Magnetized Dusty Plasma Experiment: A user facility for complex plasma research

Edward Thomas, Jr., Uwe Konopka, Auburn University
Robert L. Merlino, University of Iowa
Marlene Rosenberg, University of California – San Diego

Thanks: To many students and the world-wide dusty plasma community

This work is supported by:
Dept. of Energy, National Science Foundation and Auburn University

Presentation to:
Michigan Institute for Plasma Science and Engineering (MIPSE)
September 25, 2013

Outline

- Introduction to dusty plasmas
- Role of magnetic fields
- Experiments with magnetic fields
  - Early experiments
  - Current experiments
- Magnetized Dusty Plasma Experiment (MDPX)
- Summary

AUPSL

AUBURN UNIVERSITY

Dusty (complex, fine particle, colloidal) plasmas

- Complex plasmas - four component plasma system
  - Ions
  - Electrons
  - Neutral atoms
  - Charged microparticles

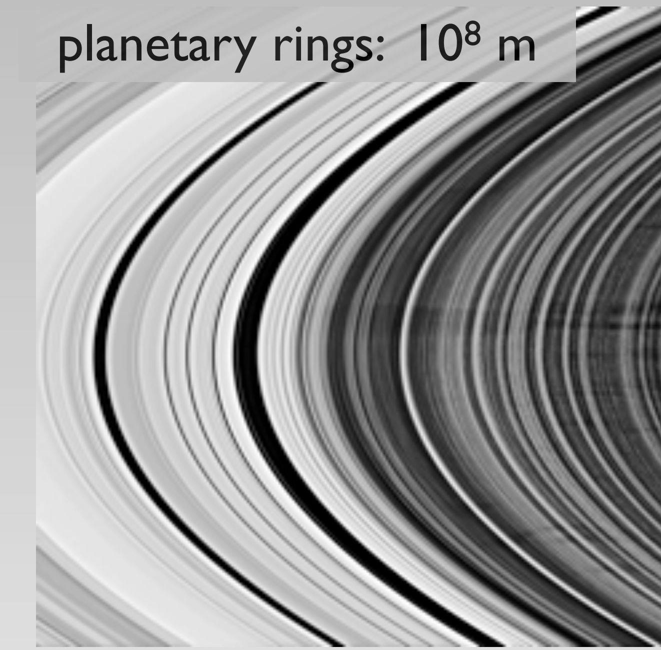
- Plasma and charged microparticles - coupled via collection of ions and electrons from the background plasma.

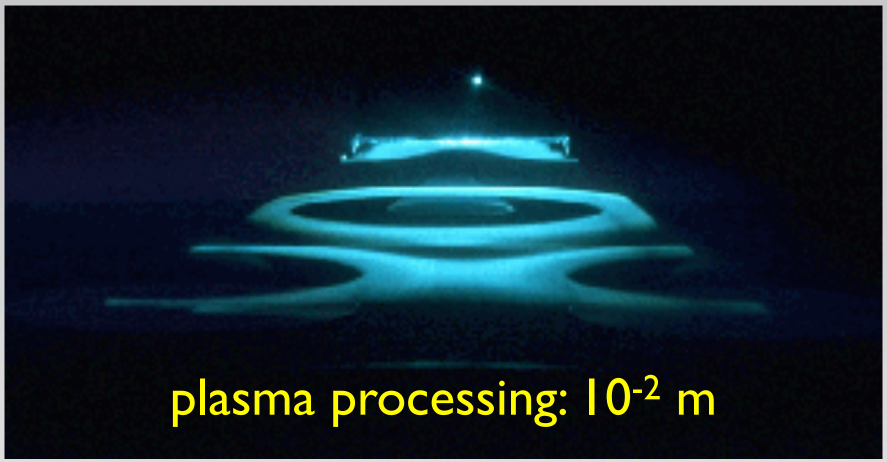
- Presence of microparticles:
  - Modifies density and charge distribution
  - Modifies plasma instabilities
  - Introduces new dust-driven waves

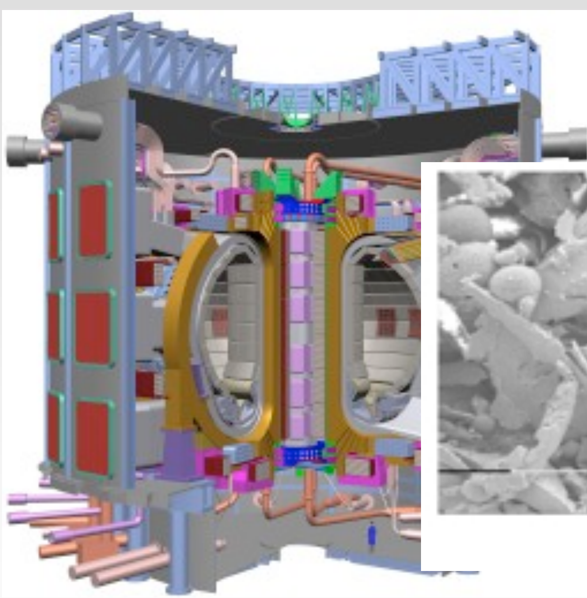
- Measurements of dust particles:
  - Forces
  - Electrostatic potential
  - Velocity distributions

Dusty plasmas cover a wide range of phenomena

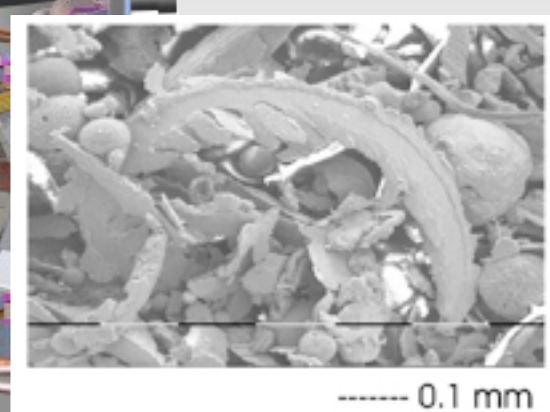
Because dusty plasmas are a topic of <u>UNIVERSAL</u> interest.

