Connecting particle growth and pattern formation in the Magnetized Dusty Plasma Experiment (MDPX)

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Presentation at Online Low Temperature Plasma (OLTP) Seminar
December 14, 2021
Plasmas: natural and man-made occur at all scales (nm to light years)

Man-made
- Manufacturing
- Plasma medicine
- Lighting
- Plasma agriculture
- Lab experiments
- Fusion energy

500 nm
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Naturally-Occurring
- Lightning
- Sun-Earth connection “space weather”
- Astrophysical jets powered by black holes
- Eta Carina nebula “star and planet formation”
- Fusion energy
Plasmas: natural and man-made occur at all scales (nm to light years)

Man-made

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DUST
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**Dusty (complex) plasmas**
Dusty plasmas are a four-component plasma system

- Dusty plasmas (complex plasmas)
  - Ions
  - Electrons
  - Neutral atoms
  - Dust particles (nm to µm)
- Plasma ⇔ dust via charging
Dusty plasmas are a four-component plasma system

- Dusty plasmas (complex plasma)
  - Ions
  - Electrons
  - Neutral atoms
  - Dust particles (nm to µm)
- Plasma ⇔ dust via charging
- Dusty plasmas occur in space, lab, and industry
The Magnetized Dusty Plasma Experiment
Magnetized Plasma Research Laboratory (MPRL)
A Department of Energy Collaborative Facility - Operated via Plasma Science Facility Program
Additional support via the NSF-EPSCoR program - CPU2AL project
Major equipment funded by the NSF (NSF-MRI), DOE, and NASA
Introduction

Magnetized Dust
Plasma Physics  Dusty Plasmas
MPDx device  Charging  Growth  Filaments  Ordering
Microgravity
PK-4 results  Summary

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Magnetized Plasma Research Lab
(MPRL @ Auburn Univ.)
http://aub.ie/mprl

MagNetUS Frontier Plasma Science - Joint Solicitation

http://MagNetUS.net

BAsic Plasma Science Facility
(BAPSF @ UCLA)

DIII-D National Fusion Lab
(San Diego @ General Atomics)

Wisconsin Plasma Physics Lab
(WiPPL @ Univ. of Wisconsin)

Magnetized Plasma Research Lab
(MPRL @ Auburn Univ.)
http://aub.ie/mprl
Technical challenges in magnetizing a dusty plasma in the laboratory

- Magnetization criterion
  - Magnetic force will be comparable to the other forces acting upon the dust grain

- Challenges:
  - Dust grain charge, $Z_d \sim 1000$
  - Dust grain mass, $m_d > 10^8 m_{\text{ion}}$

- That is: $q_d/m_d \ll e/m_{\text{ion}} \ll e/m_{\text{elec}}$

- Key parameters:
  - gyroradius to exp. size:
    $$\frac{\rho}{L} \sim \frac{a^2 v_d}{BL} \ll 1$$

  - gyrofreq. to collision freq.:
    (Hall parameter)
    $$\frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1$$

  - magnetic to gravitational force:
    $$\frac{F_m}{F_g} = \frac{Q_d v_d B}{m_d g} \sim \frac{v_d B}{a^2} \geq 1$$

- Key result: Maximize $B/a$

- Scaling of pressure vs. grain radius for the condition: $\tau_{\text{collision}} / \tau_{\text{cyclotron}} = 1$
MDPX: A cryogen-free, superconducting, multi-configuration magnetic field system

- Radial and axial diagnostic access
- RF generated plasmas: $f = 13.56$ MHz, $P_{RF} = 1$ to $10$ W
- Argon: $P = 5$ to $300$ mTorr (0.6 to 40 Pa)
- Silica microspheres $\langle \text{dia} \rangle = 0.1$ µm to 8 µm
- Diagnostics:
  - Langmuir probes
  - Triple probe ($n_e, T_e, V_p$)
  - DPSS lasers
  - High-speed video cameras (300 fps)
- Plasma parameters (@ $B = 0$ T):
  - $T_e = 1$ - 5 eV, $T_i = 1/40$ eV
  - $n_e \sim n_i \sim 2$ to $8 \times 10^{15}$ m$^{-3}$

Magnetic field: 3.5 T (to date); 4 T (max)
Magnetic field gradient: 1 - 2 T/m
Magnet cryostat: 50 cm ID / 127 cm OD / 158 cm axial
Magnet material: NbTi superconductor; cryogen-free

Dust particle growth at high magnetic field
Particle growth in reactive plasmas

- In a reactive plasma, particles can be formed directly from the gaseous phase.

- It is a multi-step process where the plasma has sufficient energy density to break up complex molecules.

