A summary of initial studies of ordered structures and collective modes using the Magnetized Dusty Plasma Experiment (MDPX) device

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Presentation at 14th Workshop on the Physics of Dusty Plasmas

May 27, 2015

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Status

- MDPX
  - Technological developments
  - Operational status

First results

- Ordered structures in strongly magnetized plasmas
- Ongoing studies
  - Transport
  - Waves and instabilities

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Properties of a magnetized dusty plasmas

- Strong magnetic field will guide ion and electron transport to surfaces - for electrodes and dust grains.
- Charging of surfaces and dust grains may be significantly modified.
- Formation of sheaths will become asymmetric parallel and perpendicular to the magnetic field.
- How is the growth of small grains affected at high magnetic field - e.g., formation of elongated particles?
- Can 2D ordering of dust be maintained at high B?

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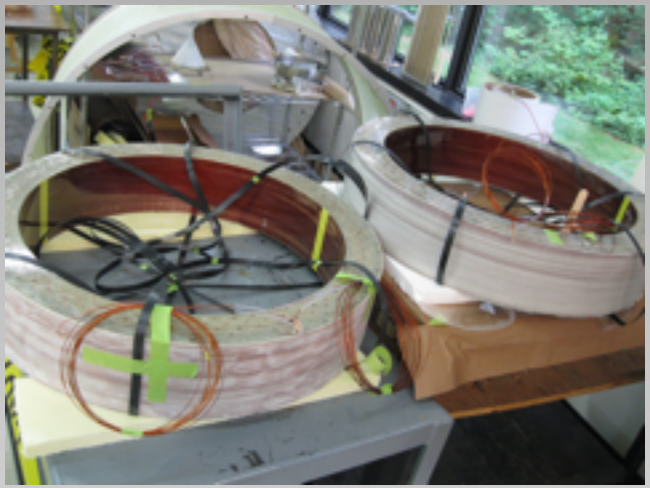
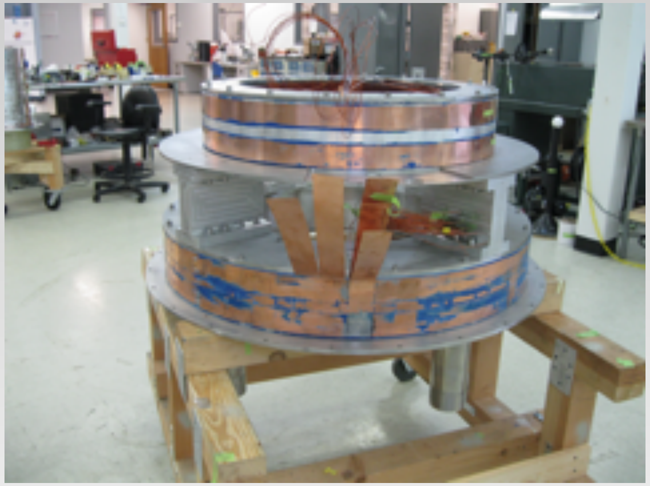
MDPX superconducting magnet system





- Four superconducting coils in a split-bore cryostat
- 1.3 mm diameter, copper wire with Nb-Ti filaments
- Use of cryogen-free cooling system (i.e., no liquid helium)

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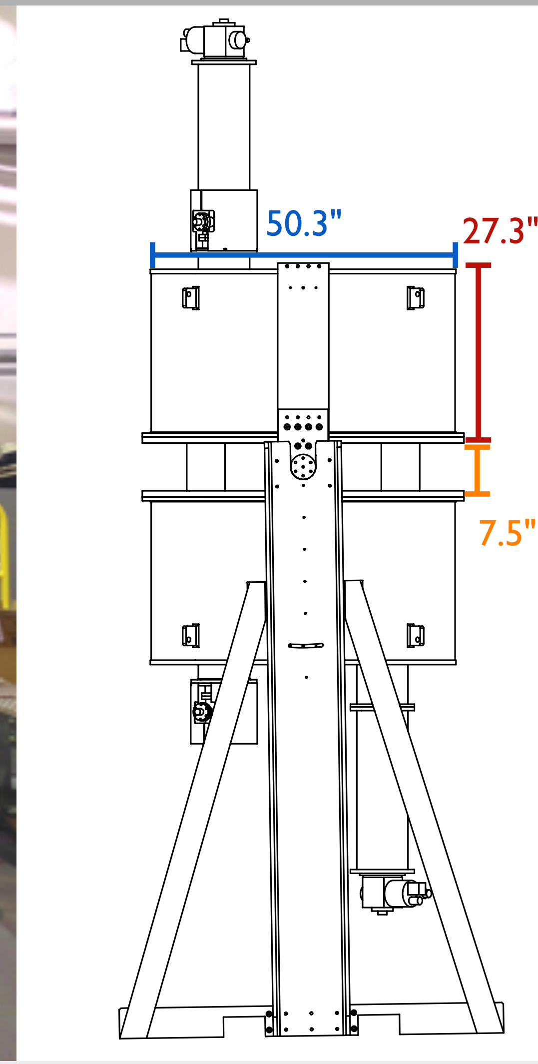
MDPX parameters: final "as-built" system

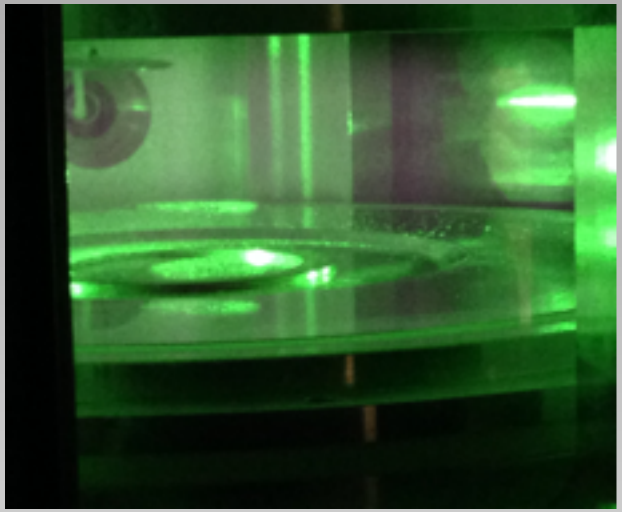


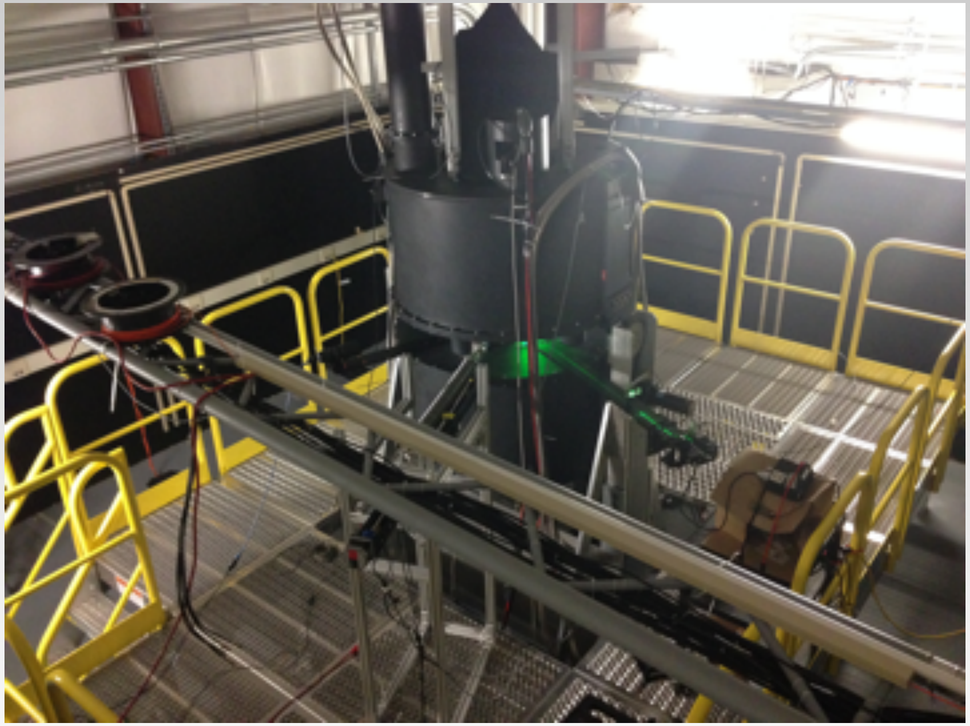
Magnetic field:	3.0 T (to date); 4 T (max)
Magnetic field gradient:	1 - 2 T /m
Magnet cryostat:	50 cm ID / 127 cm OD
Magnet material:	NbTi superconductor; cryogen-free system

Magnet performance:	$T_{critical}$ = 6.4 K; $T_{minimum}$ = 4.2 - 4.8 K
Experiment volume:*	45 cm dia. x 175 cm axial
Uniform region:*	20 cm dia. x 20. cm axial
Total cold mass:	~2.5 tons

MDPX: Plasma operations and diagnostic systems

- Octagonal vacuum chamber:
  355 mm ID, 178 mm height
  Excellent diagnostic access
- RF generated plasmas:
  f = 13.56 MHz, P_{RF} = 2 to 10 W
- Argon:
  P = 30 to 200 mTorr
- Silica microspheres
  <dia> = 0.5 μm, 2 μm, 8 μm
- Diagnostics:
  Triple probe (n_e, T_e, V_p)
  DPSS lasers
  Top camera (4 Mpix, 90 fps)
  Side camera (1.2 Mpix, 150 fps)
- Plasma parameters (@ B = 0 T):
  T_e = 3 eV, T_i = 1/40 eV
  $n_e \sim n_i \sim$ 2 to 8 x 10^{15} m^{-3}





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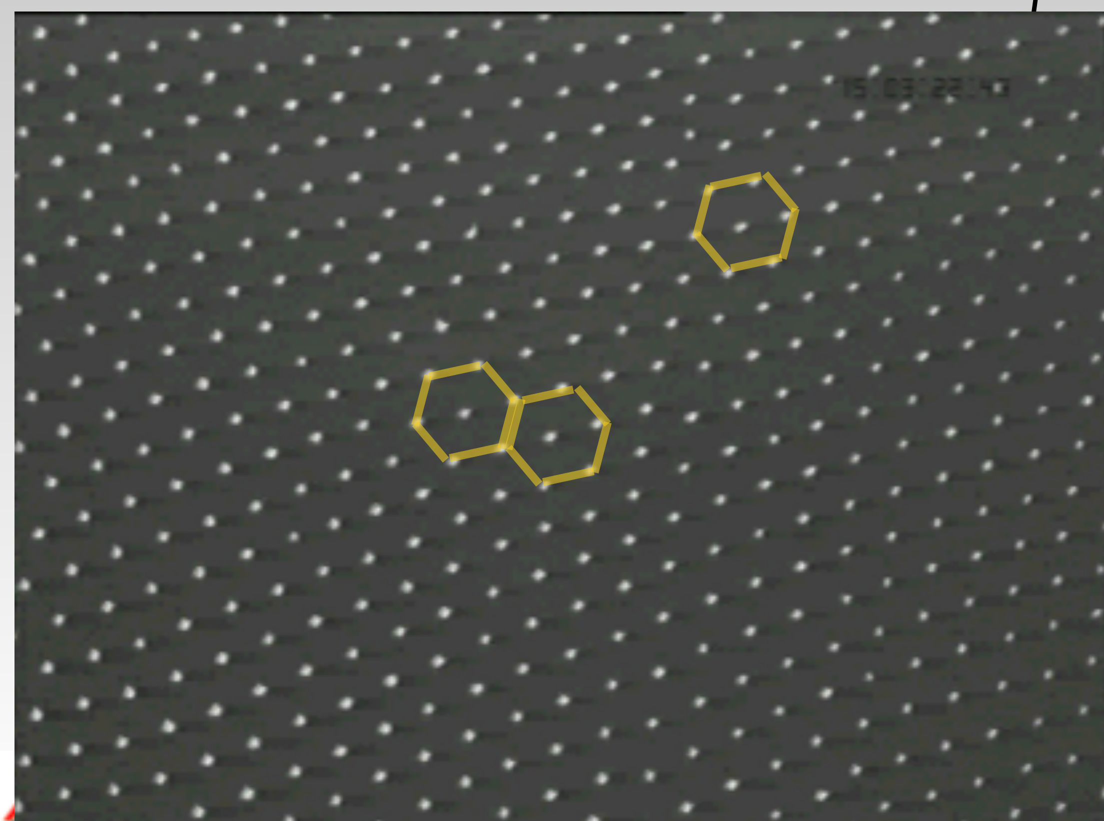
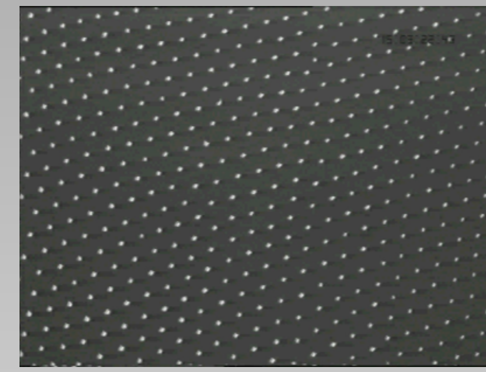
Self-organization in dusty plasmas