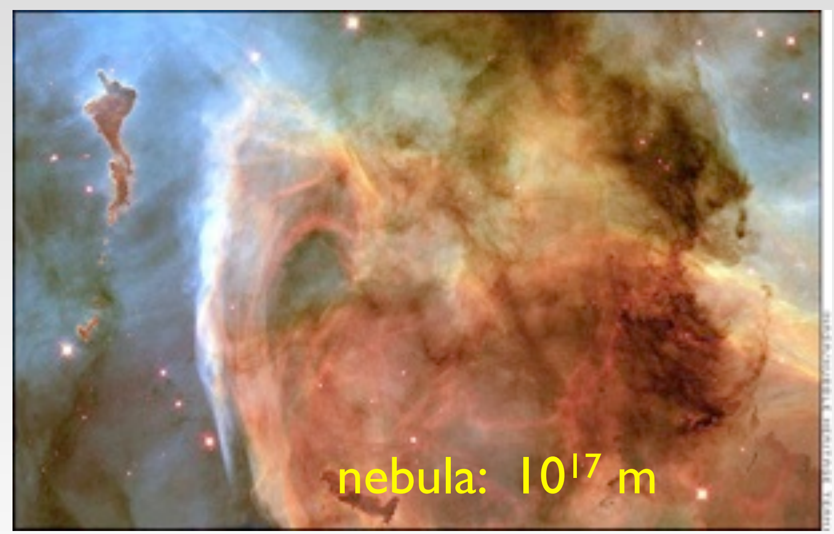






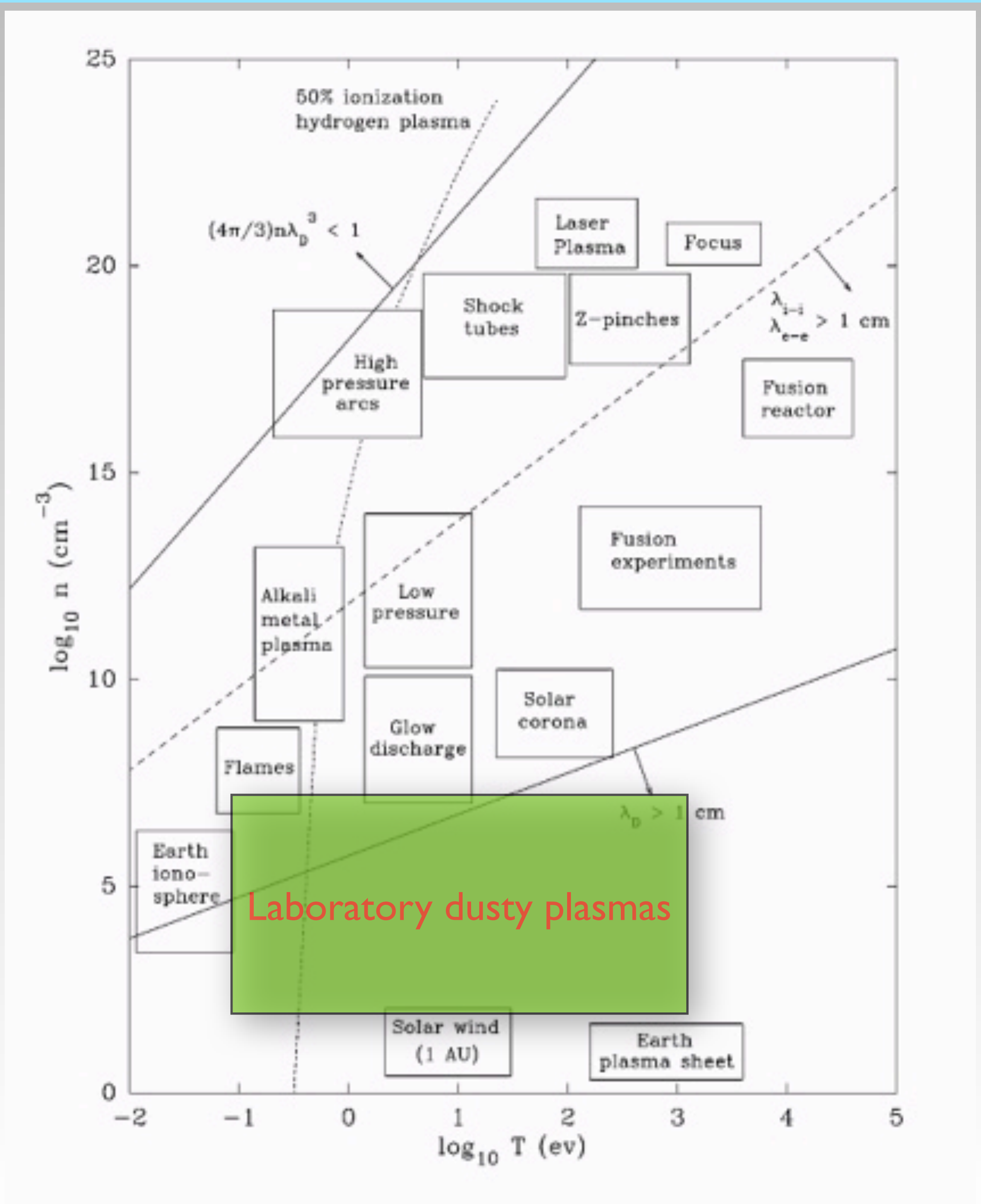
fusion: 10^1 m





Plasmas exist over a wide parameter space

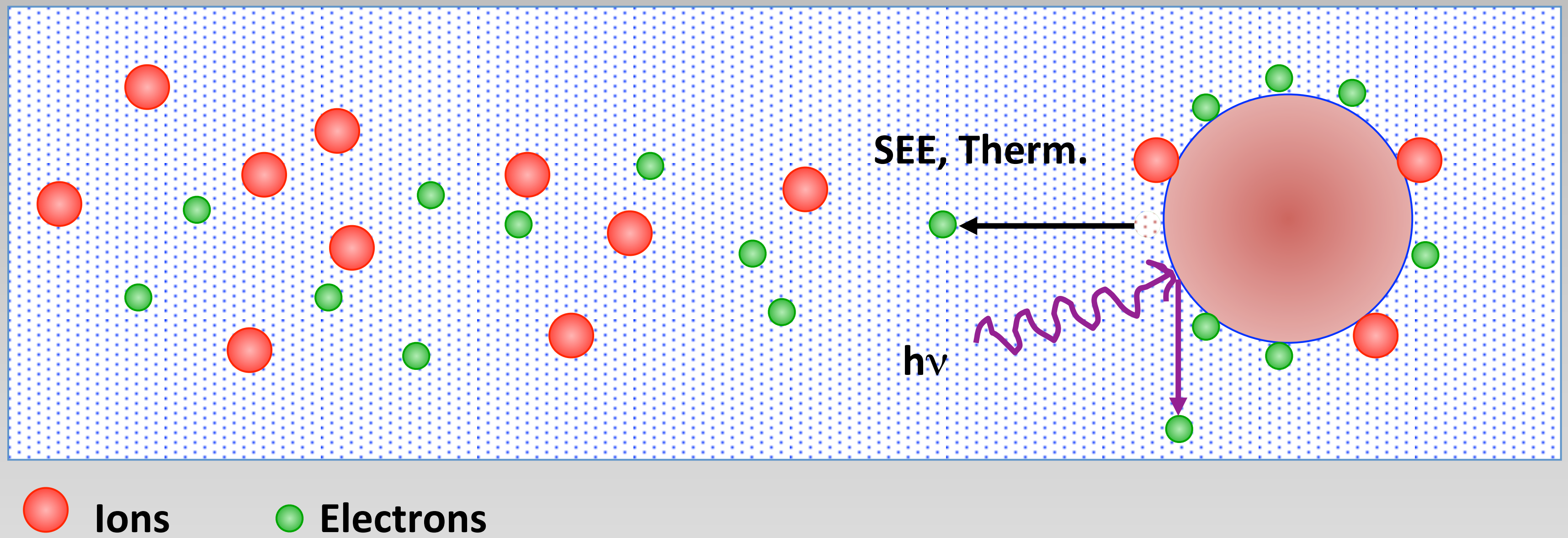
What are the parameters of a dusty plasma?



AUPSL

AUBURN UNIVERSITY

Key physics: Charging - Q_d is a new dynamic variable



- A dynamic equilibrium is established as the grain electrically floats in the plasma: $I_{total} = I_{electron} + I_{ion} + I_{see} + I_{thermionic} + I_{h\nu} = f(n_j, T_j, \varphi; \underline{r}, t)$
- Implication: $dQ_d/dt \neq$ constant
- Grain charge ($Q_d = Z_d e$) is a new dynamic variable
- In the laboratory, Q_d is negative. In space, Q_d can be positive or negative

AUPSL

AUBURN UNIVERSITY

Key physics: Mass - large m_d extends plasma timescale

- Fundamental time scale for plasma oscillations - plasma frequency

$$\omega^2 = \sum \omega_{ps}^2 = \omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2$$

$$where:\ \omega_{ps}^2 = \frac{q_s^2 n_{0s}}{\epsilon_0 m_s}$$

Parameters:

s – ion, elec, dust (i, e, d)
a – dust radius
q_s – charge; $q_d = -Z_d e$
n_s – density
m_s – mass

- For typical lab plasma parameters: $f_{ps} = \omega_{ps}/2\pi$
  $n_{i0} = n_{e0} \sim 10^{14}\ m^{-3}$, $n_{d0} \sim 10^{10}\ m^{-3}$, argon plasma, $Z_d \sim 4600$, a ~ 1.5 μm

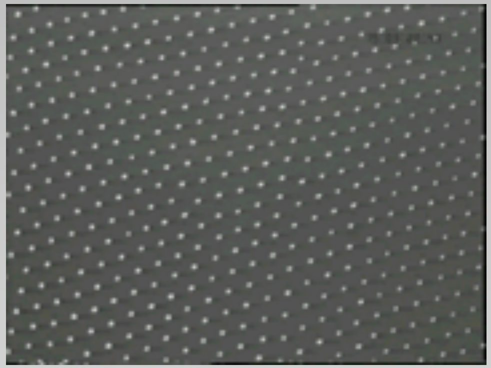
- f_{pe} = 90 MHz, f_{pi} = 330 kHz, f_{pd} = 23 Hz

Key physics: Coupling Parameter - Γ controls self-organization

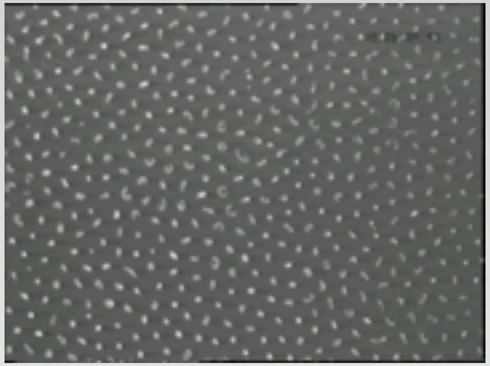
- Γ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction (Yukawa, Debye-Hückel): $$\varphi \sim \frac{\exp\left(-r/\lambda_D\right)}{r}$$

$$\Gamma = \frac{\text{electrostatic potential energy}}{\text{thermal energy}} = \frac{Q_d^2}{4\pi\varepsilon_0 k T_d \Delta}$$

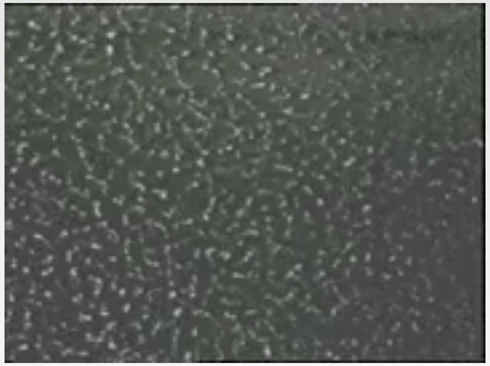
$$\Delta = \text{Wigner-Seitz radius} = \left(\frac{4\pi n_d}{3}\right)^{-1/3}$$



