deformations in dusty plasma

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Dusty plasmas can exhibit liquid-like or solid-like properties. In response to shear stresses, a strongly coupled dusty plasma can deform or flow. When it has solid-like properties, a dusty plasma is extremely soft, with a shear modulus that is many orders of magnitude smaller than that for typical solid materials. A large deformation can be developed, by applying a small force, for example, by a manipulation laser. Laboratory experiments using manipulation lasers have been reported for studying plastic deformation using compression [1] and shear stress [2].

We recently reported [3] results from a 2D electrostatic simulation, where we empirically obtained a stress-strain relationship. In the simulation, we applied two oppositely-directed forces with a gap of a few particle spacings between them. Using the stress-strain relationship, we characterized the dusty plasma in three regimes: elastic deformation, plastic deformation, and flow.

We obtained the shear modulus at the elastic limit of the stress-strain relationship. The measured modulus is found to agree with a theoretical prediction based on the speed of the transverse sound wave.

We also determined the yield stress at the onset of plastic deformation. This result, for a 2D solid-like dusty plasma, is consistent with a standard theoretical formula for 3D solid materials.

Future experiments may be able to observe the same phenomena. The required observables are position and velocity of particles during manipulation by a laser beam, which are standard experimental methods, as in the PK-4 instrument on orbit on the International Space Station (ISS) [4].

Work was supported by NASA-JPL subcontracts 1579454 and 1573629.

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Diffusive motion in a three-dimensional cluster in PK-4

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By analyzing flight data from the Science Campaign 2 of PK-4, we have identified an experimental sequence that allows a characterization of diffusive motion. In this experiment, a cloud of microspheres was localized near a radio-frequency coil which was powered, and the cloud did not flow. Microspheres in this experiment exhibit random-like motion, and the motion is damped by neutral neon gas. We tracked the motion of microspheres within the thin cross section illuminated by a laser. Microspheres typically remained within this illuminated layer for multiple frames; they disappeared eventually due to out-of-plane motion, with a half-life of 5.5 video frames. We obtained a time series of the mean-square displacement (MSD), which exhibits a power law consistent with nearly diffusive motion.

All authors acknowledge the joint ESA/Roscosmos "Experiment Plasmakristall-4" onboard the International Space Station. This work was partially supported by DLR Grant Nos. 50WM1441 and 50WM1442. Work at Iowa was supported by NASA-JPL subcontracts 1573629 and 1579454.

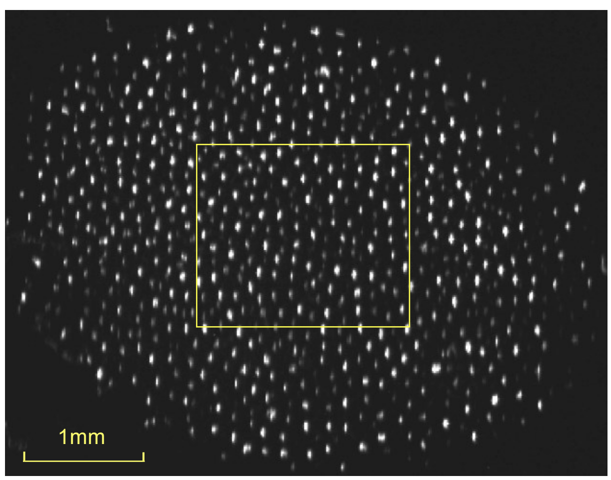

Fig. 1. Still image from a PK-4 particle-observation camera, which was operated at 35.7 frames per second. The video was recorded in Campaign 2, June 16, 2016. The particle cloud was located near a radio-frequency coil. We tracked particle motion in the region of interest (ROI) indicated by the box, which was 129 × 108 pixels.

Modeling-challenge paradigm using design of experiments method for spacecraft immersed in nonstationary, between-regimes, flowing plasma

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Because dust-in-plasma or dusty-plasma is frequently encountered in space, laboratory, and industrial settings, it is of interest to develop models of how grains modify the plasma they inhabit and how nonlocal, nonstationary, and inhomogeneous charging processes affect the sheath of a nonspherical object that is possibly susceptible to secondary electron emission. A conducting sphere and cylinder under the grain-like conditions of between-regimes, flowing plasma is adopted as a test case for a modeling-challenge paradigm based on design of experiments (DOE) methodology that merges numerical simulation and testing. A candidate set of standard experimental conditions and measurements to be modeled/simulated numerically is tailored to address specific questions in spacecraft-environment interactions, is selected to address the capability of models to describe those conditions, and is defined to facilitate a red-team/blue-team style modeling challenge for streamlining the Model/Simulation development process. The experimental results are envisioned to be made available publicly on a project data portal. Modelers will be required to archive a detailed summary of the simulation results and comparisons, including a quantitative assessment of the agreement between experiment and model and between red-team model and blue-team model.