- The resulting ions can undergo a combination of chemical and physical reactions to form nm to µm sized particles.

- These processes can occur in the cooler, denser edge plasma.
Recent results: Dust particle growth is modified by the presence of a strong magnetic field

• Experiments are being performed in MDPX to investigate dust particle growth.

• Initial studies have used an argon plasma seeded with acetylene (C₂H₂) to form a reactive plasma.

• Carbon-rich particles quickly form in the plasma - within seconds.
Recent results: Dust particle growth is modified by the presence of a strong magnetic field

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- Initial studies have used an argon plasma seeded with acetylene ($C_2H_2$) to form a reactive plasma.
- Carbon-rich particles quickly form in the plasma - within seconds.

Real-time movie of carbon nanoparticle growth at $B = 2.02$ T
Characterizing the grown particles

SEM images of grown particles

- At $B = 0 \, T$, the particles form mostly uniform spheres approximately 0.25 to 0.3 $\mu m$ in diameter.
- With increasing magnetic field:
  - Particle size is smaller
  - Large aggregates of small particles form
  - Increasing porosity of assembled particles
Decoupling: filaments vs magnetic field

- Initial results - show modification of particle growth with increasing magnetic field
- What precisely is the mechanism: is it the magnetic field or is there a contribution due to filaments - or both?
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• **What precisely is the mechanism:** is it the magnetic field or is there a contribution due to filaments - or both?

*Vertical structures*
An electrode redesign was performed to localize the formation of filaments.

### Redesign of growth experiment

- **Time/space sequence** showing the time evolution of the filaments.
- **Particularly, note** the localization of a few filaments.

#### Diagram

<table>
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<th>Time (s)</th>
<th>x-position (mm)</th>
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<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
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</tbody>
</table>

- **cycle 1**
- **cycle 2**
- **cycle 3**
- **cycle 4**
- **cycle 5**

- **No filaments**
- **mobile filaments**
Decoupling: filaments vs magnetic field

Electrode modification to reduce filamentation near the center.

Evolution of particle growth in regions with filaments and reduced filaments.
Future directions: Determine the characteristics of the magnetized plasma that lead to the modification of the particle growth.

- The initial studies have demonstrated that the particle growth process in the magnetized plasma differs from the unmagnetized case.
- However, the magnetized plasma has a number of different characteristics:
  - presence of filaments
  - modified density
  - modified electron temperature
- Is it possible to “direct” particle growth using a combination using plasma pattern formation?
Pattern formation (filamentation) in magnetized plasmas
A brief aside on plasma filaments - observations

- First reported at MPE
- Structures in the **plasma glow** aligned to the magnetic field

MDPX: Argon plasma at $B = 0.75$ T, $P = 2.9$ Pa, and $RF = 1.8$ W


E. Thomas, et al., PPCF, 62, 014006 (2020)
The presence of filaments (plasma structures aligned parallel to the magnetic field) has been reported in earlier works [e.g., M. Schwabe, et al., PRL, 2011].

Filaments generally appear at low pressure, at low rf power, and at higher magnetic fields; filaments dissipate due to enhanced collisions with neutrals.
• RF power scan shows qualitatively similar results with increasing power;.
• One difference - appearance of single, smaller filaments at center.
• But, physical process must be quite different - because pressure is constant.

Low RF power scan (top view)

P = 4.6 Pa
B = 0.75 T
Filaments in **Argon** at different magnetic field strengths and pressures

- Individual filaments were observed in argon plasma at low pressures between 5-45mTorr (~0.66-6Pa)
- Confirmed the existence of filaments with new experiment configuration.
- Reproducible!
Exploring Hall parameter space with changing ion mass

Filaments observed in **Neon** gas

- Type 1
- Type 2
- Type 3

Reproducible!

- B discharge: 3T – 1T
- Pressure: 30mTorr (~4 Pa)
- Power input: 1W

- B discharge: 3T – 1T
- Pressure: 26mTorr (~3.3 Pa)
- Power input: 1W

M = 1?
Exploring Hall parameter space with changing ion mass

Type: 1  2  3

(a) (b)

Filament Number with B at 3.5 Pa

Filament Number with B at 4.4 Pa

Filament Number with B at 5.3 Pa
Exploring Hall parameter space with changing ion mass

Type: 1

Filament Number by Type with Hall Parameter

Type 1 (Circular)

Type 2 (Elongated)

Type 3 (Spiral)

Ion Hall Parameter
M = 1 filaments observed in multiple gases

Type 4 cheerio found in Neon

Type 4 cheerio found in Argon
Filamentation: Ordered, plasma structures - initial modeling

2-D modeling of filaments
Using M. Kushner
Hybrid Plasma Equipment Model (HPEM)

M. Menati, et al.,

3-D modeling of filaments
Using Menati fluid code

Menati, Konopka, Thomas (in prep)
Experimental observations show behavior predicted by simulation.