$\Gamma >> 1$



$\Gamma \sim 1$



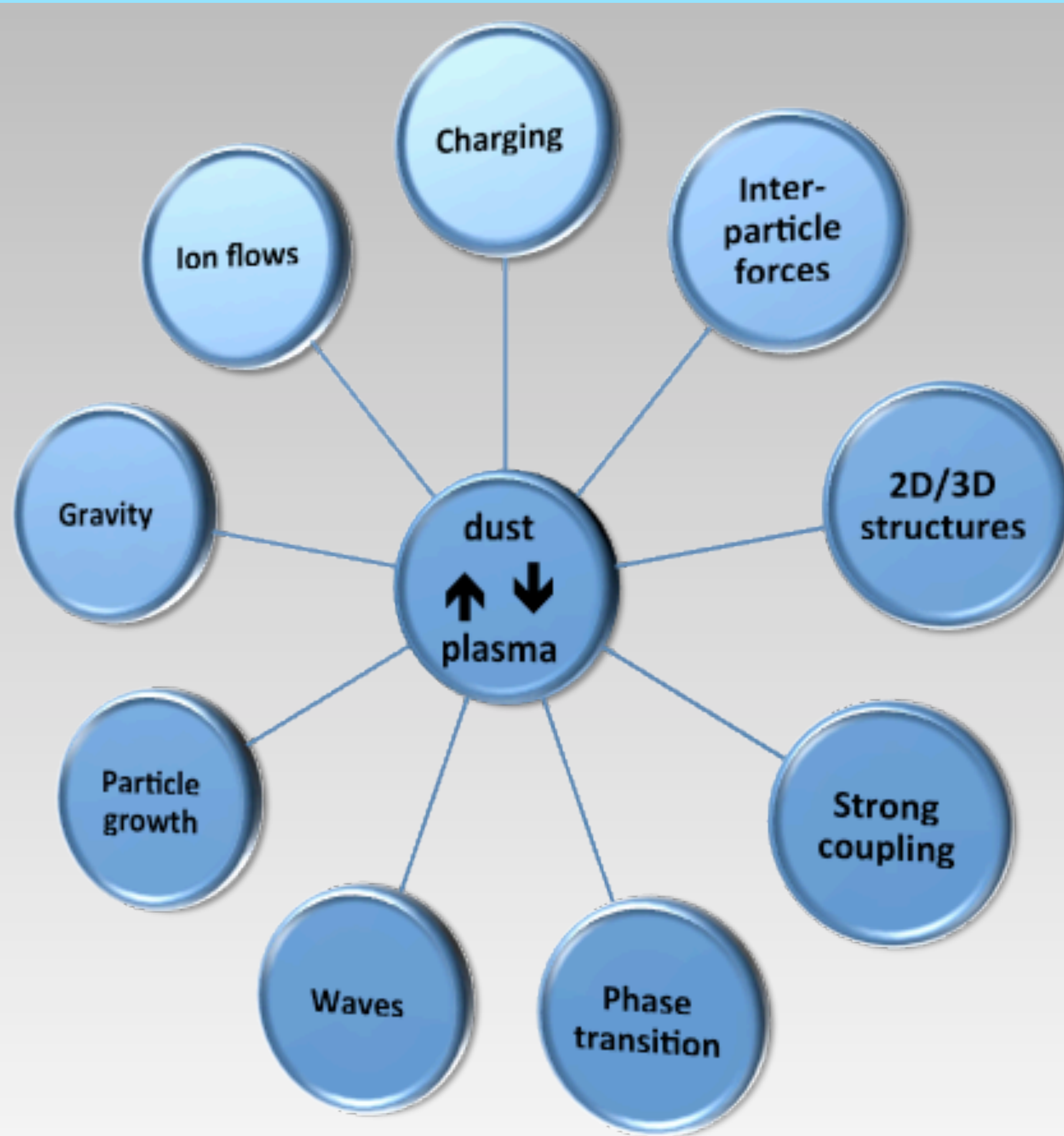
$\Gamma < 1$

Dusty Plasmas and Magnetic Fields

- Plasma and charged microparticles are coupled

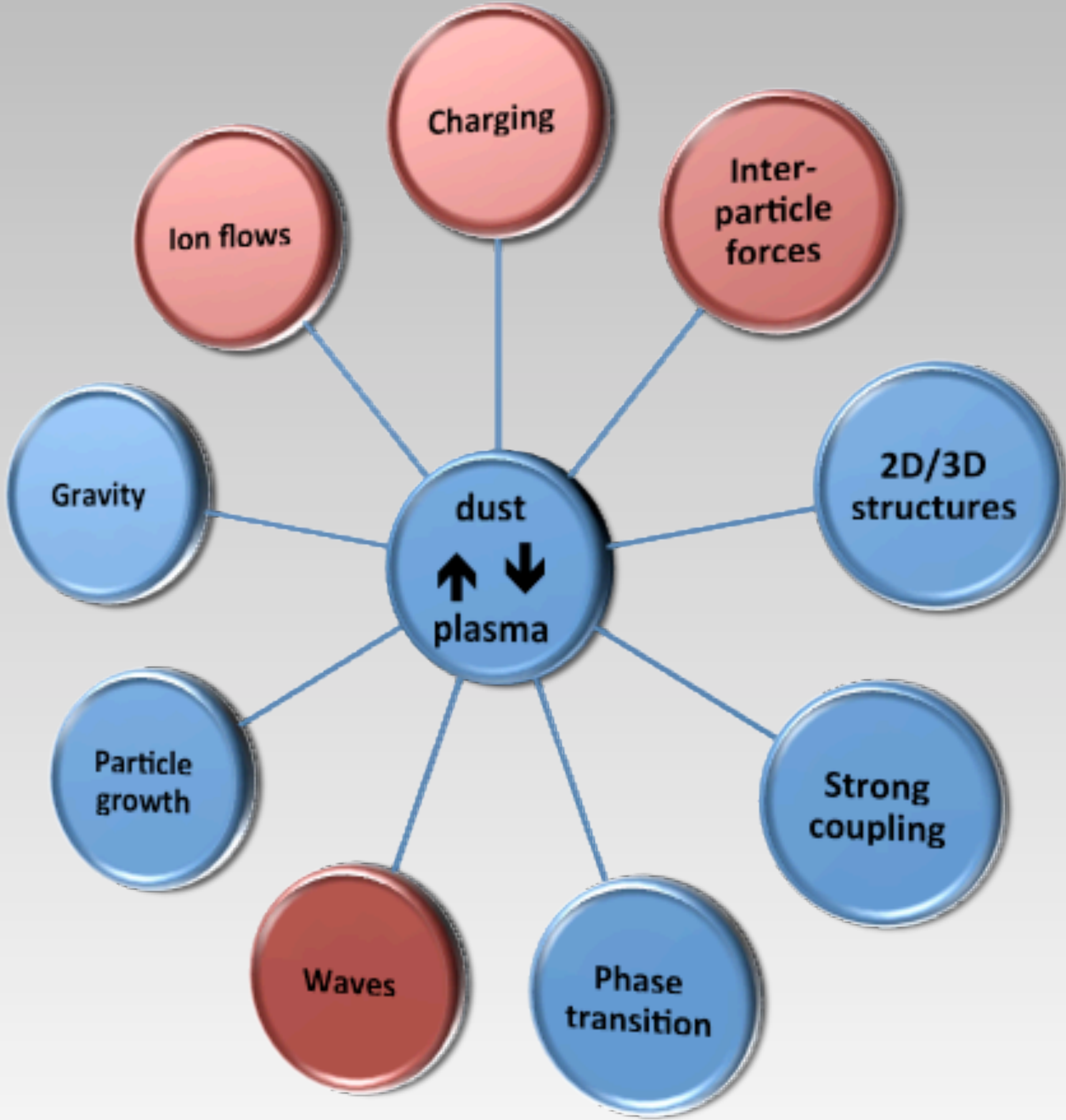
Dusty Plasmas and Magnetic Fields

- Plasma and charged microparticles are coupled
- Coupling gives rise to dynamical processes