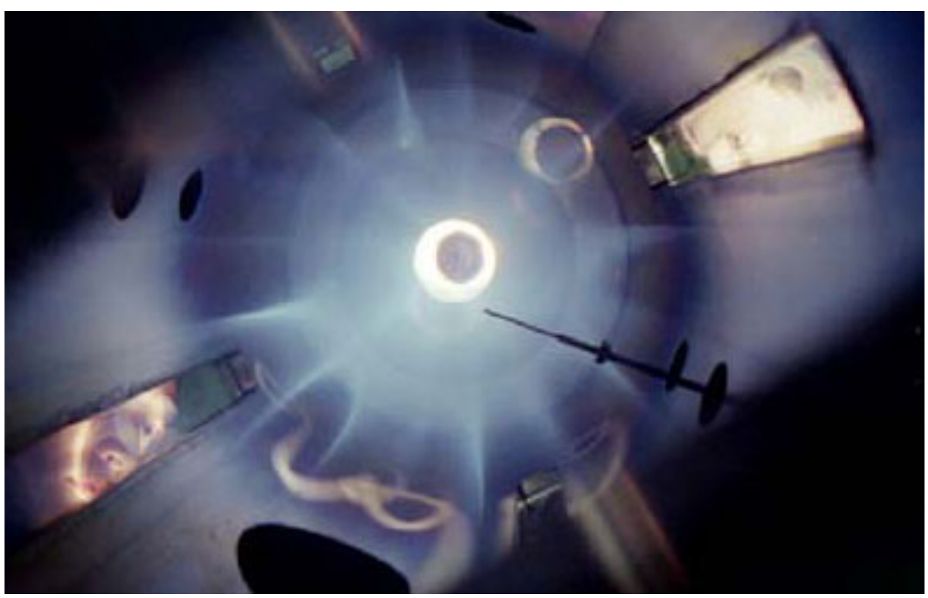

Fig1: Planned proof-of-principle modeling-challenge facility on spacecraft-environment interactions using lab facilities at WVU and high-performance-computing facilities at U. Alberta & LANL.

Microfluidic flow in single-layer dusty plasmas

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Since the early years of research on strongly coupled dusty plasmas, hydrodynamics has always appeared to be one of the topics that might be impacted by this exciting field to allow rapid progress. However, analyses of early experimental data have taught us that a more detailed understanding of dust inter-particle interactions and the fundamental system parameters involved is necessary before quantitatively meaningful results can be obtained. At the same time, single layer dusty plasma crystals produced in plane-parallel RF discharges became the main subject of many laboratory dusty plasma experiments in part because these configurations provide best controllability and reproducibility. As a result, they have become fairly well understood over time.

Here we investigate hydrodynamic flows in a complex plasma by utilizing the control provided by a plane-parallel RF discharge. Two metallic disks are placed on the powered electrode of the new large area (16" diameter) dusty plasma setup at the CASPER Lab, forming an electrostatic potential channel. Dust particle flow through the channel is induced by indirect laser manipulation as shown in figure 1. By adjusting the argon gas pressure and RF power, the channel could be tuned to allow the formation of single or multiple lanes of transiting dust particles. We use this system to address fundamental details of hydrodynamic flows like the acceleration and stopping of particles, lane formation and ordering in the channel as visualized in figure 2.

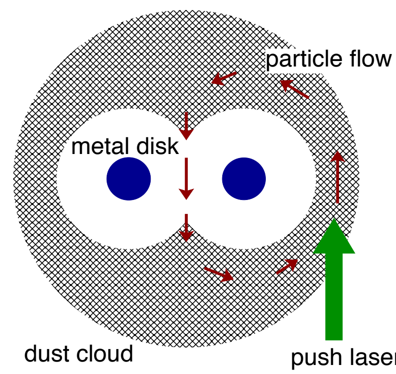

Figure 1. Sketch of the top view

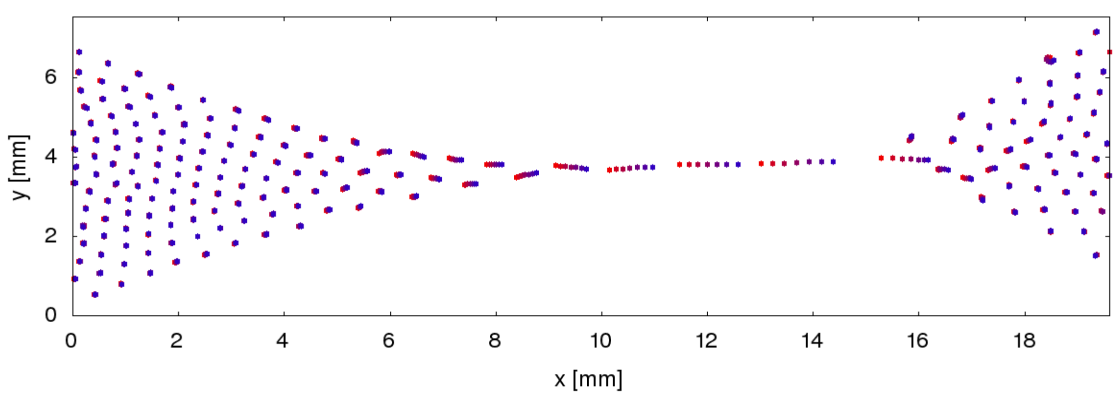

Figure 1. Color coded time-evolution of a single-lane particle flow with 60 fps resolution.

Support from NKFIH Grant number K-115805 and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences is gratefully acknowledged.

Filamentation and imposed ordered dust structure in magnetized discharge

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First experimental findings obtained with the new Magnetized Dusty Plasma Experiment (MDPX at Auburn University) include the filamentation of the gas discharge and the formation of ordered structures in high vertical magnetic fields (>1 T) imposed by the wire-grid upper horizontal electrode and visualized by micrometer dust particles levitating on top of the lower flat electrode sheath of a capacitively coupled RF discharge [E. Thomas Jr., Physics of Plasmas 23, 055701 (2016)]. Simple arguments based on charged particles being confined to helical trajectories along the magnetic field lines are not sufficient because all relevant collision processes have mean free paths well shorter than the distance between the structured electrode and the lower electrode sheath. We apply our newly implemented two-dimensional GPU accelerated particle in cell (PIC) discharge simulation both for cylindrical geometry to compute global discharge parameters and with cartesian symmetry for the determination of local plasma parameters. At the current stage the PIC simulations do reproduce both the filamentation and the imposed structure formation as shown in the figure. Detailed analysis of the magnetic field parallel and perpendicular diffusion shows strong connection between the magnetically altered particle transport and the ordering process.