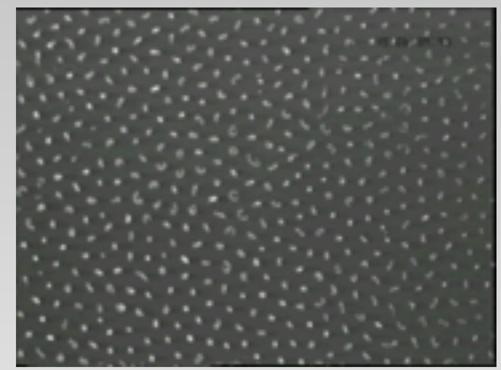
- Γ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction (Yukawa, Debye-Hückel):

$$\varphi \sim \frac{\exp\left(-r/\lambda_D\right)}{r}$$





$\Gamma >> 1$



$\Gamma \sim 1$

$\Gamma < 1$

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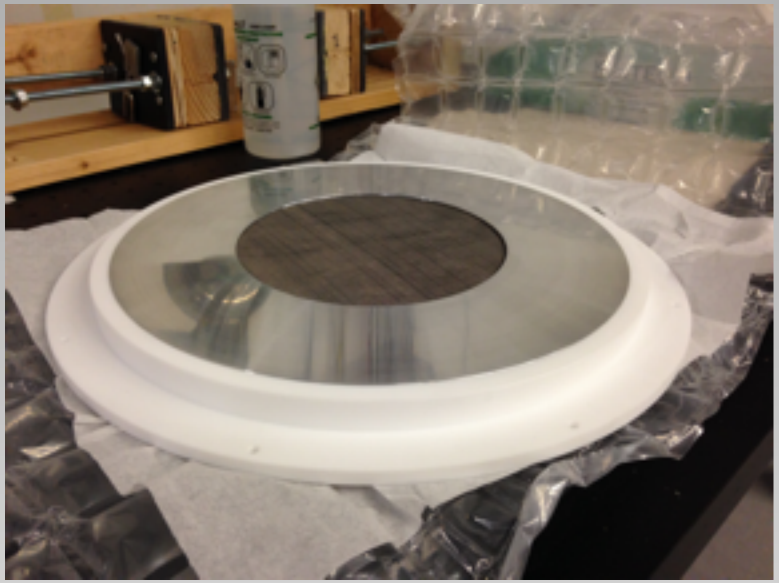
Imposed order in a dusty plasma at high magnetic field: experiment setup

Lower electrode: powered
Upper electrode: electrically floating, wire mesh
Electrode gap: 62 mm

Dust cloud: 30 - 40 mm below upper electrode



Key scale lengths:
(B = 1 T, P = 120 mTorr)

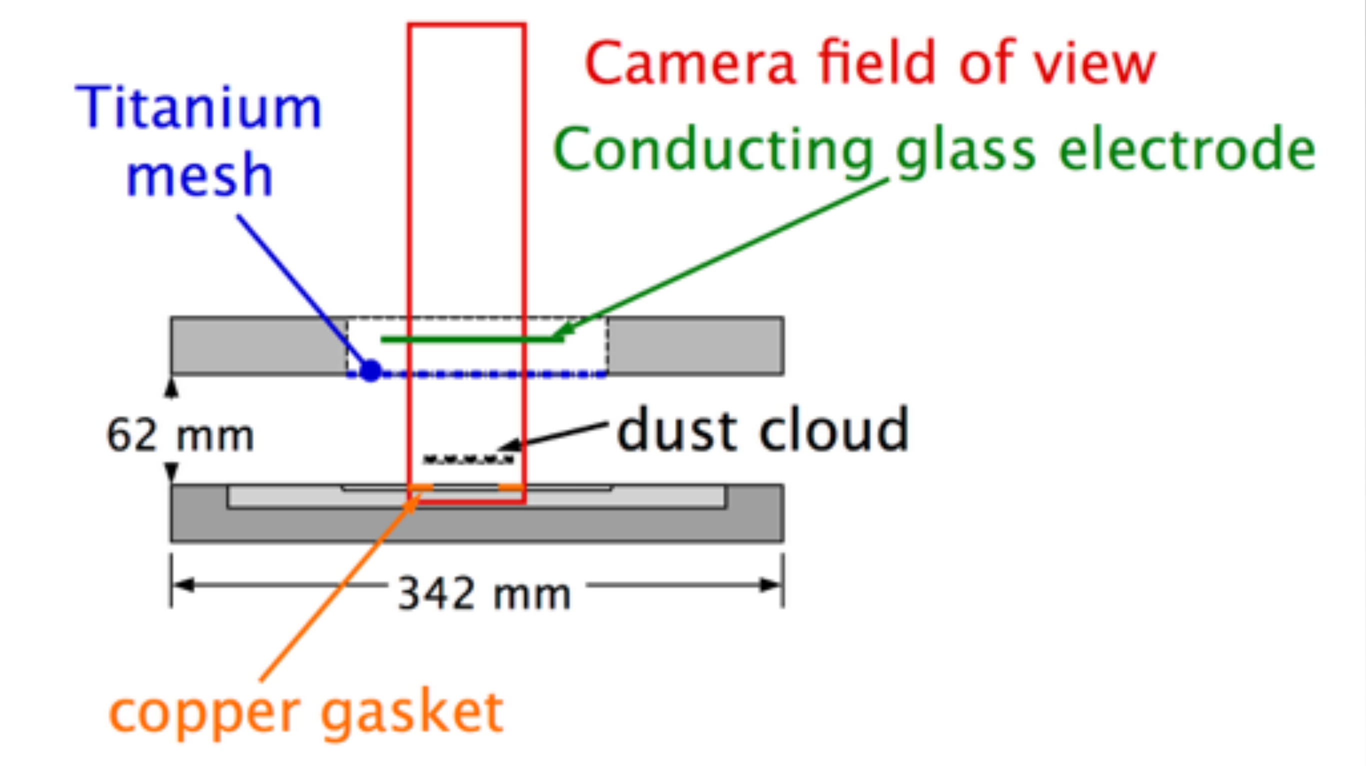
$\lambda_{mfp-ion} \sim 0.6$ mm

$\lambda_{mfp-electron} \sim 8$ mm

$\lambda_{De} \sim 0.2$ mm

$r_{Le} \sim 0.006$ mm

$r_{Li} \sim 0.15$ mm



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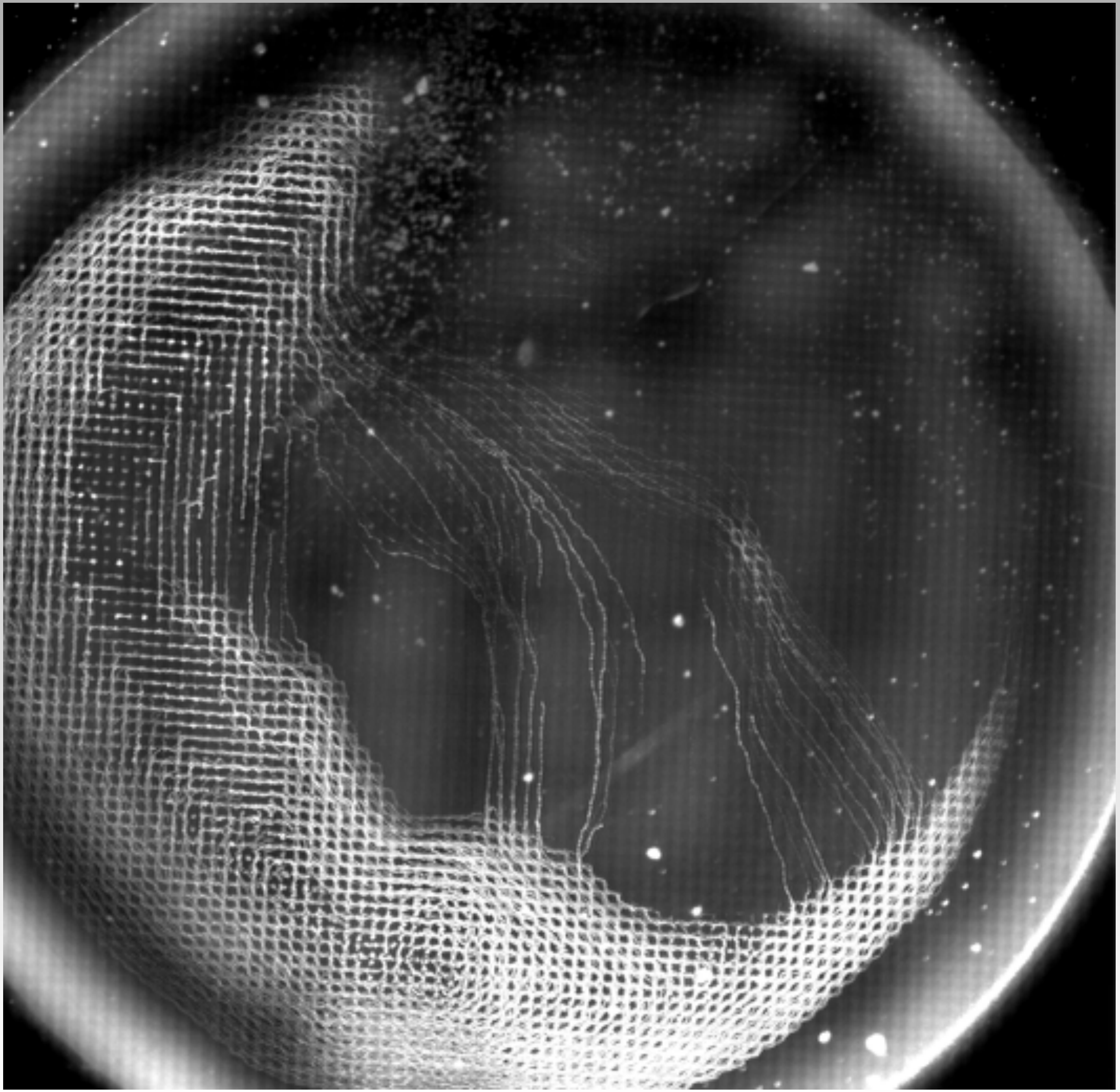
Imposed order in a dusty plasma at high magnetic field: video of dust motion