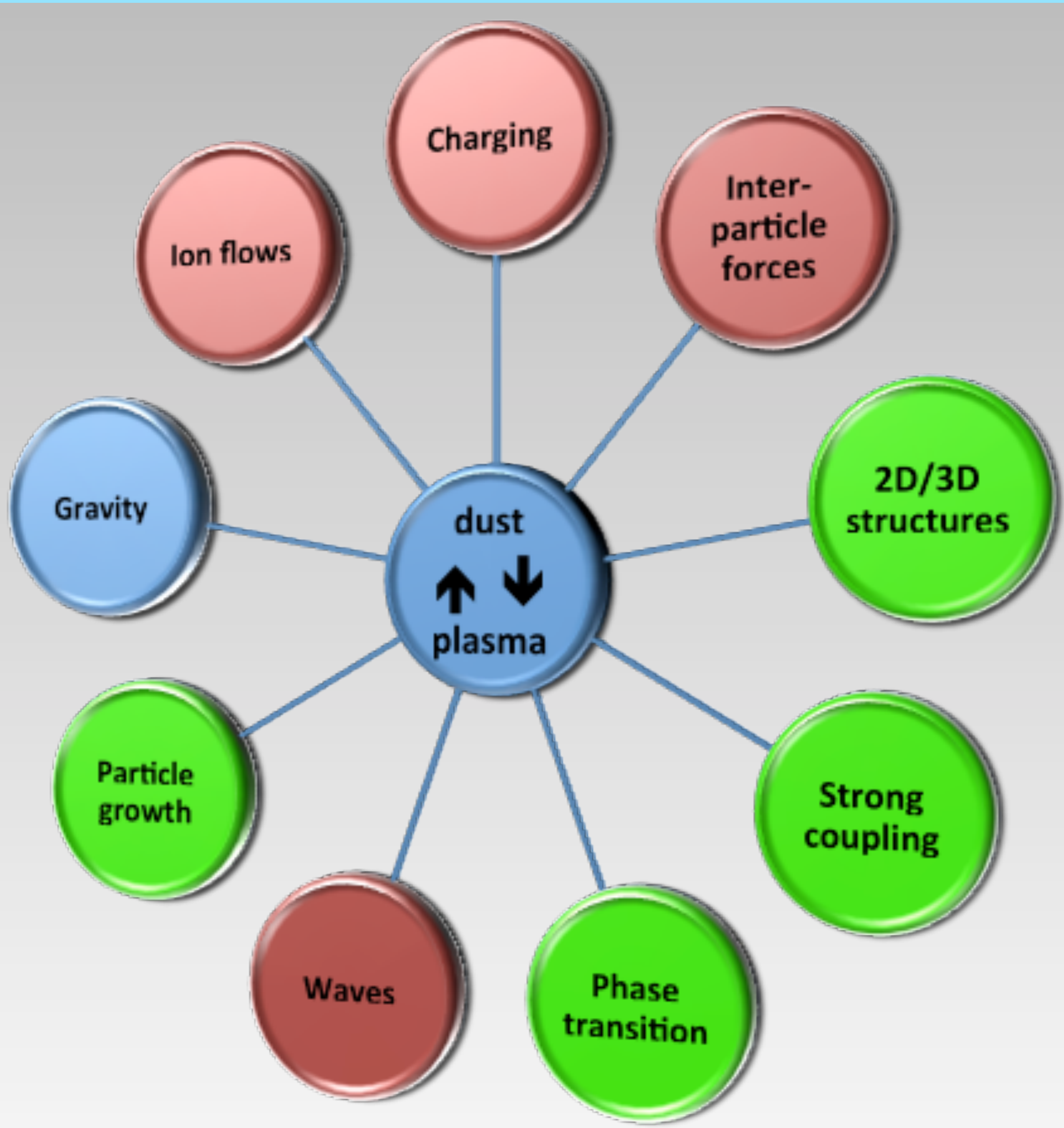
Dusty Plasmas and Magnetic Fields

- Plasma and charged microparticles are coupled
- Coupling gives rise to dynamical processes
- Magnetic field – modifies the coupling



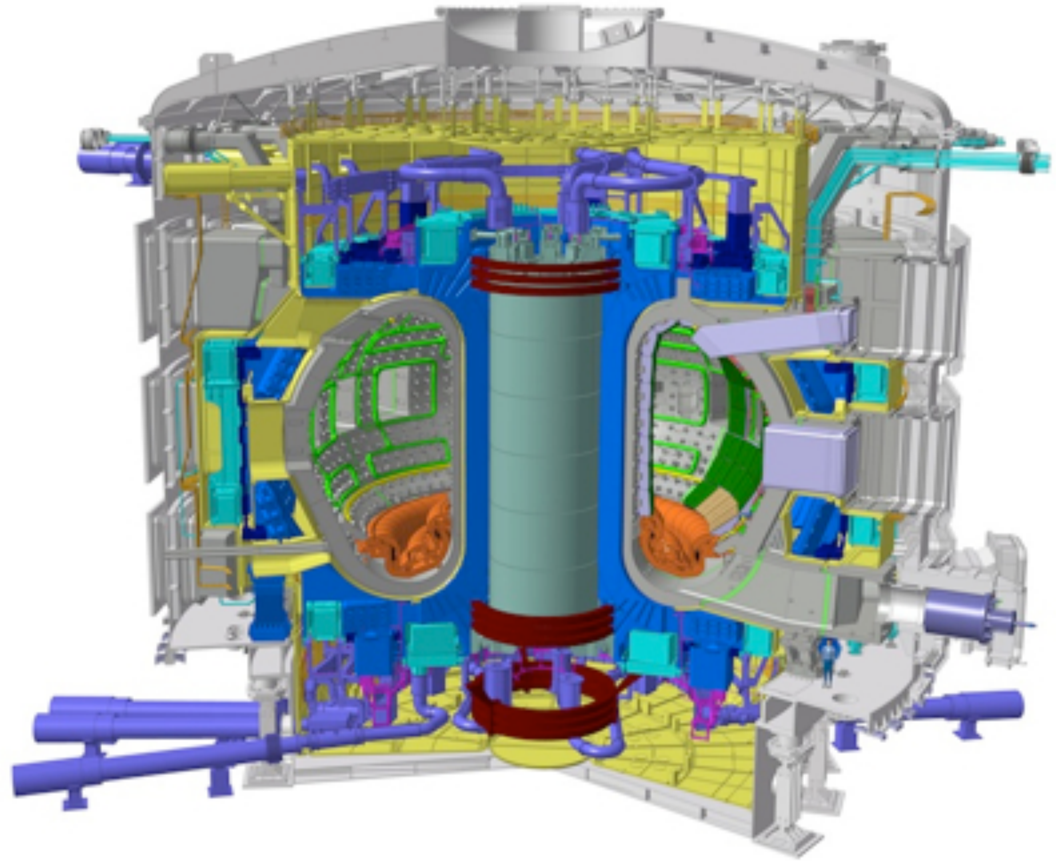
Dusty Plasmas and Magnetic Fields

- Plasma and charged microparticles are coupled
- Coupling gives rise to dynamical processes
- Magnetic field – modifies the coupling
- Magnetic field – modifies the dusty plasma dynamics



Dusty Plasmas and Magnetic Fields

- Magnetized plasma and charged dust may contribute to:
  - Fusion experiments
  - Astrophysical systems



AUPSL

AUBURN UNIVERSITY

Magnetic field effects

STAR FORMATION IN MAGNETIC DUST CLOUDS

L. Mestel and L. Spitzer, Jr

(Received 1956 July 27)*

Summary

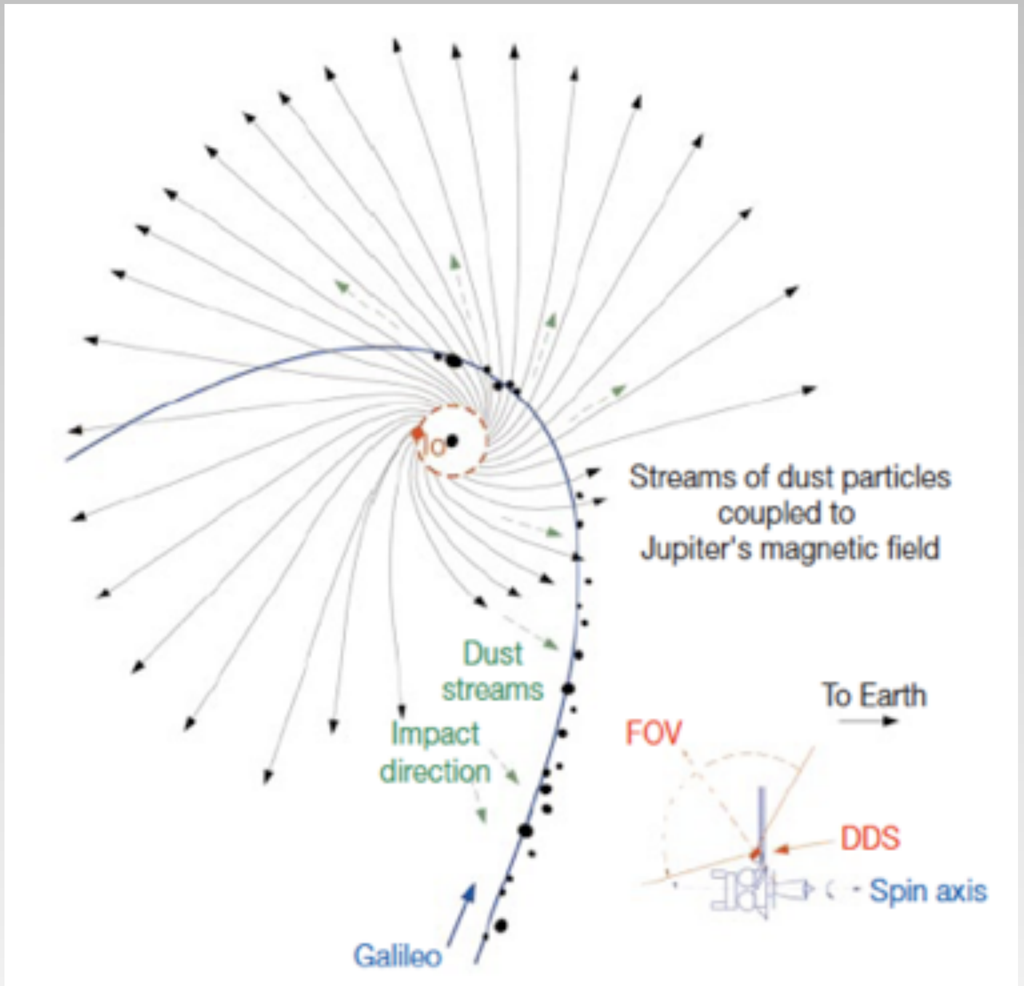
The paper deals with the problem of gravitational condensation in the presence of a magnetic field. It is shown that as long as the field is frozen into the contracting cloud the magnetic pressure sets a lower limit to the mass that can remain gravitationally bound: if the field is taken as 10^{-6} gauss in regions of density 10 H atoms/cm^3, this lower limit is $\simeq 5 \times 10^2 \odot$. However, if the bulk of the cloud is obscured from galactic starlight by dust grains, the plasma density within the cloud will decline rapidly, as ions and electrons attach themselves to the grains. When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.