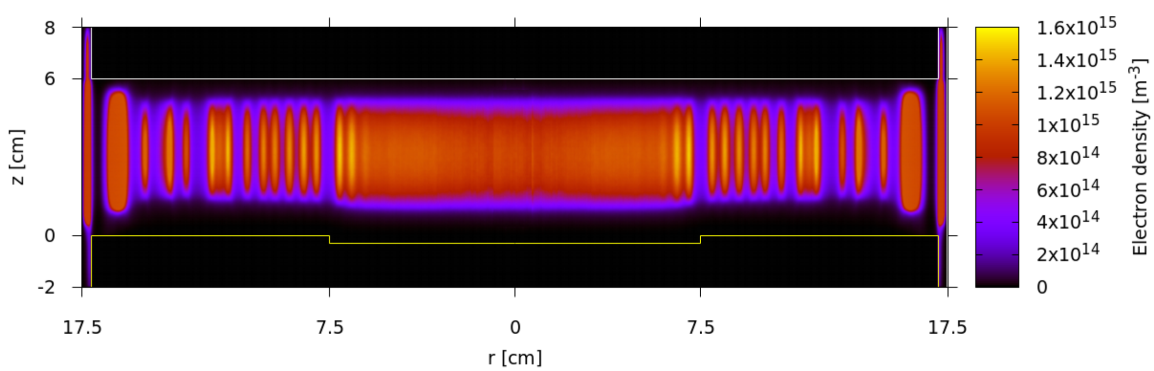

Figure 1. Electron density at B = 0.1 T magnetic field in 2 Pa argon and 160 V 13.56 MHz RF voltage amplitude in the MDPX geometry. Strong filamentation is observed.

Support from NKFIH Grant number K-115805 and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences is gratefully acknowledged.

Ionization waves in the PK-4 neon DC discharge

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The PK-4 system is the latest generation in the line of microgravity dusty plasma experiments currently in operation onboard the International Space Station (ISS). The experiment utilizes a long DC discharge with a length of 400 mm in a glass tube with inner diameter of 30 mm equipped with both neon and argon gases.

In the experiment the dust particles are suspended in the center region of the discharge tube, in the middle of the positive column. Optical observation of the dust particles as well as the discharge plasma emission is realized with imaging cameras using exposure times of 10 ms and longer. On this time-scale the positive column appears stable and homogeneous. Particle-in-Cell with Monte Carlo collisions (PIC/MCC) simulations were implemented for cylindrical geometry on GPU-accelerated architecture, the simulations were run for neon gas in the pressure range from 0.5 to 1 mbar, at 1 mA dc current. Figure 1(a) shows the 1 ms "long" time averaged excitation source (associated with the light emission), which shows the experimentally observed smooth structure at 1 mbar. On the other hand, figure 1(b) shows the same quantity with only 1.2 μs acquisition time. In this high time-resolution snapshot, a high contrast striation structure is observable along the whole positive column. These non-harmonic waves reach phase velocities up to 1200 m/s and result in local electric field oscillations of about 18 kHz with amplitudes about 10 times of the time-average value.

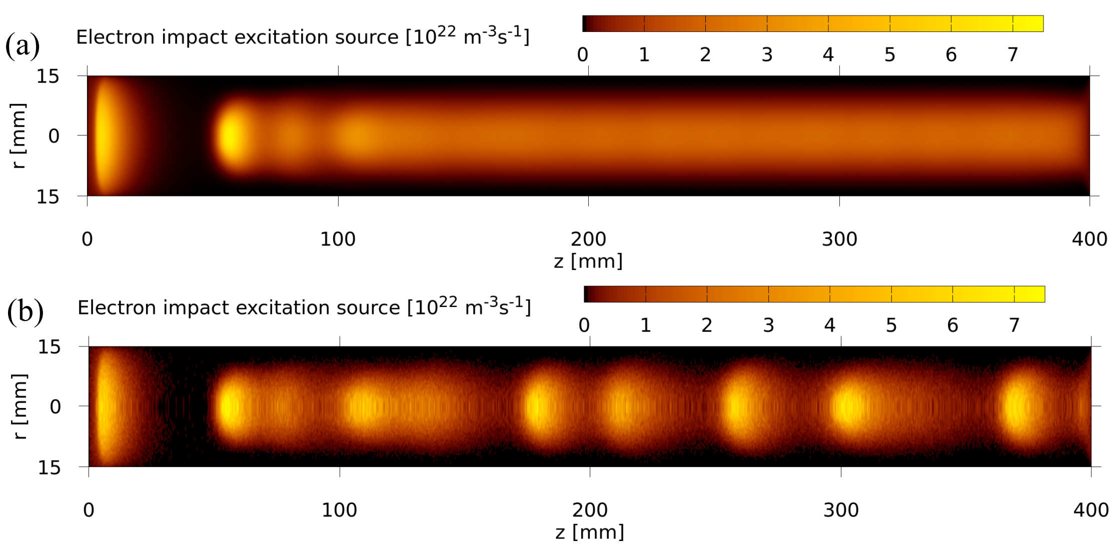

Figure 1 – Excitation source distributions for data acquisition times of 1 ms (a) and 1.2 μs (b).

15th Dusty Plasma Workshop
Title: Studies of corrosion properties of Plasma nitrided steels

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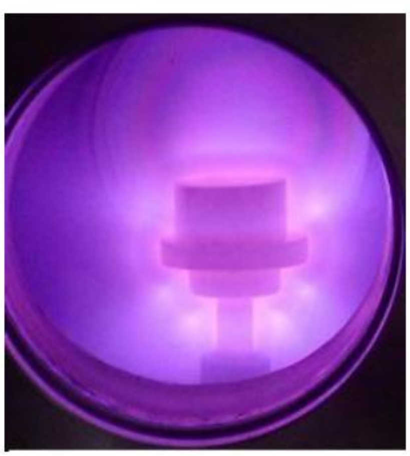
With the development of science and technology, surface engineering has immersed as a new branch dealing with modification and treatment of surfaces of sophisticated components, which are being used, in various shapes, sizes, etc in different environments. Steel is a material, which is almost universally utilized in various applications in corrosive atmospheres, non-corrosive atmospheres, wear and abrasion and other combinations. Surface nitriding, a thermo-chemical diffusion process provides a solution to most of the problems related to degradation of materials due to corrosion, wear, abrasion, fatigue and creep, etc. Plasma nitriding is a modern technique of nitriding which has drawn the attention of researchers all over the globe.