Dust motion:
p = 145 mTorr
2 micron particles
B = 2 T

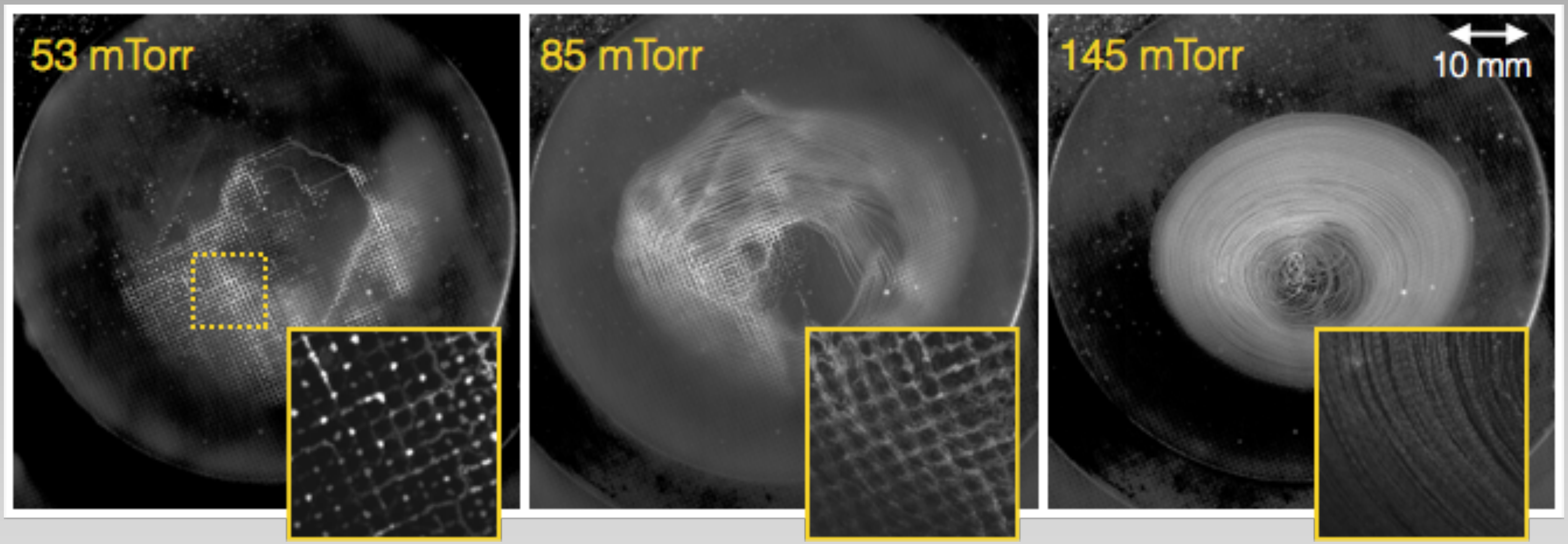
Sum over 100 frames and image contrast enhanced.

Note the grid-like pattern followed by the dust grains (in white).

There are also filaments (light gray areas) beginning to form.



Dust grid structure becomes degraded with higher neutral pressure



- Comparison of grid formation: 0.5 micron particles, B = 1.5 T
  Sum over 100 frames and image contrast enhanced
- The ordering of the dust into the grid pattern *decreases* with higher pressure.
- Fluid-like motion increases with higher pressure.
- Note differences in plasma glow and filamentation with pressure.
  (lower p, more filaments)

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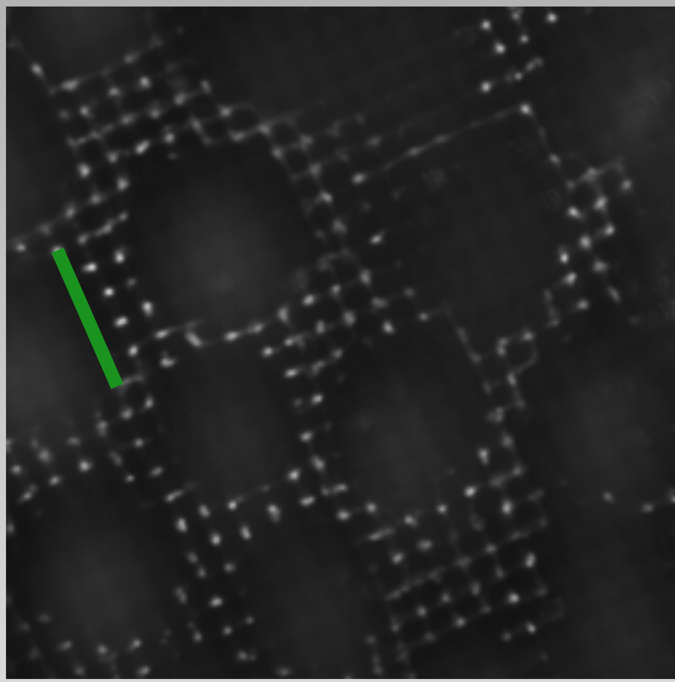
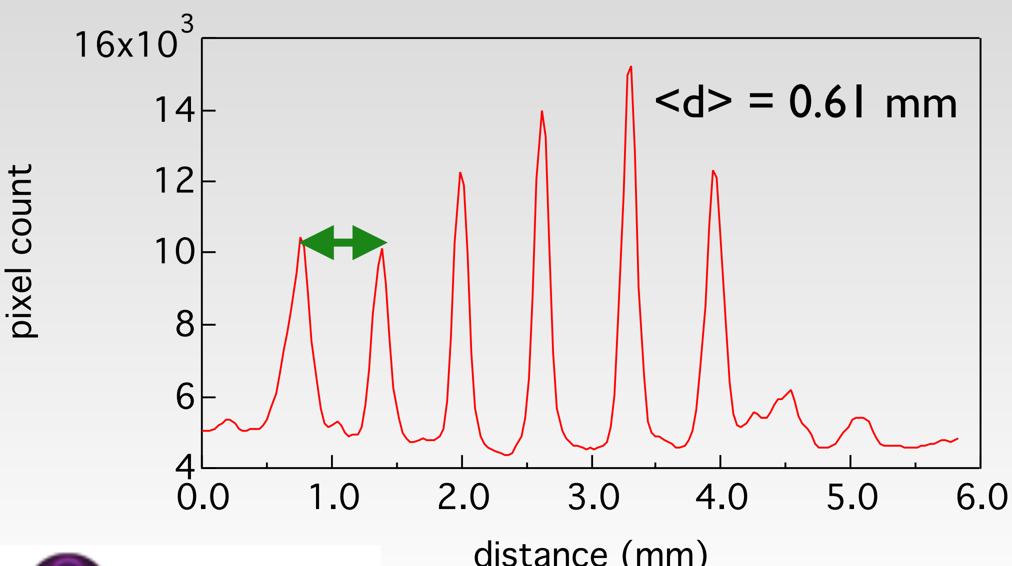
Structure persists over a range of magnetic field, pressure, and particles sizes

Close-up of a 450 x 450 pixel region

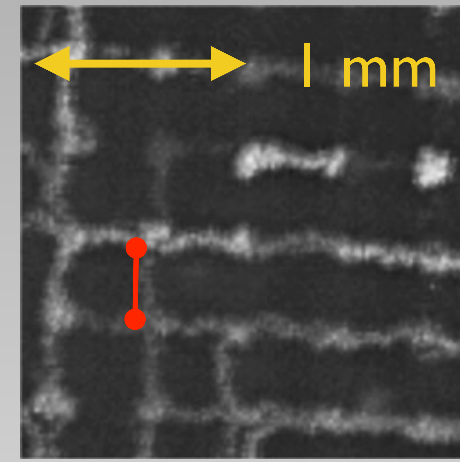


2 T
90 mTorr
0.5 µm

d = 0.61 mm

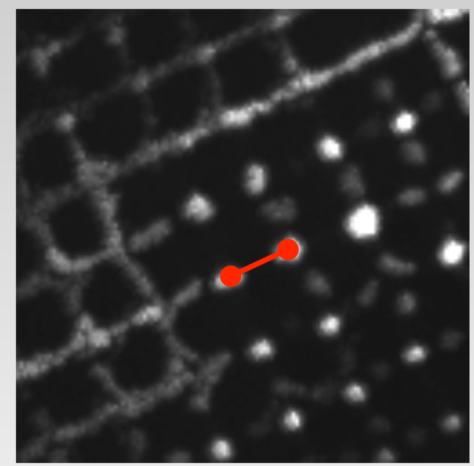


Close-up of a 125 x 125 pixel region



2 T
145 mTorr
2 µm

d = 0.65 mm



1.5 T
53 mTorr
0.5 µm

d = 0.69 mm

Grid pattern in dust: ~0.65 ± 0.02 mm

Mesh wire used: **#40 titanium mesh**
Wire: 0.25 mm diameter
Center-to-center spacing: 0.635 mm