L. Mestel and L. Spitzer, ApJ, **116**, 503 (1956)

Magnetic field effects

- Most often, the role of the magnetic field in incorporated in the dynamics of the charged dust.
- This has been particularly important for interpreting phenomena within the solar system.
- One example are the dust streams emanating from Jupiter due to volcanic activity at Io.

$$m\frac{d\vec{v}}{dt} = q_d\left(\vec{E} + \vec{v} \times \vec{B}\right) + \vec{F}_G + \vec{F}_d + \vec{F}_r$$



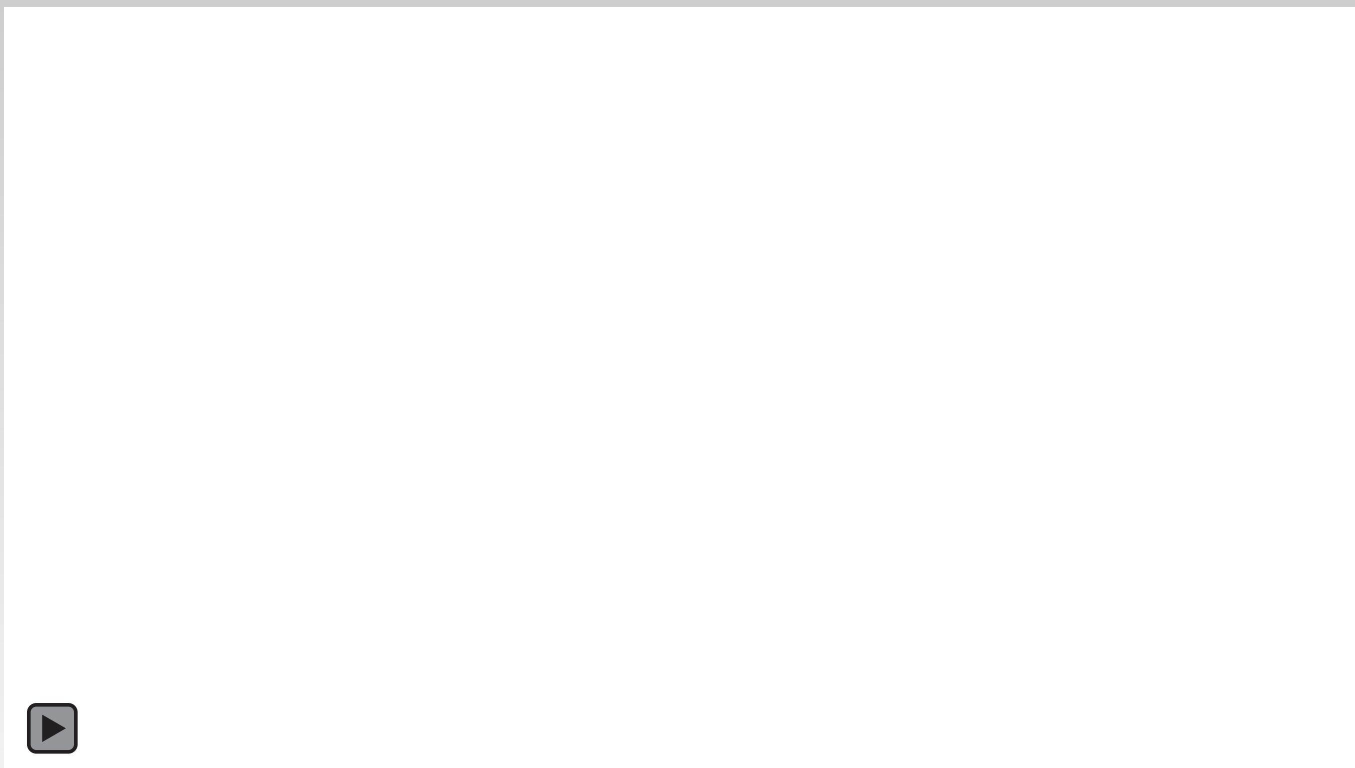
A. Graps, et al., Nature, **405** (2000)

AUPSL

AUBURN UNIVERSITY

Modification of a comet’s tail: an astrophysical example

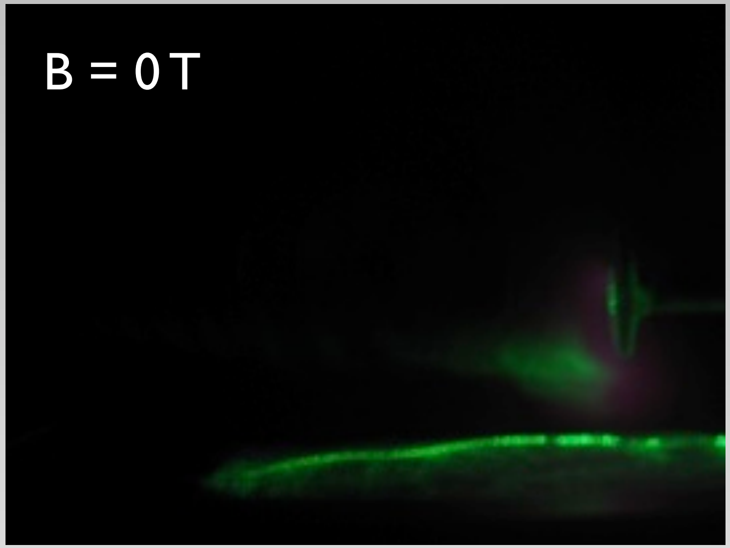
- December, 2011: Comet Lovejoy passes near the Sun
- The dust tail modified by plasma flowing along magnetic field lines

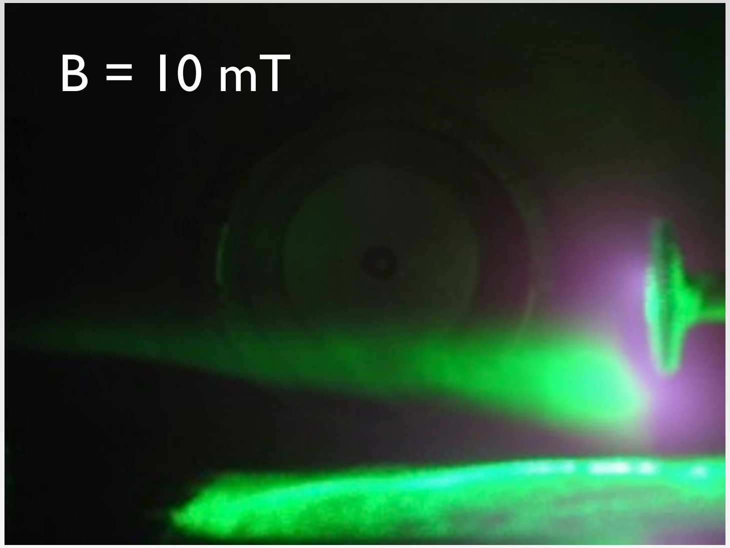


Movie from NASA: http://www.nasa.gov/multimedia/videogallery/index.html?media_id=124915541

Early laboratory studies at low magnetic field

- Low magnetic field - indirect influence on dust particles
- Modification of:
  - Ion flows
  - Inter-particle forces
  - 2D/3D structures
- The majority of these studies used magnetic field strengths, $B \leq 100$ mT (1 kG)