In the present investigation an attempt has been made to produce low temperature plasma which is employed for diffusion of nitrogen atoms into varying thicknesses of the steel (En-9, En-19, En-24, En-31 and S.S 304) components and then characterize the surface with regard to hardness and corrosion behavior using standard potentio-dynamic tests.

It is known that corrosion resistance of low and medium alloy steels for example En-9, En-19, En-24, En-31 and S.S 304 improves with plasma nitriding. However for S.S the results depend on the process temperature. The results of the investigation show that we are obtaining similar results, i.e. corrosion resistance has improved for En-9, En-19, En-24 and En-31. But for S.S 304 we observe that corrosion resistance improvement is best at 450oC thereafter it deteriorates. In a nutshell the present investigation validates that plasma nitriding not only improves surface hardness (wear resistance) but also improves corrosion resistance of various grades of steels with appropriate process variables.



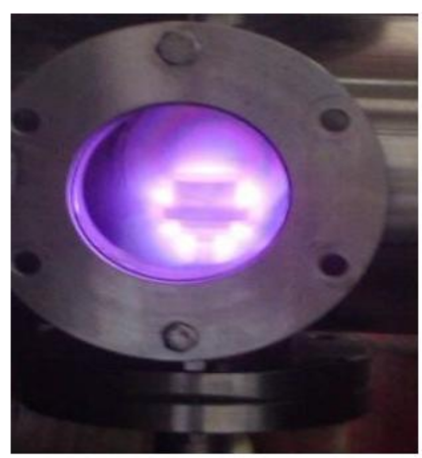


Figure 1 – Photographs of sample being plasma nitrided.

Trilayer dusty plasma lattice structure and dynamics
15th Dusty Plasma Workshop

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In a harmonic trap confined strongly coupled plasma splits into several layers [1, 2], which, in a good approximation can be considered to be a sequence of 2D lattices. It is well known that charged particles in a single layer form a triangular lattice. The available lattice structures for multiple lattices are, however, a more complex issue. The structure of Coulombic bilayer lattices has been studied by Goldoni and Peeters[3].and for Yukawa interaction by Oğuz, Messina and Löwen[4]. Here we study the lattice structure for a trilayer system, where the inter-particle interaction is through Yukawa potential, as appropriate for dusty plasmas. We search for the optimal lattice structure by minimizing the potential energy resulting from the interaction of all sites. Given the optimal lattice structure as a function of layer separation distance, we calculate the collective mode dispersion for the six eigenmodes of the system. For a stable lattice, one expects to obtain only positive eigenvalues from the dynamical matrix: negative eigenvalues are the hallmark of an ill-chosen lattice structure. Based on our MD simulation data with large coupling parameter, when the interlayer distance increases, the lattice structure in the layers changes through a sequence of transitions triangular →rhombic→ square →rhombic →triangular. The first three transitions are continuous, the last transition is abrupt. MD simulations of trapped layered Yukawa plasmas confirm our theoretical findings.

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Investigation of Dusty Plasma Effects in Hypervelocity Impacts

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Spacecraft are routinely impacted by macroscopic particles such as meteoroids and space debris, which can be travelling tens of km/s. These impacts are referred to as hypervelocity because the impactor travels faster than speed of sound in the target material, causing a shock wave and pressure stresses greater than the material strength. On impact, these particles and part of the target material vaporize and ionize, forming a dense plasma plume that expands into the vacuum. This expanding plasma can produce radio frequency (RF) emissions and strong electromagnetic pulses (EMPs) that may harm spacecraft electronics, potentially resulting in anomalies or spacecraft failure. Additionally, neutral particles ejected from the impact site may interact with the plasma and acquire a surface charge, resulting in a dusty plasma. Plasma measurements from ground-based hypervelocity impact experiments at the NASA Ames Vertical Gun Range (AVGR) suggest that dusty plasma effects may play an important role in the expansion process. Our work focuses on understanding the role of dust in the hypervelocity impact environment and its effects on potential spacecraft damage mechanisms. First, we present evidence of dusty plasma effects in the AVGR data. Second, we describe a dust charging model for simulating the plasma expansion in a dusty environment using particle-in-cell (PIC) simulations, and present preliminary results. Finally, we describe plans to better characterize the dust population and its effects on the expanding plasma in a future AVGR test campaign.

Poster Session 2

Thursday, May 31, 2018

Study of separation process of dust structure in plasma of radio-frequency discharge

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As is known, dust particles (solid particles of micron size) in plasma medium are grown either by plasma chemical process, or mechanically injected into it. As a rule, the dusts in gas discharges are negatively charged due to the high mobility of electrons and form three dimensional dust structures – a plasma crystal. Depends on discharge parameters the plasma crystal can be melted and evaporated. The behavior of such structures plays both negative and positive roles. In the 90th of 20 century, a dust formation [1-2] in the plasma was intensively studied to eliminate their negative effects in semiconductor devices production at plasma deposition and etching processes. Today, the study of plasma crystal is closely related not only with the solution of the fundamental problems of plasma physics, but also of astrophysics, nanotechnology, hydrodynamics, kinetics of phase transitions, etc., among which one can distinguish an interesting task - Study of separation process of dust structure in plasma of radio-frequency discharge [3-4].

In proposed work, the results of investigation of dust structures behavior in different types of trap in the plasma of radio-frequency discharge are considered. The experiments were carried out in plasma of argon gas at different values of pressure of 0.02-0.6 Torr and discharge power of 1-50 W. Closed and non-closed rings with various diameters and heights were used as a trap. As is known, the dust structure in radial direction is captured by trap of ring type. Hence, varying of plasma parameters and trap forms it is possible to increase or decrease the capture area, which allows extraction of dust particles from trap by sizes – a separation process. It is found, that with decreasing of gas pressure the dust structure is less affected by the trap and in case of thin ring trap the separation process goes better.