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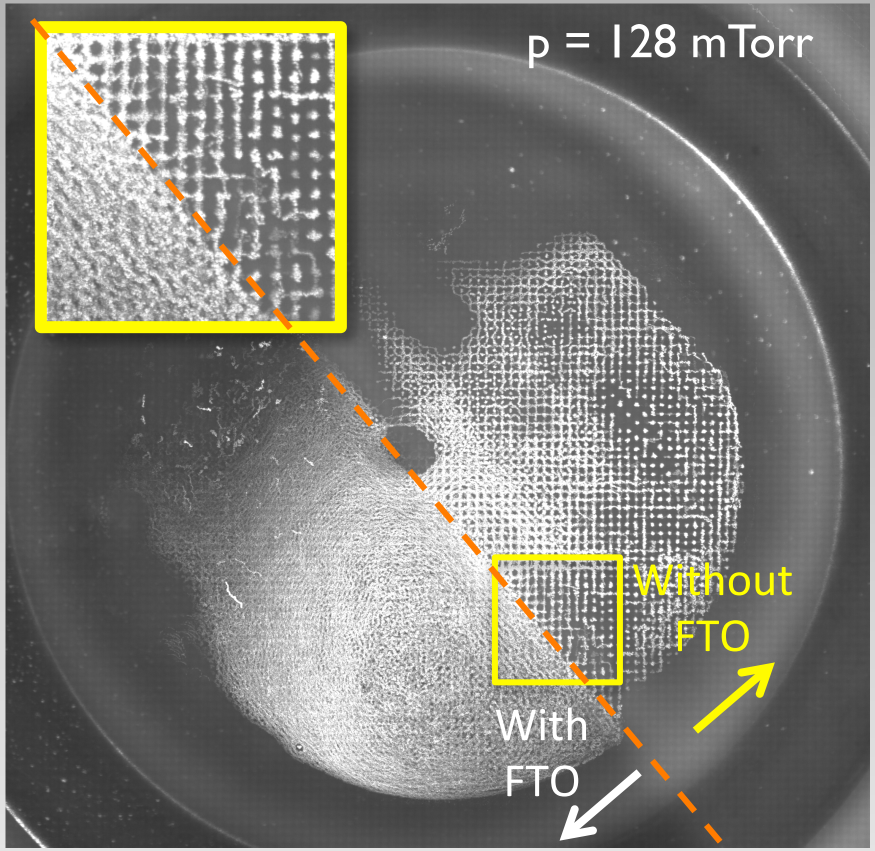
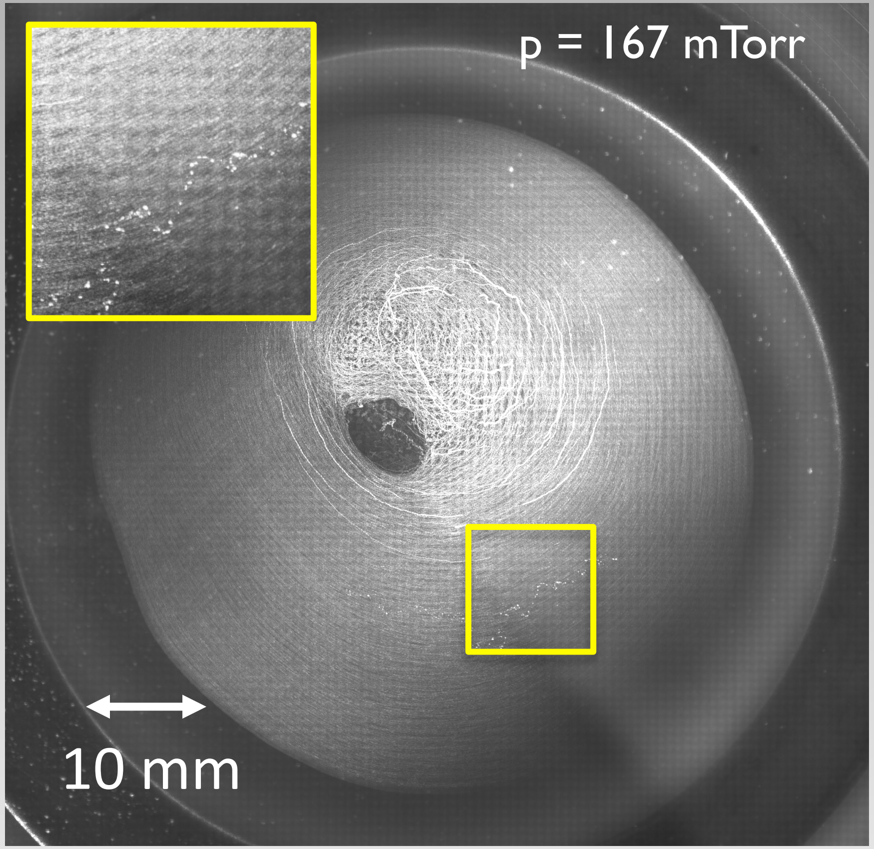
The dust structure is modified using a conducting glass electrode

2 micron particles, B = 1.5 T, RF power = 4 W





- A conducting, transparent electrode (FTO-coated glass) is placed on 1/2 of the grid.
- Formation of grid structure is reduced on the side with the FTO glass - is the conductor "shorting" the grid or the holes?
- At the higher pressure, dust grid is degraded.

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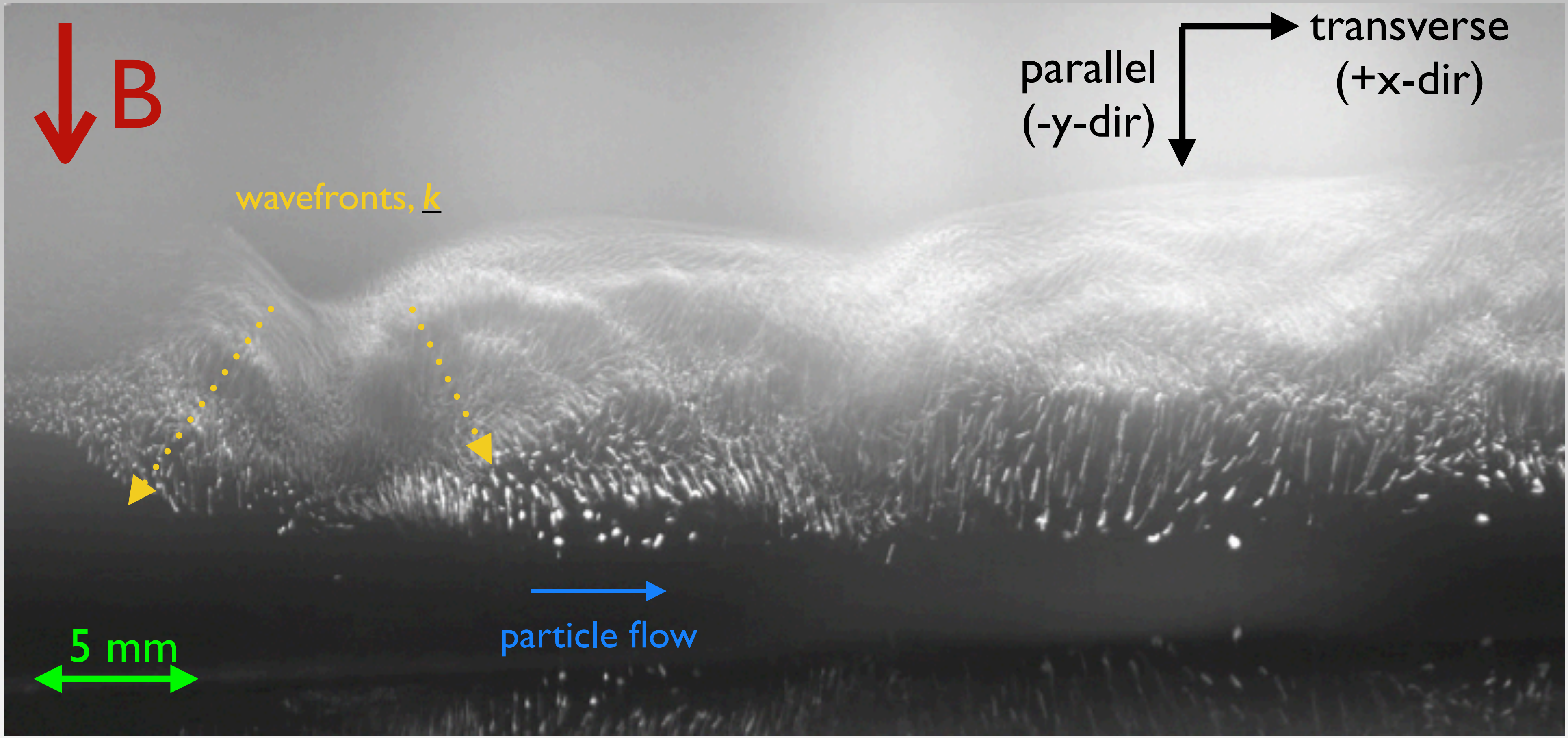
Initial result: imposed order in a dusty plasma at high magnetic field

Many outstanding issues:

- How does the dust remain constrained by the flux tubes extending from the wire mesh?
- Is the confinement mechanism due to a net attractive force to the region underneath the grid or a net repulsive force to the region between the grids (i.e., is it the wire or the holes)?
- Is it the ion or electron dynamics that is controlling the system?
- Can the grid pattern be modified or controlled?
- Is it possible to use any arbitrary grid pattern?
- How does the grid formation related to the generation of filaments?
- What is the 3-D structure of the dust grid structure?
- How can these structures be diagnosed not-invasively?

Beginning studies of dust acoustic/dust density waves

Most recent wave measurements:
B = 1.0 T
2 micron diameter particles
p = 140 mTorr



Original video: 100 fps, slowed by 1/10th

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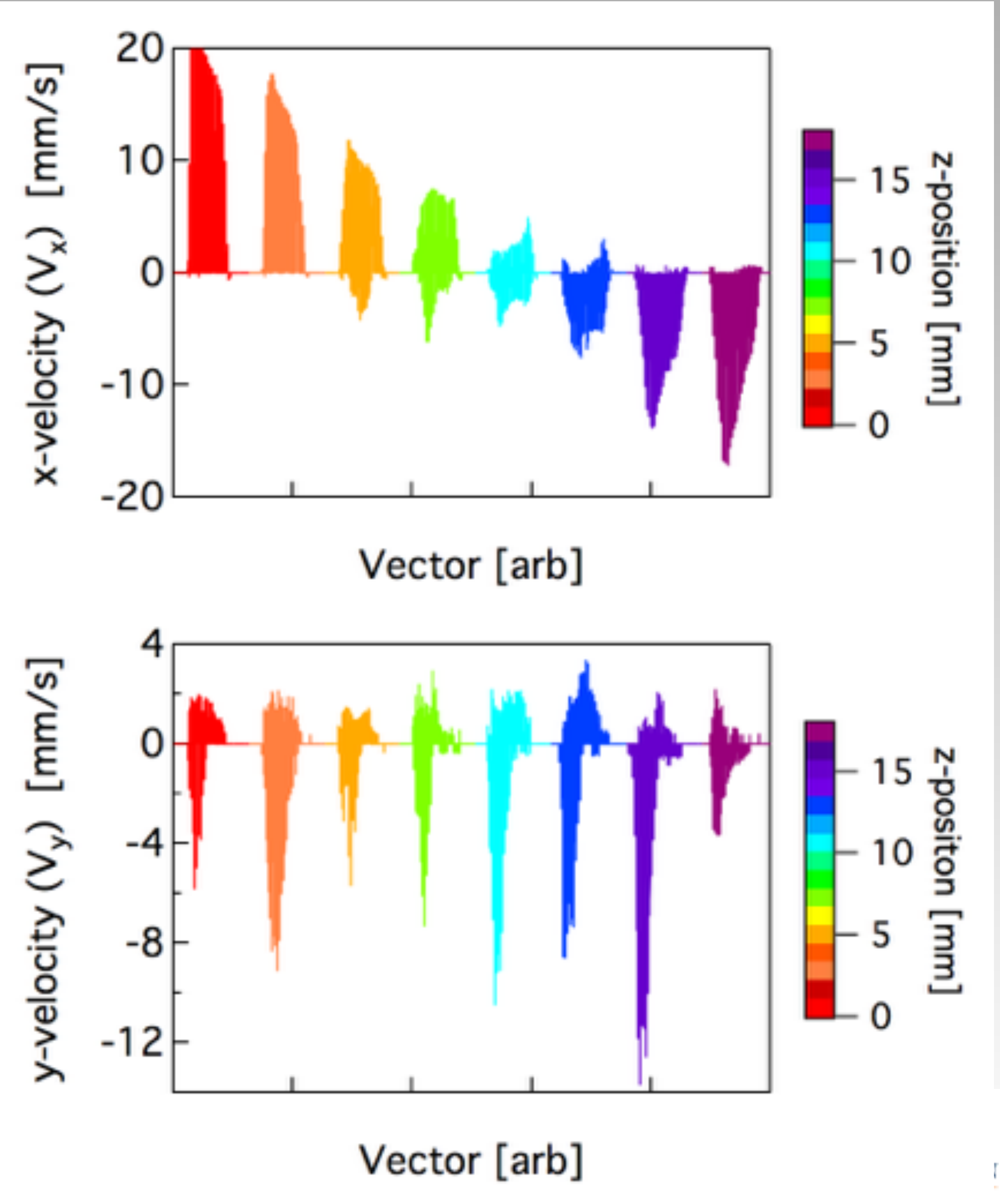
Beginning studies of dust acoustic/dust density waves

Most recent wave measurements:
B = 1.0 T
2 micron diameter particles
p = 140 mTorr

- Analysis of global particle motion using particle image velocimetry (PIV).
- Plots show a distribution of the measured PIV velocity vectors as a function of z-position (i.e., into the plane).
- This is suggestive of the circulation of the particles from the front of the cloud (**+V_x**) to the back of the cloud (**-V_x**).