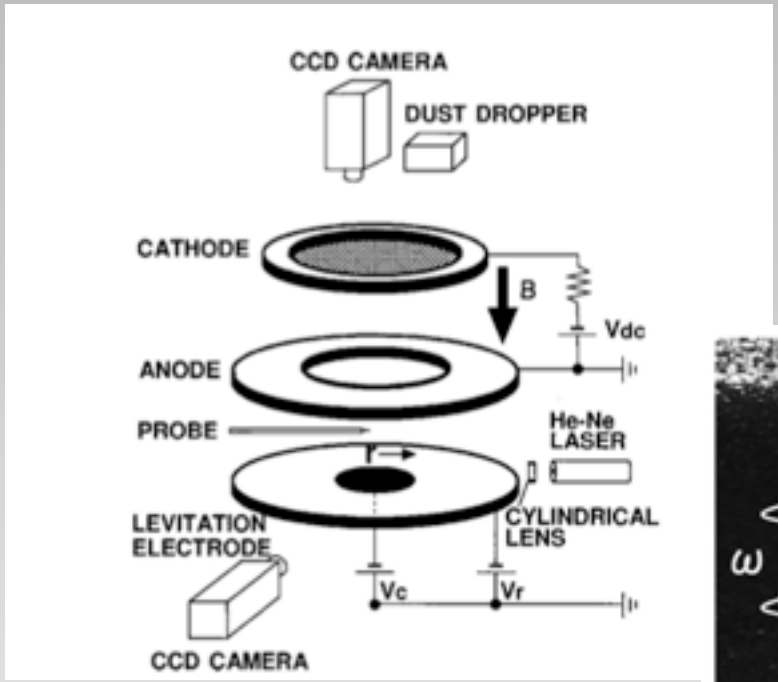
Enhancing microparticle confinement by extending the anode spot region.
(R. Merlino, Univ. of Iowa)

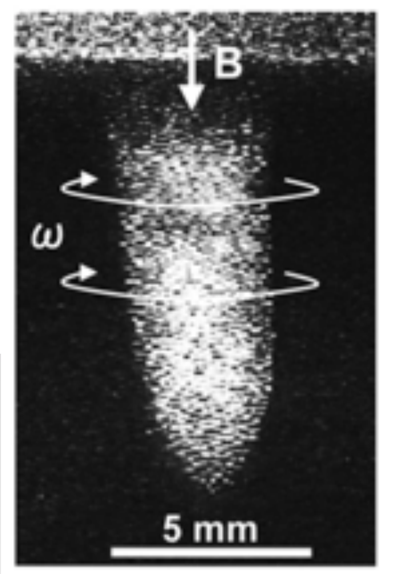
AUPSL

AUBURN UNIVERSITY

Early laboratory studies at low magnetic field

- Low magnetic field - indirect influence on dust particles
- Modification of:
  - Ion flows
  - Inter-particle forces
  - 2D/3D structures
- The majority of these studies used magnetic field strengths, B $\leq$ 100 mT (1 kG)





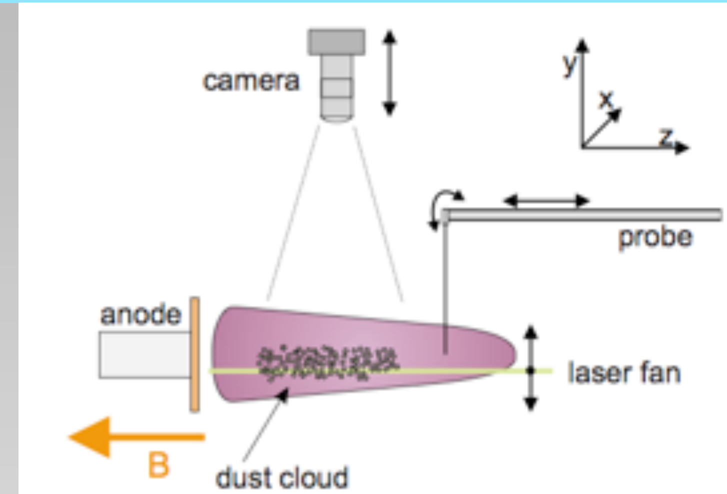
Rotation of a microparticle cloud due to E x B drift.
(N. Sato, et al., Phys. Plasmas, 2001)

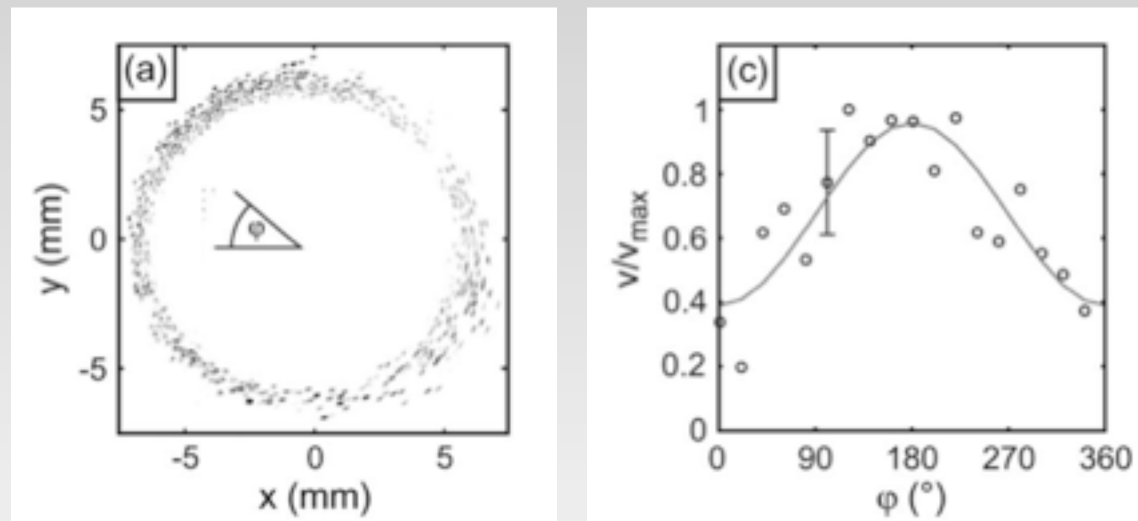
AUPSL

AUBURN UNIVERSITY

Early laboratory studies at low magnetic field

- Low magnetic field - indirect influence on dust particles
- Modification of:
  - Ion flows
  - Inter-particle forces
  - 2D/3D structures
- The majority of these studies used magnetic field strengths, B ≤ 100 mT (1 kG)





Toroidal rotation of a dusty plasma cloud – Kiel Univ.

(I. Pilch, et al., Phys. Plasmas, 2008; T. Reichstein, et al., IEEE TPS, 2010)

AUPSL

AUBURN UNIVERSITY

Magnetizing a dusty plasma

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

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

- That is: $q_d/m_d << e/m_{ion} << e/m_{elec}$

- Key parameters:
  - gyroradius to exp. size: $\frac{\rho}{L} \sim \frac{a^2 v_d}{BL} << 1$
  - gyrofreq. to collision freq.: $\frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1$
  - 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