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Pattern formation and filamentation in low temperature, magnetized plasmas – a numerical approach

Mohamad Menati, Uwe Konopka and Edward Thomas, Auburn Univ.

In low-temperature discharges under the influence of high magnetic field, pattern and filament formation in the plasma has been reported by different groups. The phenomena present themselves as bright plasma columns (filaments) oriented parallel to the magnetic field lines at high magnetic field regime. The plasma structure can filament into different shapes from single columns to spiral and bright rings when viewed from the top. In spite of the extensive experimental observations, the observed effects lack a detailed theoretical and numerical description. In an attempt to numerically explain the plasma filamentation, we present a simplified model for the plasma discharge and power deposition into the plasma. Based on the model, 2-D and 3-D codes are being developed that solve Poisson's equation along with the fluid equations to obtain a self-consistent description of the plasma. The model and preliminary results applied to the specific plasma conditions will be presented.

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Development of an RF Transmission Diagnostic for Dusty Plasmas

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When dust is added to a plasma, the dust collects a net charge determined by the balance of ion and electron currents to the dust. Because of the ion-electron mass ratio, the net charge of dust particles is typically highly negative. Due to the overall charge neutrality requirement, the negative charging of the dust leads to a reduction of the electron density in the surrounding plasma. This electron depletion contains information about the dust charge state, and thus may be used to estimate the average dust particle charge. A direct measurement of this electron number density depletion is difficult because many common plasma diagnostic techniques are undesirable for use in dusty plasmas. For example, a Langmuir probe is undesirable for use in dusty plasma because it can perturb the dust, or it can become unreliable as a result of dust contamination. One class of plasma diagnostics which is promising for use with dust is active plasma resonance spectroscopy (APRS), which makes use of the plasma's ability to resonate at or near the electron plasma frequency, ω¬pe. In this poster, we present experiments in which a double probe is used to couple an RF signal to the plasma and measure the spectral response as a function of the excitation frequency. We show results from experiments with and without dust, and with and without magnetic field. We also discuss a potentially less perturbative design for future experiments using electrodes at the edge of the plasma, rather than probes immersed in the plasma.

This work is supported by funding from the NASA/Jet Propulsion Laboratory (JPL-RSA 1571699) as well as the National Science Foundation EPSCoR program (OIA-1655280).

Molecular dynamic simulation of weakly magnetized dusty plasmas

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Dusty plasmas are made up of four components, electrons, ions, neutrals and micro particles. As the main dynamics of the system in which we are interested in is based on the time scales of the dust particles dynamics, we only simulate the motion of latter, treating the other components via inclusion in the model of the particle charge and their mutual interaction as well as including a neutral drag to cover the interaction with the background gas. The simulations are done as a molecular dynamic simulation where we sometimes further include the influence of an externally applied magnetic to study its effect on the dust particles motion. With the simulation we are able to better visualize the forces and their effects on the overall dust cloud but also between the individual particles.

We will present the computational approach taken in the simulation as well as the physical systems we are attempting to model. We plan compare the detailed modeled dynamics in the dust cloud to real experimental data such as data obtained from the PK-4 space experiment operated aboard the International Space Station or those obtained in a high magnetic field dusty plasma environment.

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Novel configuration for creation and study of probe-induced dust voids

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Dust-free voids within a complex plasma have been observed and studied for some time, both in laboratory and microgravity settings. These voids are caused by a balance between a Coulomb force on the negatively charged dust grains, and an ion drag force on the grains due to an ion stream that is in the opposite direction of the Coulomb force on the dust. It has been shown that voids can be self-induced (thought to be due to a local concentration of ions within the plasma bulk) [1] as well as being driven via a biased Langmuir probe inserted into the dust cloud [2]. A new apparatus is presented which is used to form voids within dust monolayers, formed with a biased Langmuir probe, a previously undocumented configuration. In addition, preliminary results are presented of experiments on voids formed in a region with a strong magnetic field vector within the plane of the dust monolayer, using the MDPX superconducting magnet system at Auburn University.

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DC response of dust equilibria to AC signals

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Changes in the equilibrium shape and position of dust clouds suspended in an argon, DC glow discharge plasma have been observed in response to applied AC signals between the dust plasma frequency and ion-neutral collision frequency. In these experiments, clouds of 2-micron diameter silica microspheres are suspended between a plasma-generating anode and a confining cathode ring above an electrically floating dust tray. When signals in this frequency regime are applied to the confining ring, the dust particles experience a vertical displacement. The dust response to AC signal is characterized and the effects of the signals on background plasma properties and potentials are examined using Langmuir and floating potential probes. Distinctions between the observations seen here and those in electrorheological plasmas are discussed and a preliminary model of the phenomenon is presented. This work is supported by funding from the US Dept. of Energy, Grant Number DE-SC0016330, the National Science Foundation, Grant Number PHY-1613087, and additional support from the NSF EPSCoR program (OIA-1655280).

Anomalous diffusion in 1D dusty plasma structures: A fractional Laplacian model for strong correlations

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In the normal diffusion regime, the mean square displacement (MSD) of an ensemble of moving particles increases linearly in time, i.e. $\langle x^2 \rangle \sim t^s$ where $s = 1$. However, exponents $s \neq 1$ are also possible, yielding two distinct examples of anomalous transport: subdiffusion when $s > 1$ and superdiffusion when $s < 1$. Here we present a study of anomalous diffusion using the spectral approach to transport problems characterized by Anderson-type Hamiltonians with fractional Laplacian operators $(-\Delta)^s$, $s \in (0,2)$. The proposed model is applied to 1D dusty plasma systems, where strong interactions, structural defects, and collective effects are present.