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Beginning studies of dust acoustic/dust density waves

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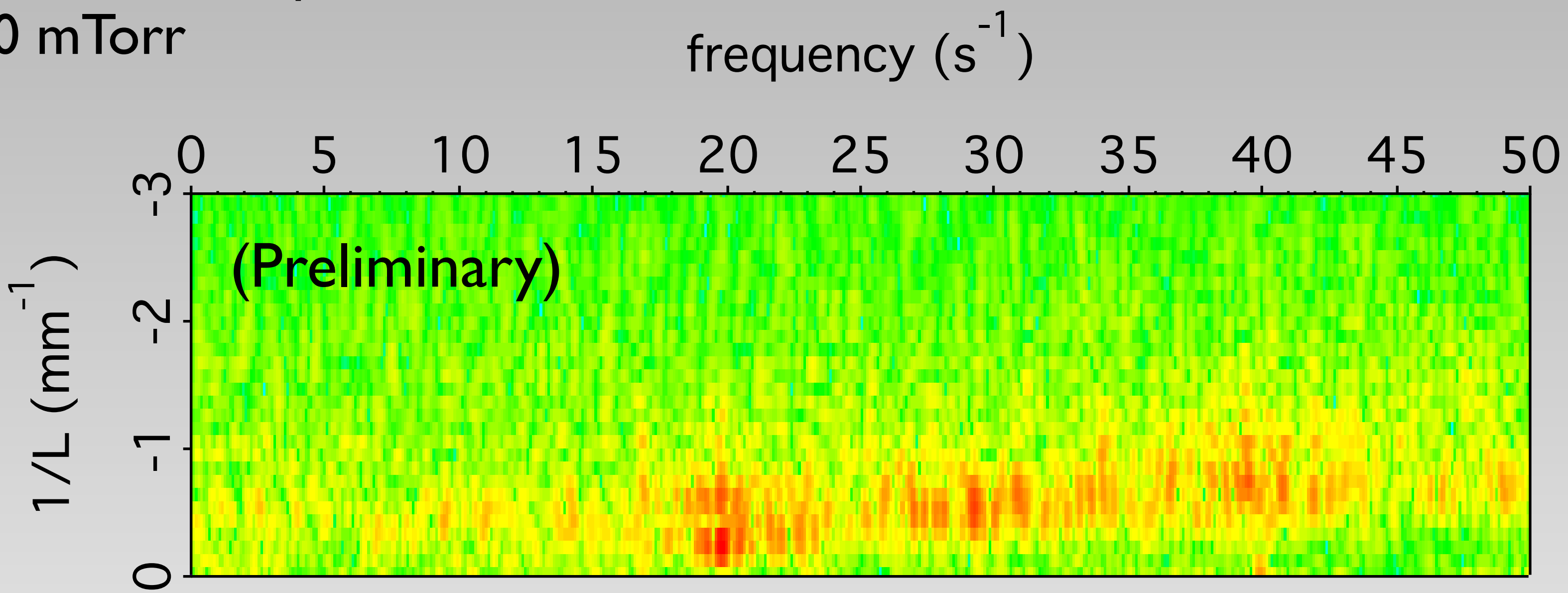
Collaborative study:
Experiment: R. Merlino
Analysis: M. Rosenberg, J. Williams



Dispersion relation derived from time-space analysis of wave video along the direction of propagation of the wave.

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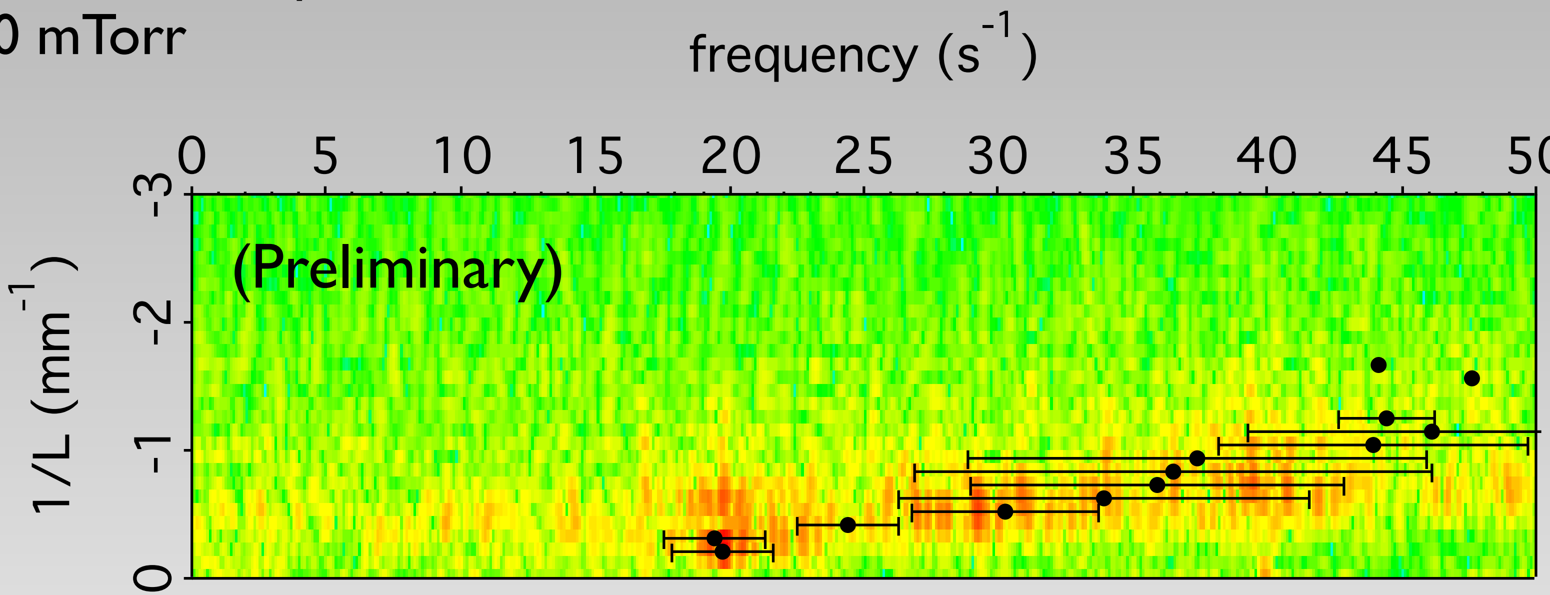

Dispersion relation derived from time-space analysis of wave video along the direction of propagation of the wave.

Current work: to understand and interpret the apparent motion of the wavefronts perpendicular to the magnetic field

Slide on transverse motion here

Most recent wave measurements:
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2 micron diameter particles
p = 140 mTorr

Collaborative study:
Experiment: R. Merlino
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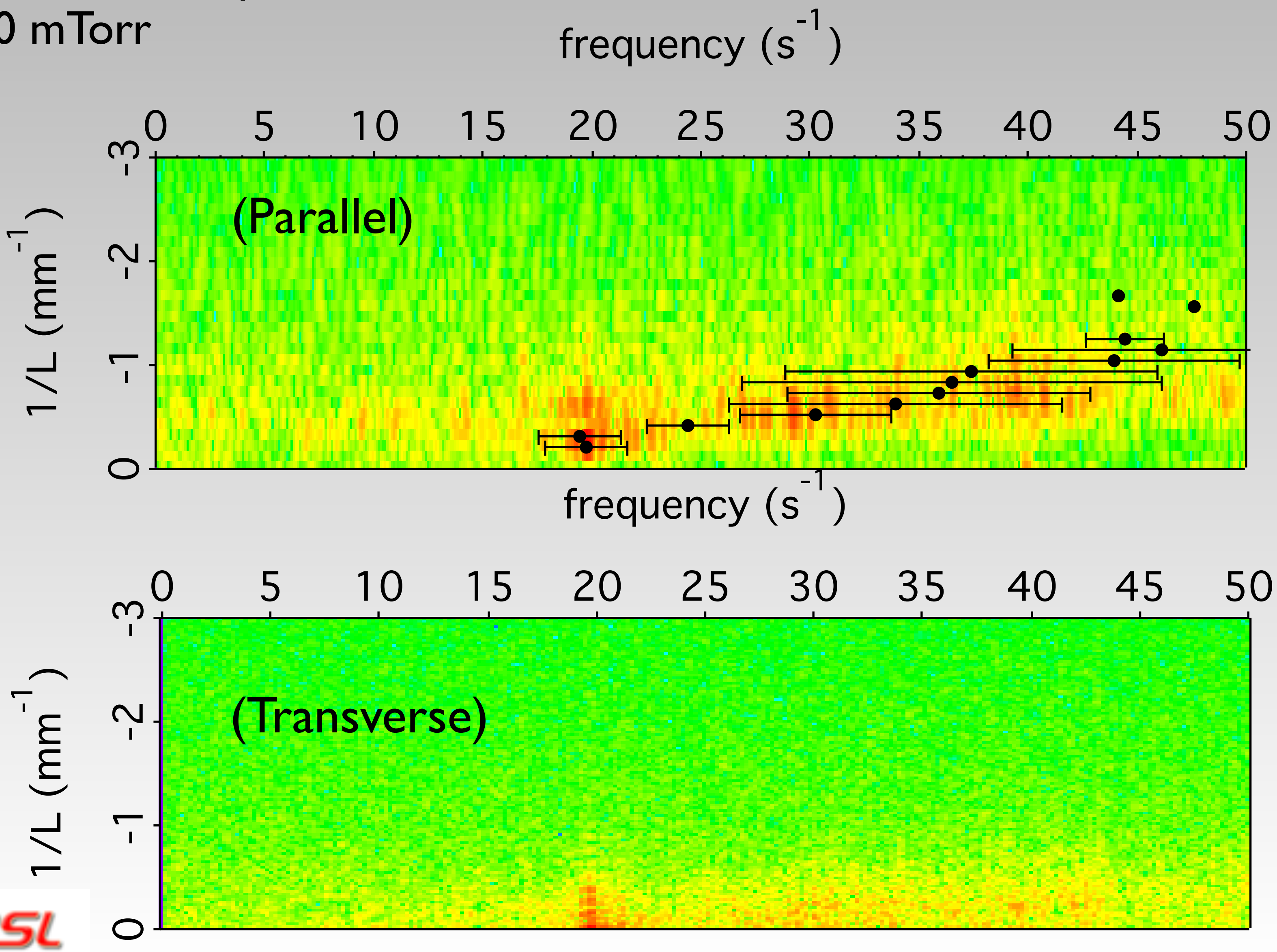

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Summary: current status of the MDPX device

- Engineering status:
  - MDPX is generally performing well; peak field B = 3 T
  - Operations are shifting from a testing to operational mode.
  - Gaining experience with making reliable and reproducible plasmas and dusty plasmas.

- Research status:
  - Experiments are focused on the interaction of magnetized ions and electrons with charged dust.
  - Use of wire mesh has led to the observation of a new of "imposed ordering" in a dusty plasma whose characteristics strongly differ from previously observed plasma crystals.
  - Thomas, et al., J. Plasma Phys., **81**, 345810206 (2015); Thomas, et al., *Phys. Plasmas,* **22**, 030701 (2015).
  - We are making detailed observations of transport and instabilities.
  - Seeking to expand collaborations with national and international groups.

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Installation of the MDPX device:
5 days in 4.5 minutes!

Come see MDPX at the laboratory tours!

Thank you!