Gas = Krypton
B = 2.2T
P = 42mT
RF = 3W forward, 2W reflected

• A three-dimensional, two-component fluid model has been developed to model the ion and electron dynamics at high magnetic field.

• Model allows for neutral collisions and ionization.

• After the initial perturbation, there is a competition between electron fluxes (parallel) and ion fluxes (parallel and perpendicular).

• Equations take the form of an activator-inhibitor system, which we believe may be responsible for the pattern formation.

M. Menati, PhD. Dissertation (2020)
M. Menati, et al., PSST, 29, 085015 (2020)
Similar framework is used to explain imposed, ordered pattern formation in dust

**Image spatial resolution**

45.5 \( \mu \text{m/pix} \)

**Wire center-to-center spacing**

\( a = 838.2 \pm 139.7 \ \mu \text{m} \)

**Sample measurements**

1. 19.80 pix \( \sim \) 900.9 \( \mu \text{m} \)
2. 19.91 pix \( \sim \) 908.6 \( \mu \text{m} \)
3. 18.77 pix \( \sim \) 854.0 \( \mu \text{m} \)
Observations of the dust particles using a macroscopic mesh gives a new view of how they are becoming trapped in the plasma

- A three-dimensional, two-component fluid model has been developed to model the ion and electron dynamics at high magnetic field.
- Model allows for neutral collisions and ionization.
- A grounded, conducting wire mesh is placed in the plasma.
- Trapping is dependent upon $B$, $w$, $d$, $P$, generally consistent with experiments.

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Formation of the trapping structures is a competition between electron confinement / flow along $B$ vs. cross-field diffusion of ions perpendicular to $B$. 

M. Menati, PhD. Dissertation (2020)
M. Menati, et al., PSST, 29, 085015 (2020)
Even higher filamentary modes may exist

4 arm filaments
Gas = Krypton
B = 3.25T
P = 50mTorr
RF = 3W forward, 2W reflected

5 arm filaments
Gas = Krypton
B = 2.2T
P = 42mTorr
RF = 3W forward, 2W reflected

5/6 arm filaments
Gas = Krypton
B = 2.2T
P = 42mTorr
RF = 2W forward, 1W reflected
A last few words...
Magnetized Plasma Research Laboratory (MPRL) at Auburn University:
Advancing the study of magnetized plasmas, dusty plasmas, and magnetized dusty plasmas

Thermal properties in dusty plasmas
Studying strongly vs. weakly coupled plasmas in lab, magnetized, and microgravity plasmas.
Collaborations: Baylor, UCSD, ESA, Roscosmos

Controlling charge
Using UV to control dust without modifying background plasma.

Plasma filaments and plasma self-organization
Experiments and modeling of plasma pattern formation show good qualitative agreement.

Particle growth
Nanoparticle growth in magnetized plasmas filaments leads to control over morphology.
Collaborations: CPU2AL, Tuskegee Univ., U. Saskatchewan, Univ. of Alabama - Birmingham

Imposed ordering
Using dust particles as a diagnostic for sheath and filament formation in magnetized plasmas.

Panoramic view of the Magnetized Dusty Plasma Experiment (MDPX) device. Insert of plasma and dust cloud.

More information can be found at [http://aub.ie/mprl](http://aub.ie/mprl).


**MPRL Research Team**

**MDPX design/construction**
- Uwe Konopka, Auburn
- Robert Merlino, Iowa, Marlene Rosenberg, UCSD
- Mark Cianciosa, Ross Fisher, Ami DuBois
- Saikat Chakraborty Thakur, MPRL Project Scientist
  - Cameron Royer, MPRL Manager

**Charging**
- Brian Lynch, Michael McKinlay

**Plasma filamentation**
- Mohamad Menati, Stephen Williams

**Particle growth**
- Bhavesh Ramkorun, Surabhi Jaiswal
  - Lenaic Couedel - CNRS / University of Saskatchewan*

**Dust ordering**
- Taylor Hall, Spencer LeBlanc

**Microgravity**
- Lori Scott, Eva Kostadinova, Auburn
- Truell Hyde, Lorin Matthews, Baylor
- Jeremiah Williams, Wittenberg
- Mikhail Pustylnik, Hubertus Thomas, DLR
- Andrey Lipaev, Sasha Usachev, Russian Academy of Sciences

**Diagnostics and instability experiments**
- N. Ivan Arnold, Jared Powell, Leo Nofs, Evan Aguirre

**http://aub.ie/mprl**

Open to receive 2022 proposals