It is expected that for $s > 1$ the wave propagation in the medium slows down due to negative correlations, while for $s < 1$, transport is enhanced due to positive correlations. In the spectral method we use, one calculates the mathematical distance D from a vector in the space to an infinite-dimensional sequence representing the time evolution of the wave propagation. It can be shown that if D approaches a nonzero value as time goes to infinity, the wave delocalized from the origin to the exterior of the medium. Below we present preliminary results from a toy-model code, which confirm that, in a 1D disordered system, $s > 1$ enhances localization effects, while $s < 1$ facilitates transport.

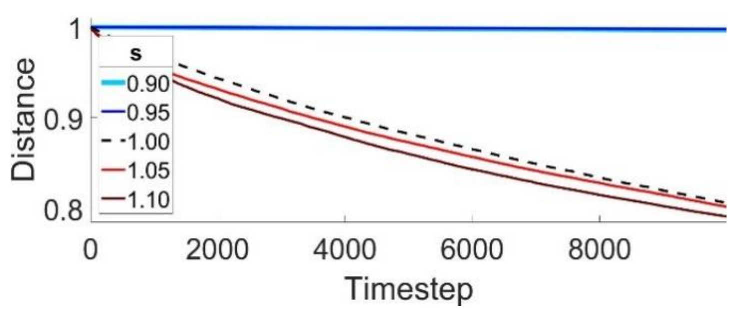

Figure 1 – In the normal diffusion and subdiffusion regimes ($s = 1, 1.05, 1.10$, shown as black dashed, light red, and dark red lines, respectively) the values of D tend to 0 as the number of timesteps increases. In agreement with theory, this corresponds to localized behavior. In the superdiffusion case ($s = 0.90, 0.95$, shown as light blue and dark blue lines, respectively), the values of D show negligible drop, indicating the existence of extended states.

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Nematic transition in microgravity complex plasma liquid crystals

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Liquid crystals (LCs) are a form of matter existing in the mesophase intermediate between liquid and solid. Important examples of LCs are found both in the natural world (proteins, DNA, polypeptides) and in technological applications (electronic displays, anisotropic nanoparticles, smectite clays). The structural formation and stability of a liquid crystal can be modeled by a nematic phase transition, during which the molecules in the liquid acquire similar average orientation along a preferred direction (often accompanied by positional alignment in the same direction). Microscopic experimental treatment of liquid crystals is challenging due to their high material density, the presence of strong interactions, and the effect of many-body correlations. One possible solution is the use of complex (dusty) plasma analogues, which consist of charged micron-sized particles suspended in weakly-ionized gas. The self-organization and stability in complex plasmas is dependent on both strong correlations and collective effects. However, unlike molecular liquid crystals, dusty liquid crystals are optically thin and macroscopic, which allows for real-time observation of the particle dynamics at the kinetic level.

Here we investigate the isotropic-to-nematic transition in extended dusty plasma clouds using video data from the experimental facility Plasma Kristal-4 (PK-4) on board the International Space Station. We define the liquid crystal phase with the help of an orientation "director" parameter d (defined as the change in orientation of small structures within the dust cloud) and a structure order parameter α (defined as the degree of individual particle alignment in the preferred direction). In each video frame, the mean square displacement of the dust grains is extracted and used to obtain the values of d, α, and the total energy of the dusty liquid crystal as a function of time. The onset of the isotropic-to-nematic transition is then determined using a spectral analysis of the system's energy map.

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Dust-Plasma Interactions in Extended Field Aligned Dust Chains

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The IonWake code is a molecular dynamics simulation capable of resolving the dynamics of extended dust chains on both ion and dust particle time scales. Different boundary conditions are employed to model the dust-plasma interactions within the glass box experiment at CASPER [1] and the PK-4 experiment on-board the ISS [2]. A leapfrog integration method is used to calculate the trajectories of positive ions and dust particles. To account for the shielding from thermal electrons, ion-ion forces are calculated using a shielded coulomb force while dust-ion forces are calculated using an unshielded Coulomb force [3]. A two-step integration scheme is employed to handle the drastically different time scales of the ions and dust. In the first step, the dust particles are held fixed and the ion trajectories are calculated. During this step, ion-dust collisions are used to self-consistently charge the dust particles. Once the ions reach an equilibrium distribution, the ions are held fixed and the dust particles are advanced a single time step. The results are compared with the paired experimental studies.

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PLASMIANTE: A plasma filter for the detection of airborne asbestos

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Even if forbidden in french constructions since 1997, asbestos remains present in most of the buildings constructed before this date. Thus, in the case of degradations, asbestos fibers can be emitted in air. The smaller the asbestos particles, the longer they stay in suspension in air, increasing the risk of inhalation.

The current determination of asbestos presence in air in France follows a long and cumbersome normative protocol (NF X 43-050), with an analysis carried out on a Transmission Electron Microscope at laboratory after air filtration on-site. Such a protocol is therefore accompanied by numerous error factors.

PLASMIANTE aims to develop a direct and global on-line analysis method to detect, identify and characterise in real time asbestos fibers potentially present in the air. To this end, particles will be trapped in a low pressure plasma and analyzed with several metrological methods such as multi angle laser light scattering, the effect of the particles on the electrical characteristics of the plasma and the discharge, Infra-Red spectroscopy and Laser Induced Breakdown Spectroscopy (LIBS).

This contribution presents the aim of the project along with the first results and the challenges we will face.

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Acknowledgment:

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Effects of discrete stochastic charging on the non-spherical growth of water-ice grains in a dusty plasma

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Water-ice grains are common in many astrophysical environments such as protoplanetary disks, Saturn's rings, cometary tails, molecular clouds, etc. Most theoretical and observational investigations of astrophysical environments assume that grains are spherical in shape even though collisional growth leads to non-spherical grains. Recent experiments where ice aggregates were grown from a water vapor injected into an RF discharge showed that these aggregates varied in both size and aspect ratio as the background gas pressure and type of gas was varied. They also exhibited greater aspect ratios in lighter-mass gases and lower gas pressures [1]. In this research, a numerical model designed to study the coagulation of water ice grains as they condense from water vapor under various plasma environments will be introduced. It will be shown that for very small newly condensed grains, fluctuations in the grain charge as electrons and ions are randomly collected from the plasma can affect overall particle dynamics. In order to examine this, a dynamics simulation employing a discrete stochastic charging model to simultaneously track the charge and orientation of grains as they collide and stick is used [2]. It will be shown that stochastic charge fluctuations tend to produce aggregates which are much more linear or filamentary than aggregates formed in an environment where the charge is stationary.