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Backup Slides

Magnetized dusty plasmas in the laboratory

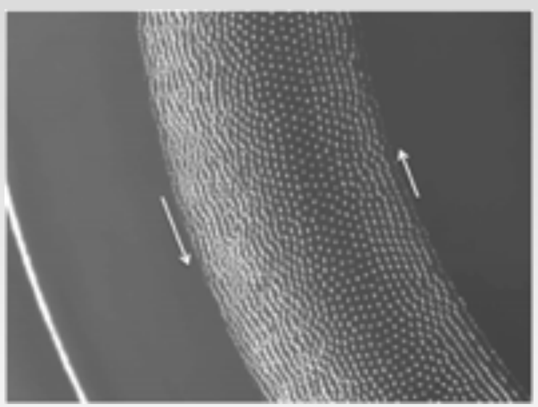
- Research on: microgravity and magnetized dusty plasmas

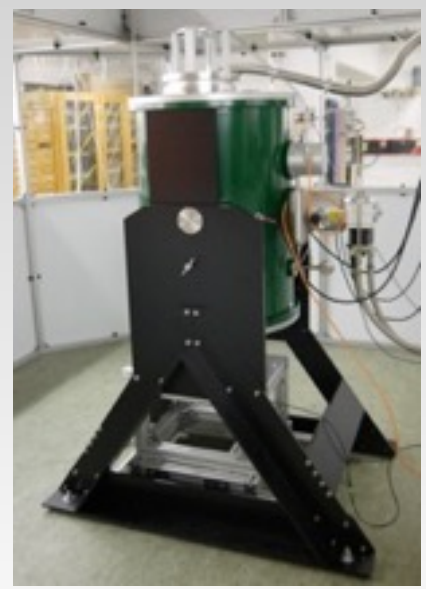
Max Planck Institute / Giessen University

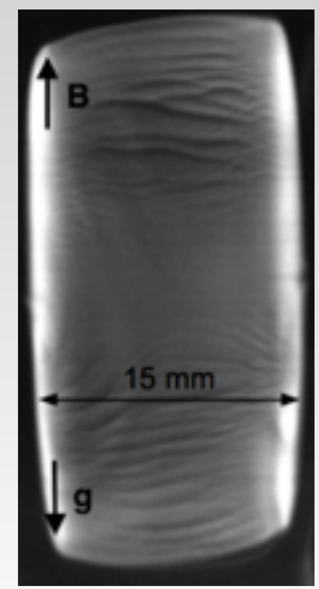
- Magnetic field: 4 Tesla
- Inner diameter: 40 cm (dia.)
- Vacuum chamber: 20 x 20 cm
- Orientation: Rotatable
- Particles: 1 - 5 μm

Kiel University

- Magnetic field: 4 Tesla
- Inner diameter: 30 cm (dia.)
- Vacuum chamber: 10 cm x 100 cm
- Orientation: Rotatable
- Particles: 0.1 - 0.5 μm







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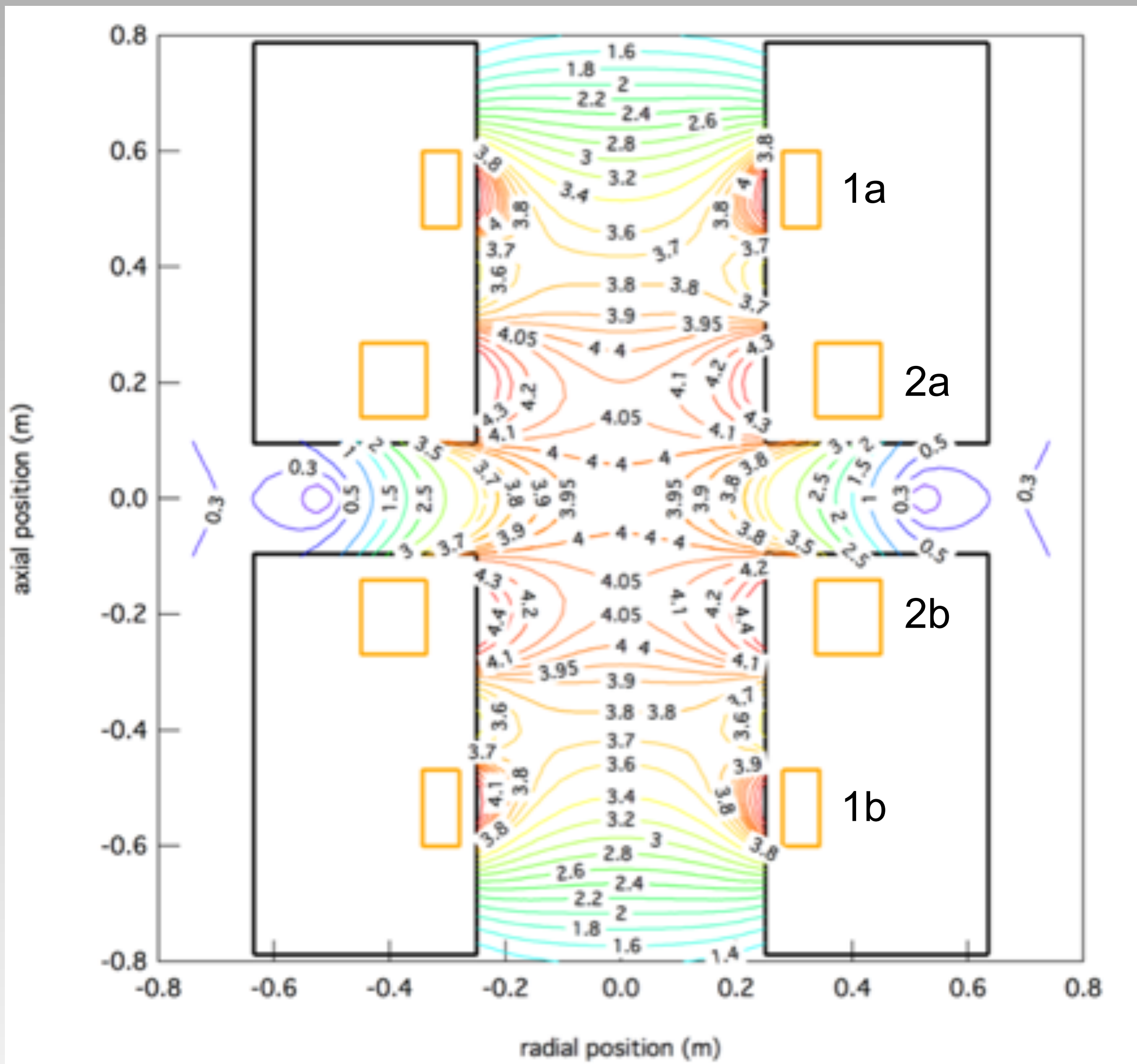
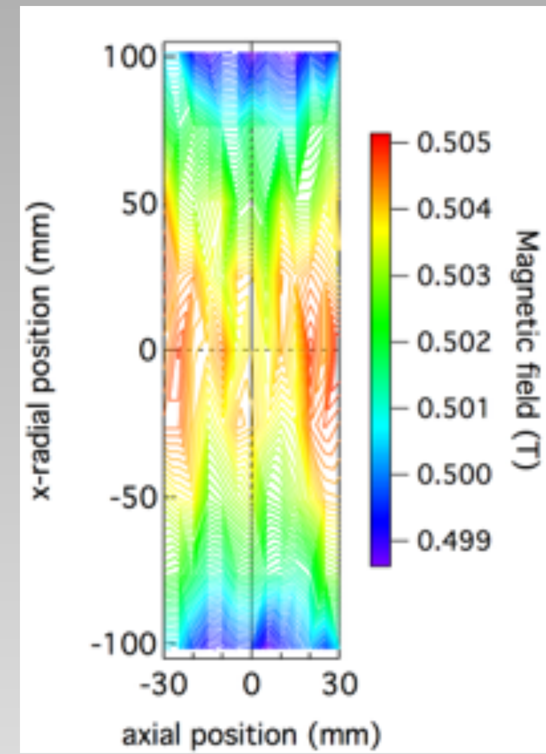
MDPX superconducting magnet system met or exceeded the design criteria





Magnetic field uniformity
(central region of MDPX)

$$\varepsilon = \frac{(B_{max} - B_{min})}{\frac{1}{2}(B_{max} + B_{min})}$$

$\varepsilon_{radial} = 0.95\%$

$\varepsilon_{axial} = 0.25\%$ to 0.45%

$\varepsilon_{design} < 1\%$

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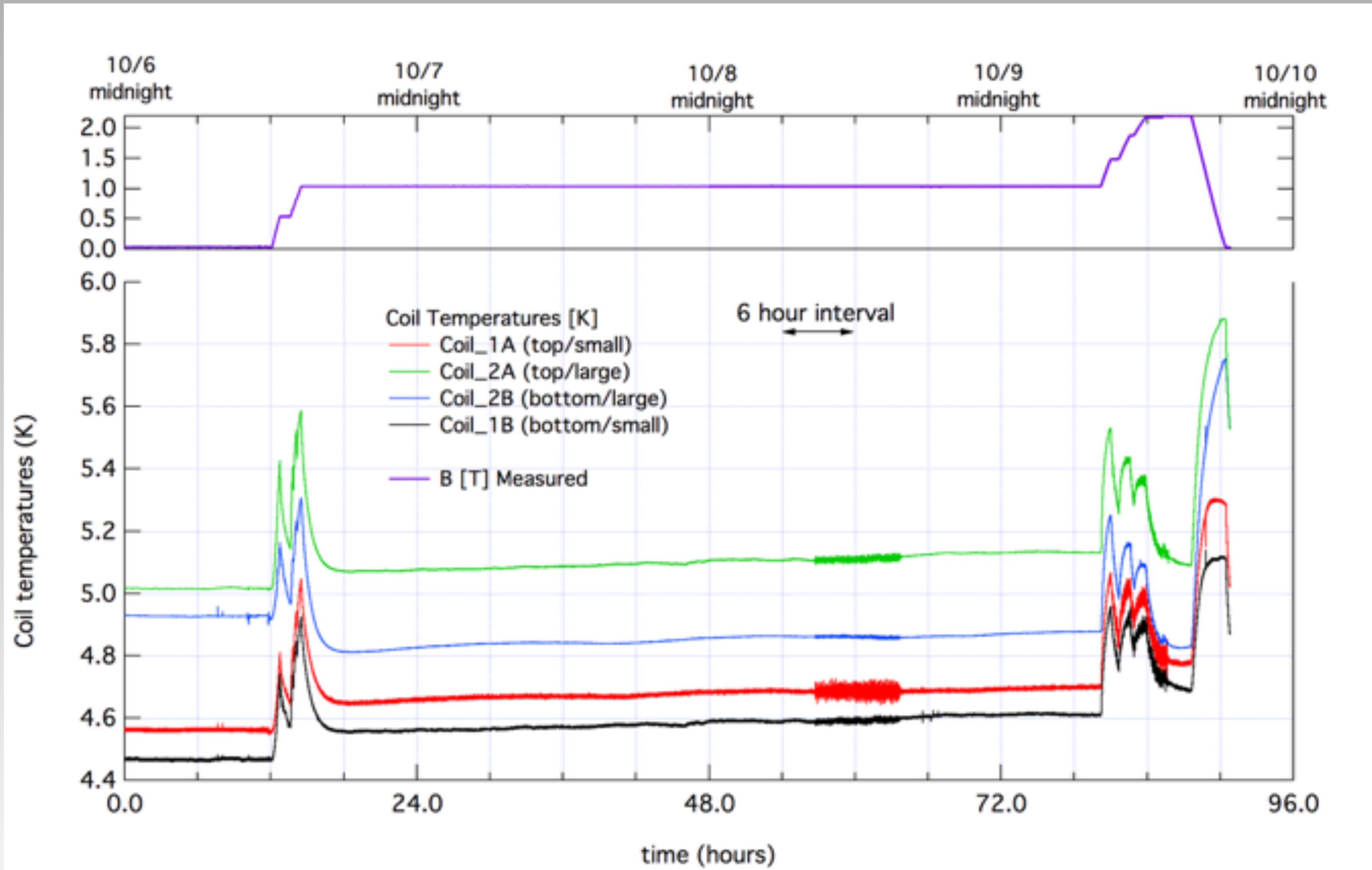
Cryogen-free magnet system can operate for extended periods at high magnetic field