AUPSL

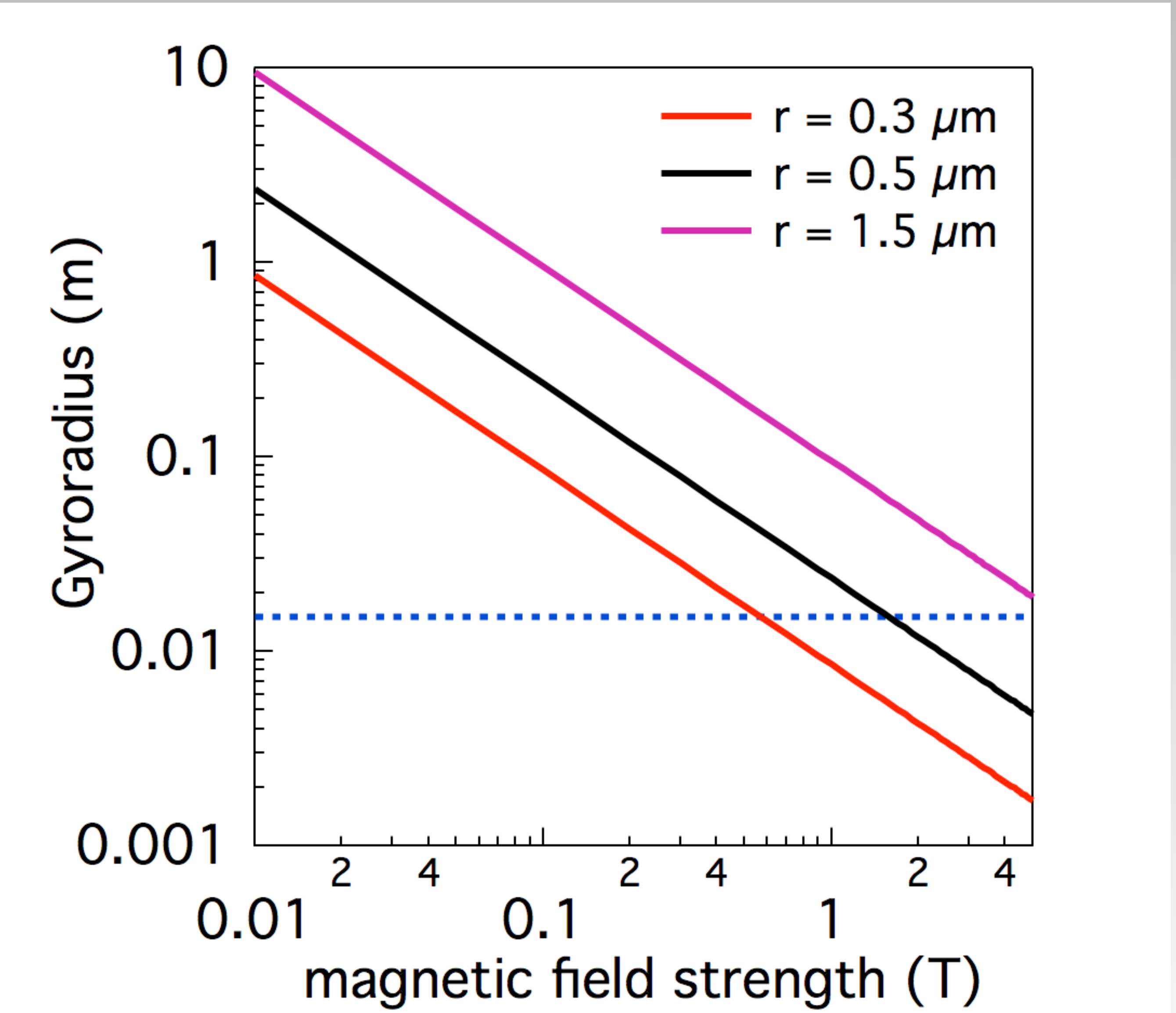
AUBURN UNIVERSITY

Magnetizing a dusty plasma

Gryo-orbit size vs. B

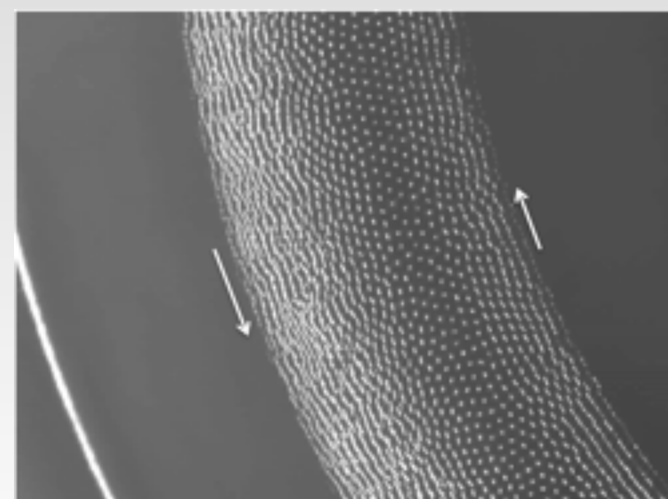
Assumptions:

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



High magnetic field experiments: Max Planck Institute

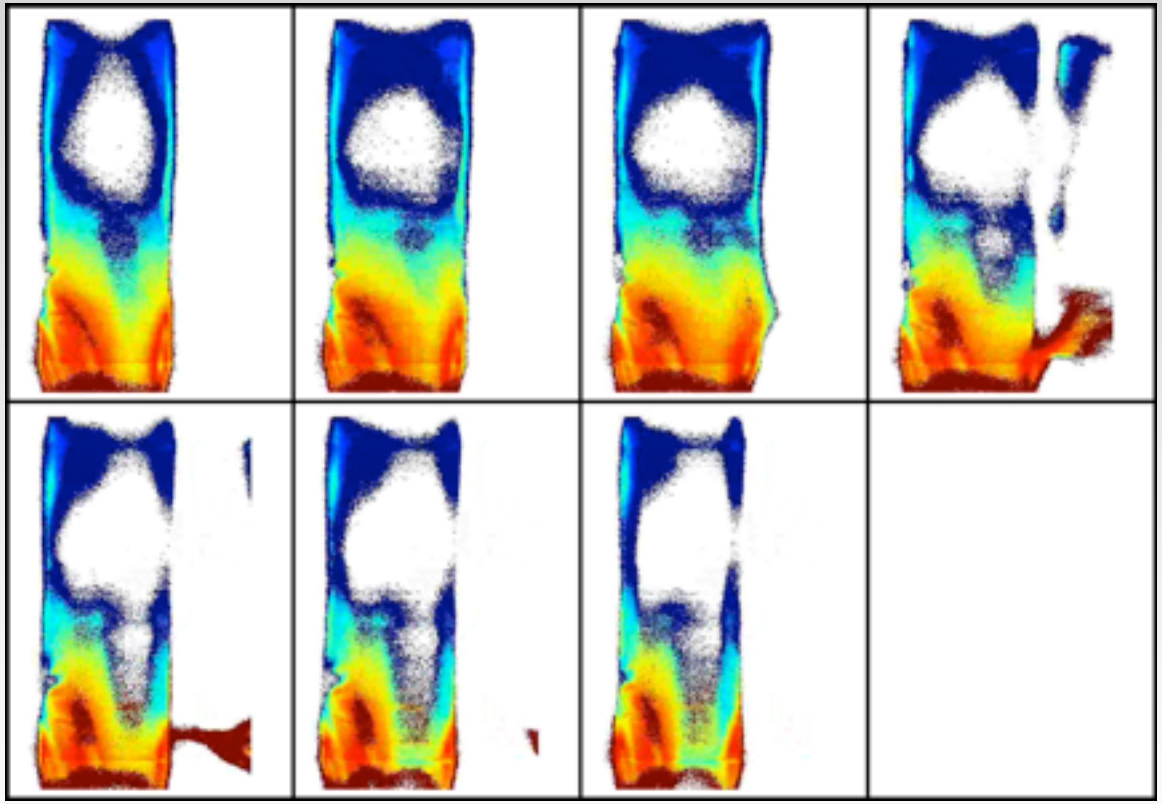
- Magnetic field: 4 Tesla
- Inner diameter: 40 cm (dia.)
- Vacuum chamber: 20 x 20 cm
- Orientation: Rotatable
- Particles: 1 - 5 μm

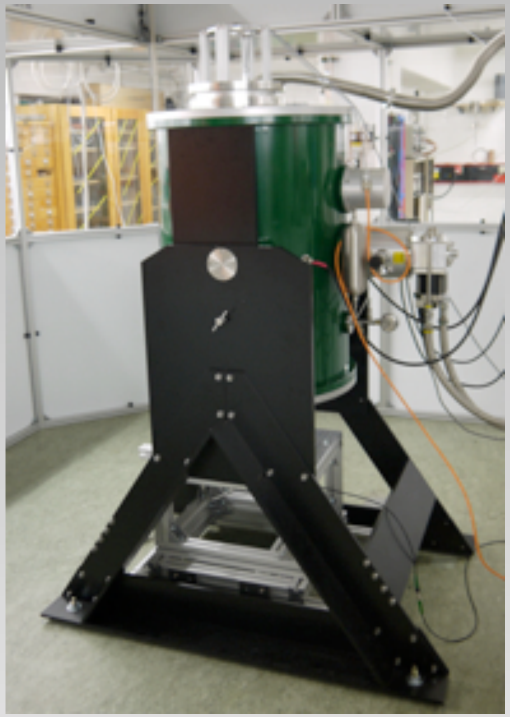


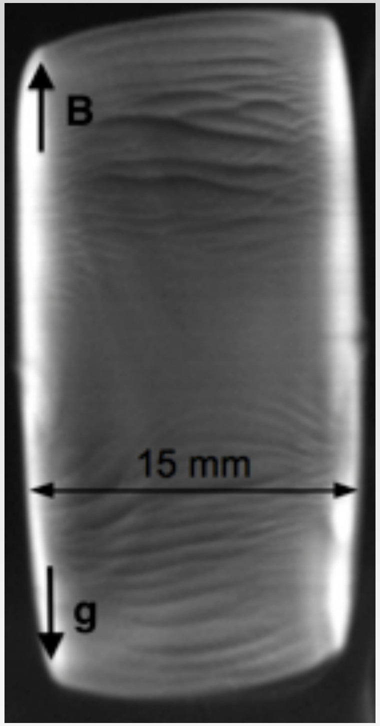
Images courtesy of U. Konopka, P. Bandyopadhyay, MPE

High magnetic field experiments: Kiel University

- Magnetic field: >4 Tesla
- Inner diameter: 30 cm (dia.)
- Vacuum chamber: ~10 cm x 1m
- Orientation: Rotatable
- Particles: 0.1 – 0.2 μm







Images courtesy of F. Greiner, Kiel University

Magnetized Dusty Plasma Experiment (MDPX)

- MDPX project:
  - Develop a fully magnetized dusty plasma
  - Develop flexible, multi-configuration magnetic geometry
  - Operate as a multi-user facility

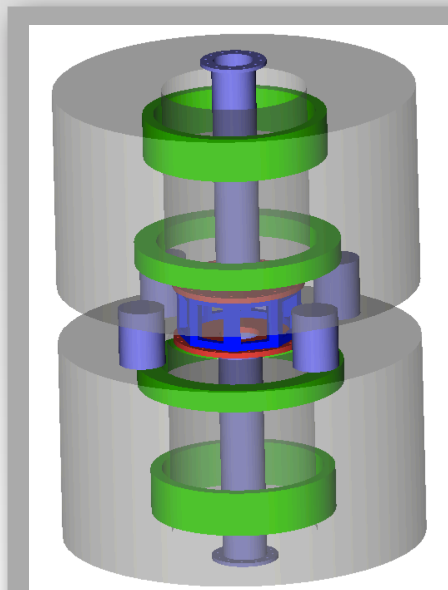
- Two primary scientific questions:
  - As a dusty plasma becomes magnetized - how do the structural, thermal, charging, and collective properties of the system evolve?
  - If a dusty plasma has magnetic particles - how does the system evolve in the presence of uniform and non-uniform magnetic fields?