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Dust Lattice Waves and dust influenced Ionization Waves in PK-4 complex plasmas

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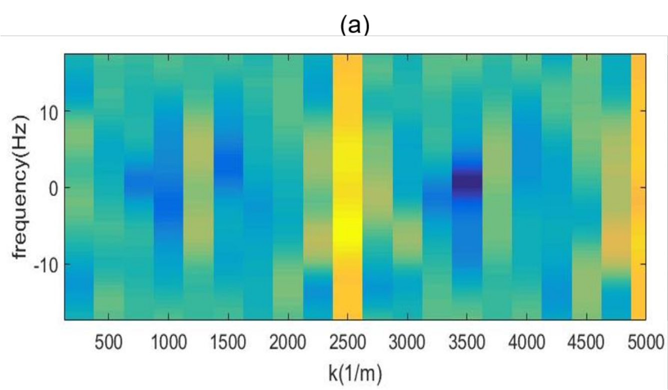
In this project, two wave modes, the dust lattice wave (DLW) and dust influenced ionization wave, are examined employing data from the PK-4 experiment onboard the International Space Station.

The phonon spectra for thermally excited DLWs propagating along the chain direction in a multiple chain system formed within the DC trap is obtained from the spontaneous motion of particles in a single chain (Fig. 1a). The spectra for longitudinal DLWs consistently exhibits dispersion relations with sinusoidal characteristics and a period of $1/a$ (where a is the interparticle spacing) for wave number k, as expected. In this case, the maximum frequency appears to be slightly above the range of the detectable frequency and is limited by the framerate of the cameras, which will need to be increased for future quantitative measurements.

Experimentally in the PK-4, stable striations have been observed in the positive column which appear to trap dust clouds (Fig. 1b). Comparing these to the ionization waves (fast moving striations) recently observed in a 2D PIC/MCC PK-4 simulation, a possible connection between the two is explored.



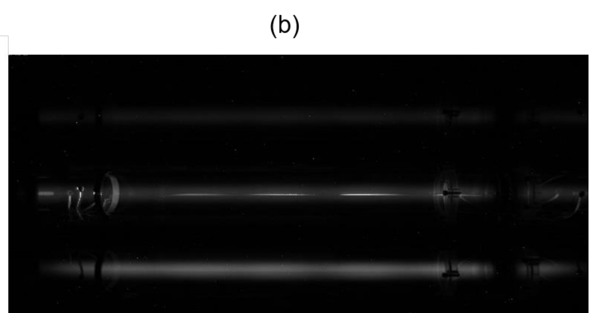


Fig. 1. (a) The phonon spectrum for longitudinal DLWs (b) Striations and associated dust clouds. The bottom image shows the plasma glow, while the middle image shows the laser-illuminated dust clouds.

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Ekoplasma – The Future of Complex Plasma Research in Space

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The Ekoplasma project, a Russian-German cooperation, is the future multi-purpose laboratory for the investigation of complex plasmas under microgravity conditions on the International Space Station (ISS), following in a line of successful preceding experiments aboard the ISS: PKE-Nefedov, PK-3 Plus, and the currently operating PK-4 facility.

The experimental apparatus of Ekoplasma features a newly developed large, cylindrical plasma chamber (the Zyflex chamber) with an adaptive internal geometry and 4 rf-driven electrodes for plasma generation. With the implemented technology, the accessible experimental parameter range will be extended by magnitudes (e.g. particle charge, neutral gas pressure range) and it will allow an independent control of plasma parameters. Further, particle dynamics will be investigated by a 3D optical diagnostic system, giving new insights into physical phenomena by adding the information of the 3rd dimension, which is usually lost when observing a 2D cross-section of the observation volume.

The experimental setup and the current project status will be presented, as well as selected results of experiments on earth and in parabolic flights, which demonstrate the scientific possibilities of this new laboratory.

Ekoplasma is planned to be launched to the ISS after 2022, and it will cover a wide range of research topics such as solidification and melting, phase separation in binary systems, the transition to turbulence, active matter or electrorheology.

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Radial confinement of dense dust structure at cryogenic temperature

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The plasma-dust trap parameters in neon dc discharge at room and cryogenic temperature have been simulated. The simulations were based on the diffusion/drift model of the uniform glow discharge positive column with dust particles developed in [1]. At room temperature in neon dc discharge of a few centimeters in diameter, the dust structures were formed from individual dust particles, with number density n_d less than 4 10^{11} m^{-3}. With decreasing temperature, the individual dust particles formed clusters [2], which then formed dust structures with a high average number density of dust particles about 10^{13} m^{-3} at cryogenic temperature. The dust particle confinement in the potential trap in a radial direction was determined by potential energy Y [3], which at room temperature, was mainly, determined by the action of the radial electric field force, thermophoretic force and ion drag force. To describe the dense dust structures formed by clusters the model assumed that the ion drag force was proportional to the distance between the dust particles in the cluster if the distances were smaller than the Debye ion radius. It was found that in super dense dust structures formed at cryogenic temperature (77K), there was an inversion of the radial electric field E_r (fig. 1), of the electric force and the ion drag force. It was found that these forces form a potential trap for the ordered complex dust clusters [2] in the center of the discharge with a radius r_d close to that observed in experiments (fig. 1).

The study was supported by the RFBR, Grant No. 16-02-00991.