Magnet requires careful management of coil temperatures during magnet charging and discharging

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Expanding dusty plasma studies at Auburn

- Research on: microgravity and magnetized dusty plasmas

Installation Photographs

Expanding dusty plasma studies at Auburn

- Research on: microgravity and magnetized dusty plasmas

Expanding dusty plasma studies at Auburn

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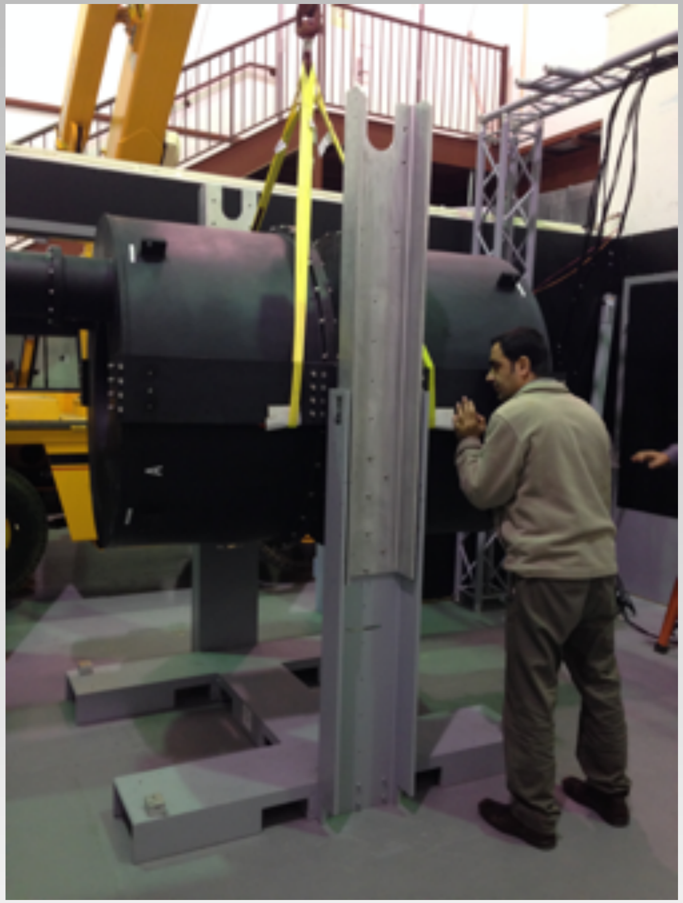

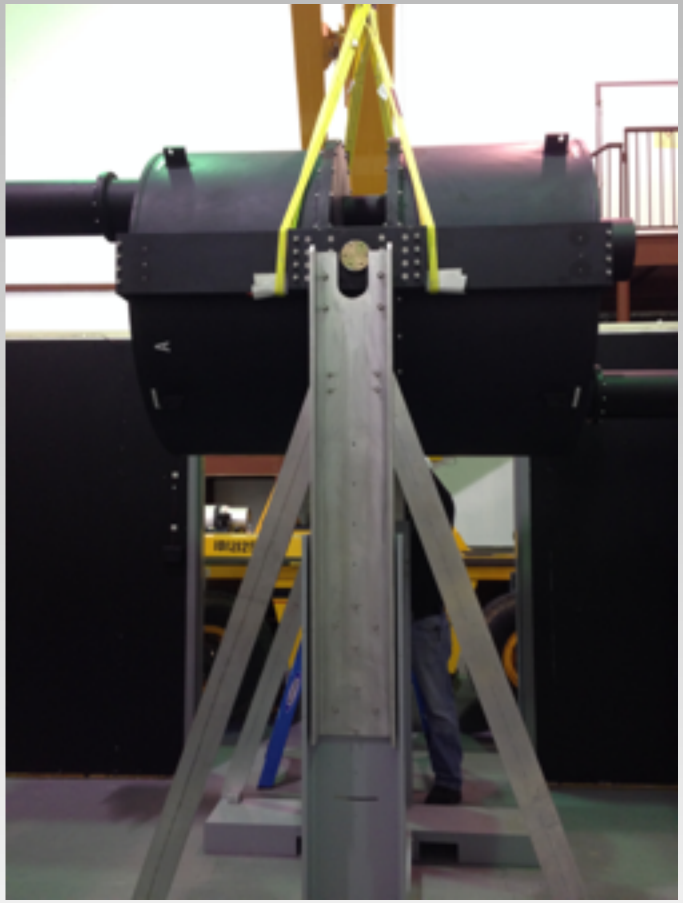

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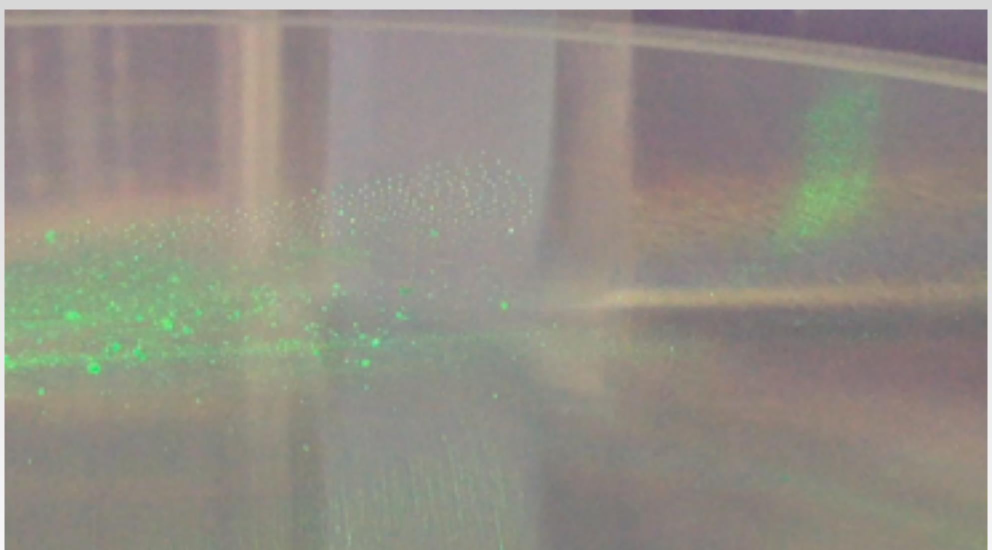
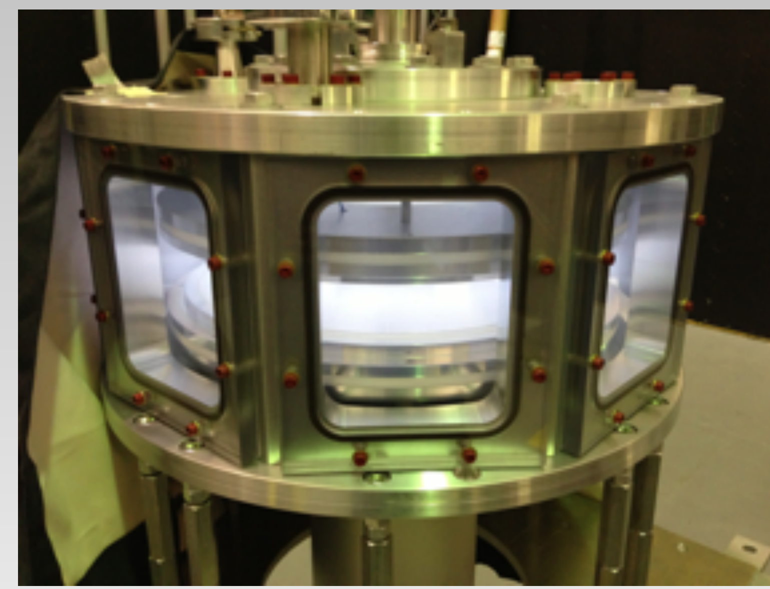
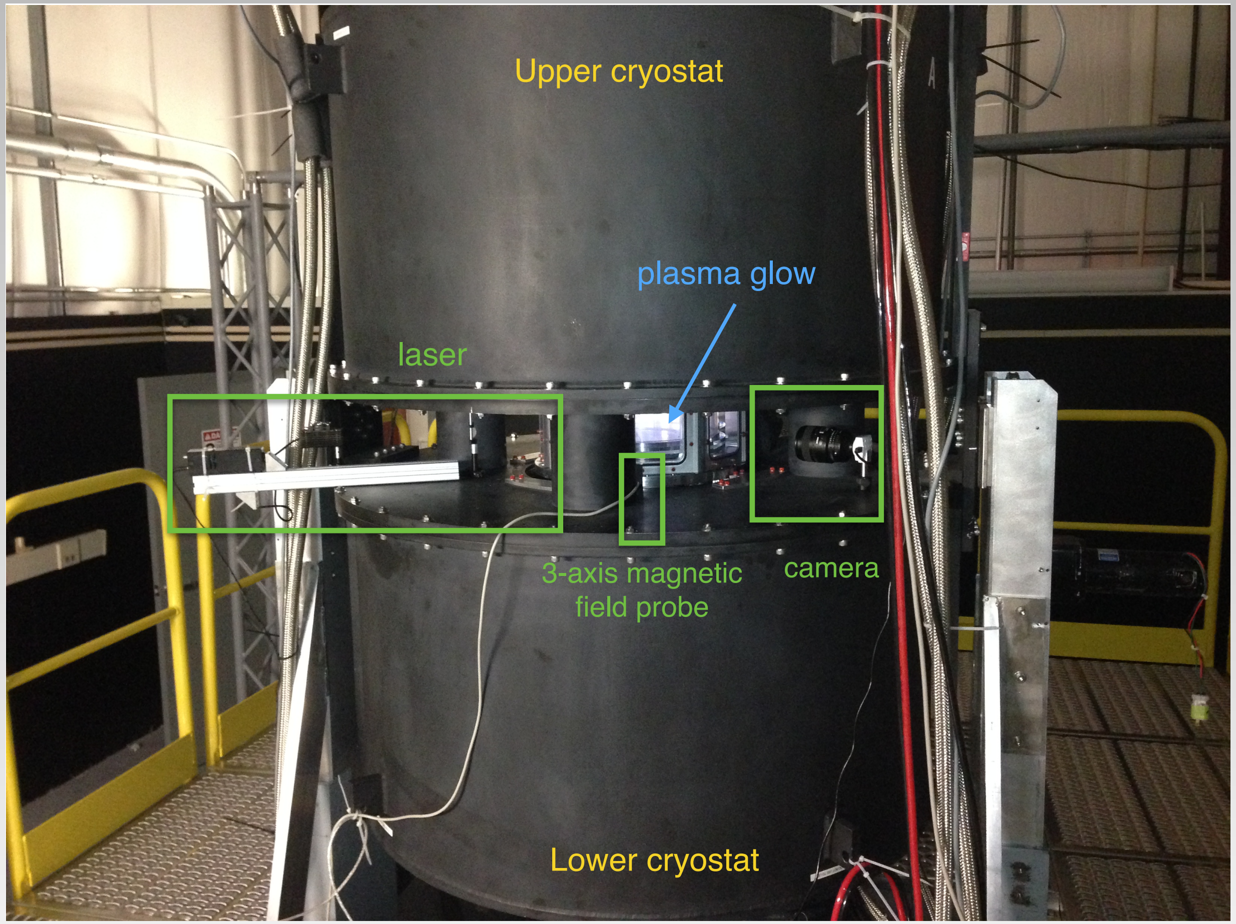