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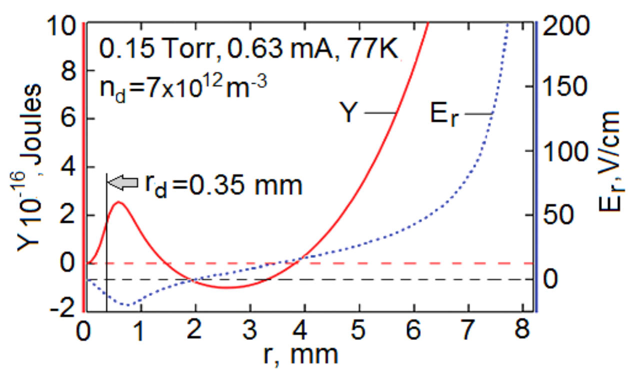

Figure 1 – The radial distribution of potential energy of dust particle (Y), and of radial electric field of discharge (E_r).

Investigation of carbon nanowalls synthesis by chemical vapor deposition method in the plasma of a radio-frequency capacitive discharge

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Today, a study of nucleation and formation of dust structures in the plasma medium is an actual task, due to the practical application of obtained results. One of the most interesting directions is the synthesis of various carbon nanostructures in the plasma of different types of discharge. For example, electric (arc) discharge plasma is used for a synthesis of carbon nanoparticles and formation of unique nanostructures such as carbon nanotubes or fullerenes. Nevertheless, a more popular plasma instrument for the synthesis of various nanomaterials, such as carbon nanoparticles, carbon nanotubes, carbon nanowalls, graphene and etc., is a radio-frequency capacitive discharge plasma, where synthesis process depends on plasma parameters: discharge power, temperature, pressure, gas mixture, etc. Hence, the study of plasma parameters influence on nanostructures synthesis is still interesting task, due to the fact that these structures find their application in various industries, for example: carbon nanoparticles is used for obtaining of hydrophobic nanofilms [1], carbon nanotubes are used as reinforcing elements for obtaining of high-quality building material [2] and also as targeted drugs delivery [3], graphene for the creation of high-sensitivity sensors and semiconductor elements [4], carbon nanowalls (CNW) can be used as completely blackbody for bolometers [5] and solar cells [6], and as electrodes for supercapacitors [7] and etc.

In this work, the synthesis of carbon nanostructures by chemical vapor deposition method from gas phase in the plasma of a radio-frequency capacitive discharge on the surface of various materials at different plasma parameters was experimentally studied. Carbon nanowalls were synthesized on the surface of a silicon substrate with a nickel nanolayer and a copper substrate. The experiments were carried out in argon and methane plasma at the temperature of 500°C, discharge power of 8-15 W and pressure of 1.1-1.4 Torr. As a result, carbon nanowalls of different qualities on the surface of copper and silicon substrates were obtained and studied by scanning electron microscopy and Raman spectroscopy.

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High-speed imaging and analysis of a high-temperature microparticle interactions with a magnetron plasma

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High-temperature microparticles may be not avoidable in a magnetic fusion environment like ITER. These objects can play multiple roles such as miniature probes and sensors for the edge plasmas and plasma-material interaction (PMI), validation of various computer codes, and for development of material and plasma control techniques. However, there are fundamental physics remain to be understood about the hot microparticle-plasma interaction physics. For example, what are the charged state of these objects? how are their motion affected by the plasma and magnetic fields? Are the responses of an ambient plasma different from their cold counterparts? Using an exploding wire technique, we describe a recent fast imaging experiment to characterize hot microparticle motion in a DC magnetron plasma, and compare the observations with other experiments in vacuum, air. Image analysis using a machine learning technique is also included. Possible physics models are discussed for the observed motion.

Synthesis of dust particles by combined discharge at atmospheric pressure.

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Synthesis of nano and micrometer size dust particles from the gas phase in low pressure non thermal plasma is well studied [1-2]. Also, atmospheric pressure plasma is widely used for deposition of thin films, for surface treatment and for the synthesis of nanoparticles [3-4].

In this work the results of experiments on the dust particle synthesis and it's deposition on the surface of a silicon substrate by combining two types of discharge at atmospheric pressure is presented. The experimental setup consists of two pin type copper electrodes connected to the pulsed high voltage source (spark discharge) and two copper tapes wrapped around quartz tube powered by kHz high voltage sinusoidal signal (APP jet). In that case, the spark discharge served as a source of precursor and small-size nanoparticles which in the region of a uniform dielectric barrier discharge of the plasma jet, increased in size (due to coagulation or surface growth) and settled on the surface of the substrate. As a working gas pure Ar and He were used.

The characteristics of the plasma jet and the properties of the deposited nanoparticle contained thin films depend on the material, location and on the geometry of the electrodes of spark discharge and other experimental parameters. Therefore, several types of the location of the spark discharge electrodes have been studied and a dynamic I-V characteristic of a combined discharge was also obtained. The temperature of the substrate surface interacting with a plasma jet flow of combined discharge was investigated by a thermocouple and compared with results of just spark discharge temperature measurements. The particle size distributions were determined as a function of the synthesis time and the spark discharge power. Chemical composition of the of the deposited nanoparticles at different experimental conditions was also obtained by energy-dispersive spectroscopy (EDS).

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Surface Temperature of the Dust Particle in Cryogenic Conditions

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In present work the surface temperature of the dust particle in cryogenic complex plasmas at low gas pressure is considered. It is shown that comparing with background gas, the dust particle surface temperature at low pressure is significantly higher. The gas temperature near the grain surface is a slowly decreasing function of distance with asymptotic ~ 1/r behavior. Effects related to the dust particle surface temperature are important for space around dust particle with double radius of average interparticle distance. At the distances comparable with average interparticle distance, these effects are not influencing on the gas temperature [1]. But as a whole can affect ion temperature and energy distribution function, dust particle charge screening, and the neutral shadowing force. The temperature ratio of the dust particle surface and the surrounding gas in the low-pressure weakly ionized complex plasmas is calculated using the formula derived in [2]. Orbit motion limited theory was used to calculate the electron and ions fluxes to the dust particle surface in a weakly collisional regime [3].

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