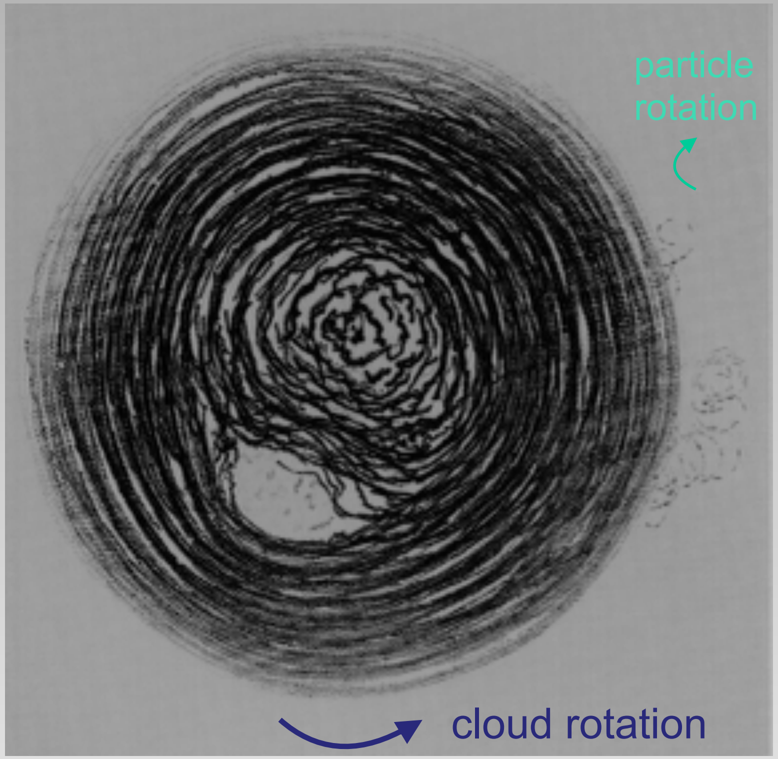


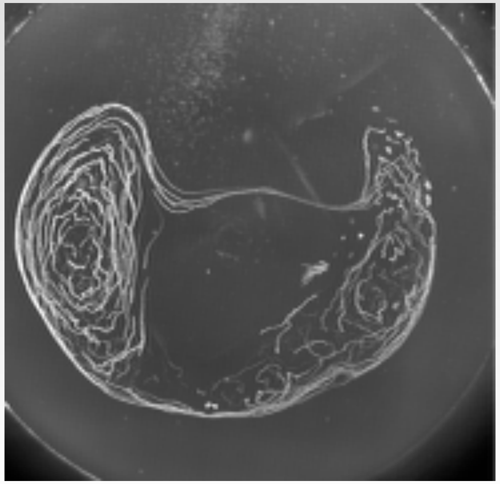
[MDPX Team]

Expanding dusty plasma studies at Auburn

- Research on: microgravity and magnetized dusty plasmas







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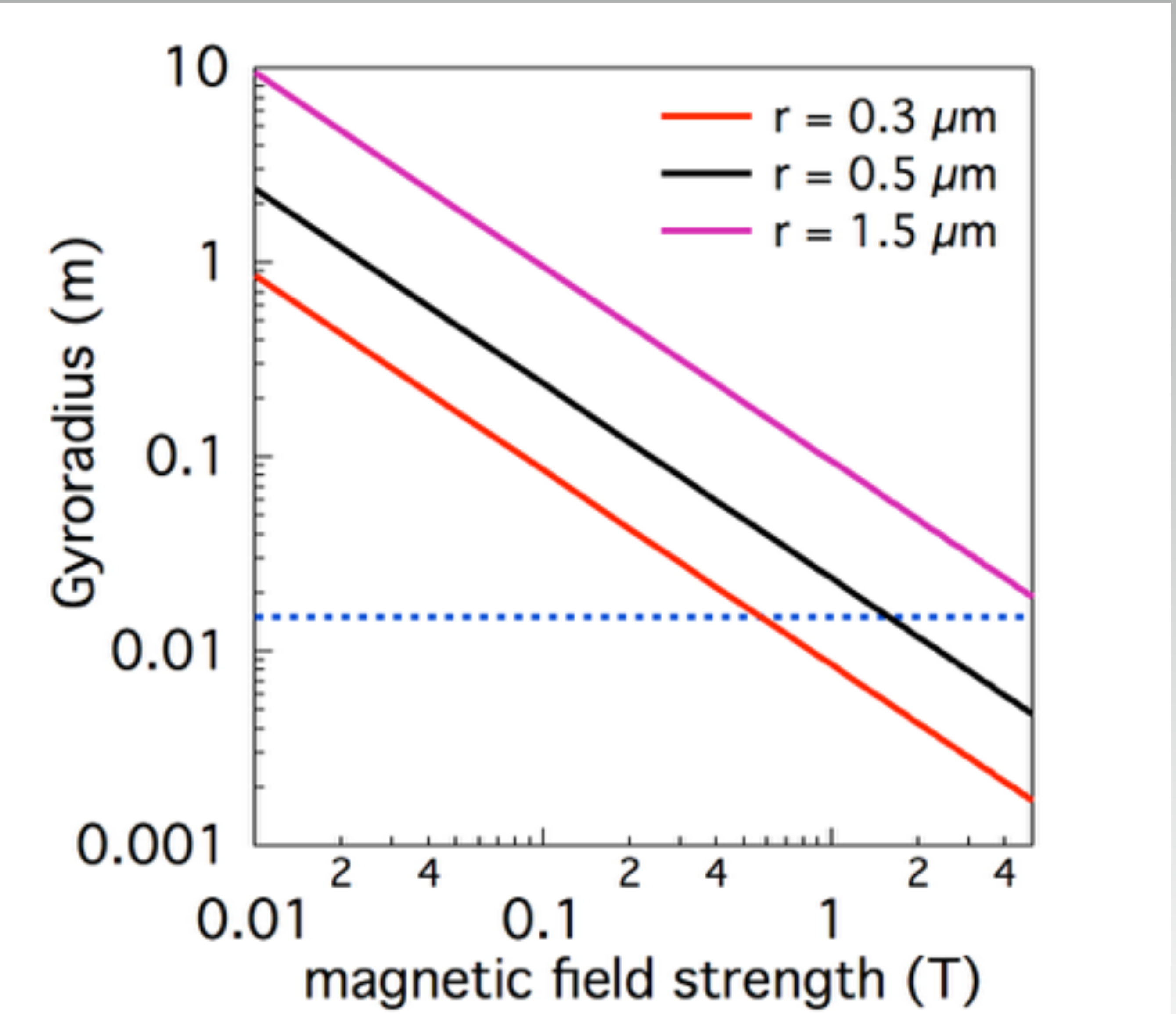
Magnetizing a dusty plasma

Gryo-orbit size vs. B

Assumptions:

- Uniform size melamine particles
- Charge from OML
- Velocity, v ~ 10 mm/s
- Critical radius, r = L/10 ~1.5 cm



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Dust grid structure becomes degraded with higher neutral pressure

Dust motion:
0.5 micron particles
B = 1.5 T

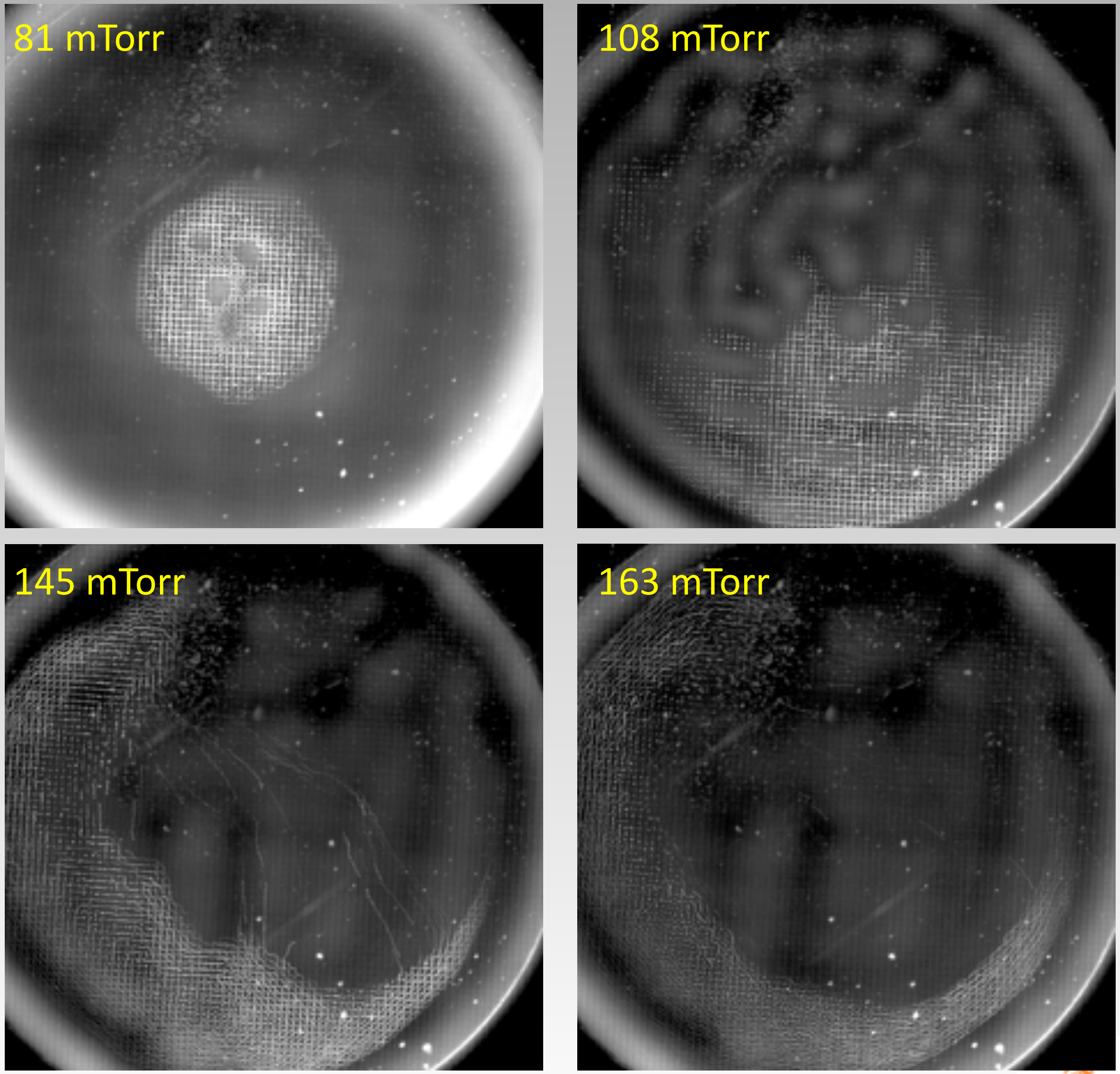
Particle behavior at:
p = 81, 108, 145, and 163 mTorr

Sum over 100 frames and image contrast enhanced

The ordering of the dust into the grid pattern *decreases* with higher pressure.

Fluid-like motion increases with higher pressure.

Note differences in plasma glow and filamentation with pressure.
(lower p, more filaments)



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