Dusty plasma experiments with high magnetic fields have been built around the world

Device*	B_{max} (T)	Plasma chamber dimension: Diameter (cm)	Plasma chamber dimension: Axial (cm)	Plasma Source	Dust diameter (μm)	Refs.
JIHT	0.25	3.6	60	DC	5.5	24
DUSTWHEEL (Kiel)	0.5	15	67	RF	-	28
Tohoku	4	10	2	DC, RF	5 - 10	25
MPE	4	20	20	RF	2 – 9	26
Suleiman (Kiel)	> 4	5	100	RF	0.1 - 0.2	29
MDPX	>4	35	200	RF, DC	0.5 – 10	30

*JIHT – Joint Institute for High Temperatures, Moscow, Russia; Kiel – Kiel University, Germany, Tohoku – Tohoku University, Sendei, Japan, MPE – Max Planck Institute for Extraterrestrial Physics, Garching, Germany.

The MDPX experiment based at Auburn University will be the latest experiment in this series.



AUPSL

AUBURN UNIVERSITY

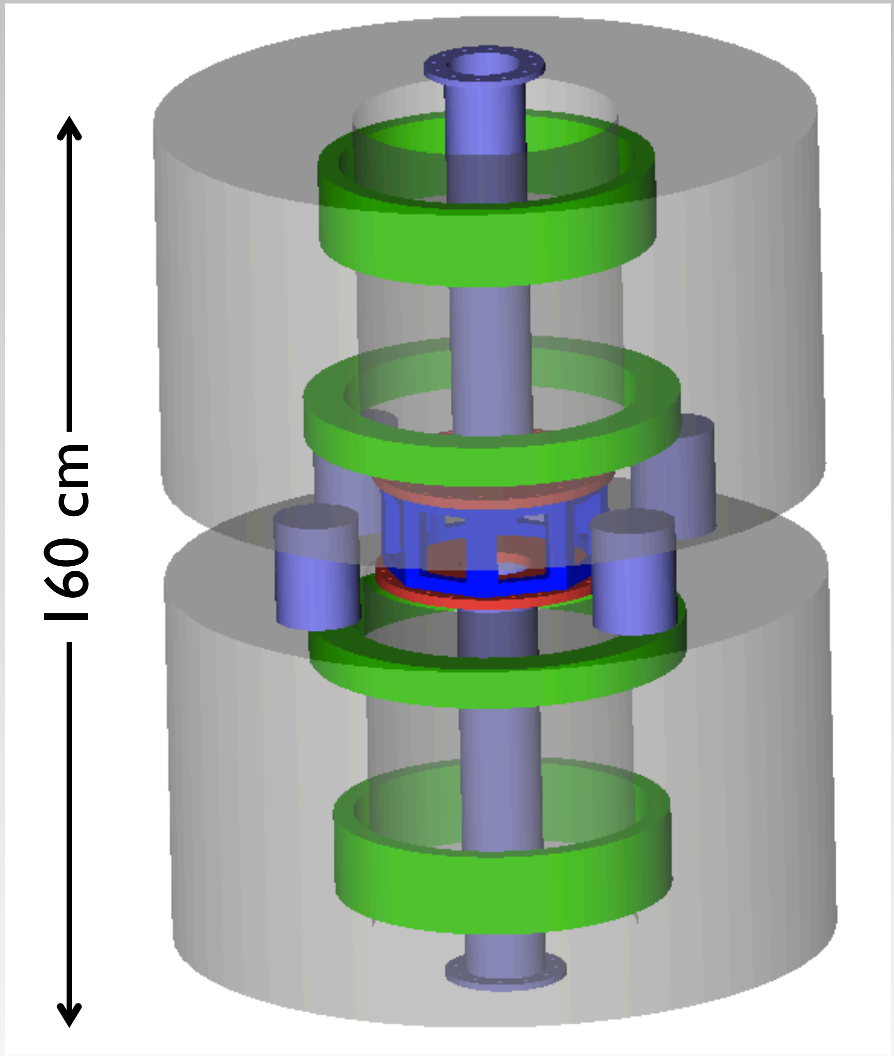
MDPX baseline configuration

Parameters:

Magnetic field:	> 4 T (uniform)
Magnetic field gradient:*	1 - 2 T /m
Magnets:	50 cm ID / 125 cm OD
Magnet material:	NbTi superconductor
Experiment volume:*	45 cm dia. x 175 cm axial
Uniform region:*	20 cm dia. x 20. cm axial
Project cost:	$2.1 million
Project start:	Sept., 2011
Construction time:	2 years

New capabilities:

Magnetic field:	Variable configuration
Plasma chamber:	Large plasma volume
Microparticle imaging:	r > 0.3 μm
Data storage:	Robust database and storage capabilities

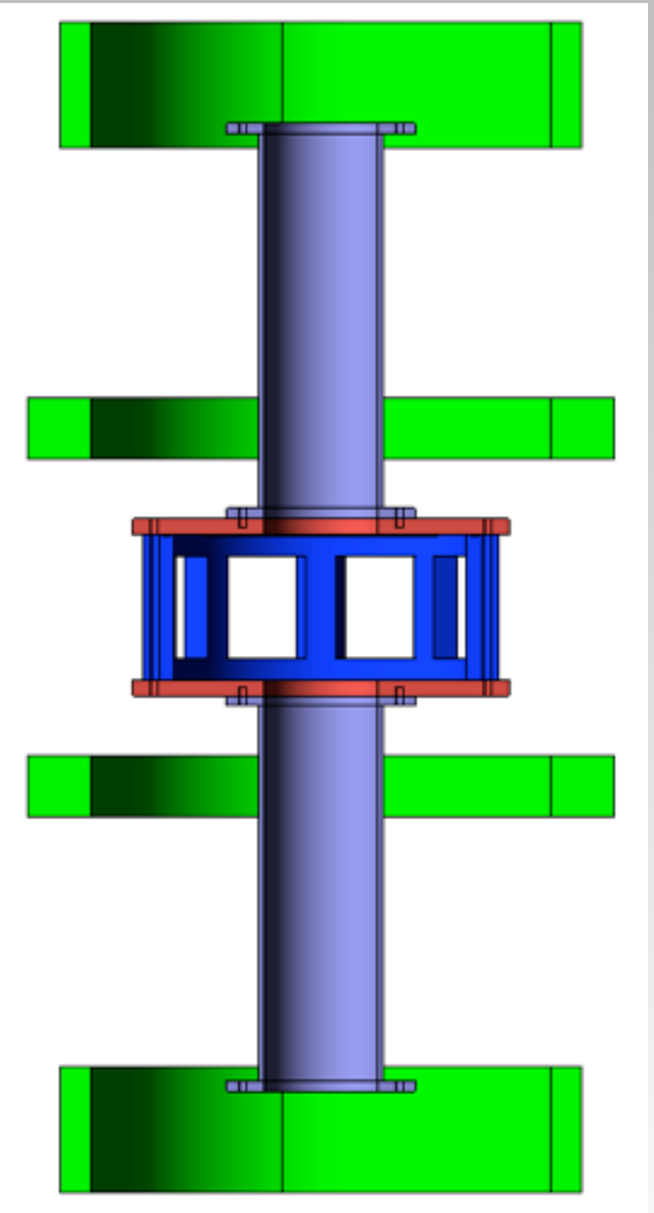


E. Thomas, Jr., et al., PPCF, **54**, 124034 (2012)
E. Thomas, Jr., et al., IEEE TPS, **41**, 811 (2013)

MDPX capabilities: Flexible magnetic configuration

A key feature of the MDPX design is the use of independently controlled magnetic field coils.

This enables a variety of magnetic field configurations to be used.



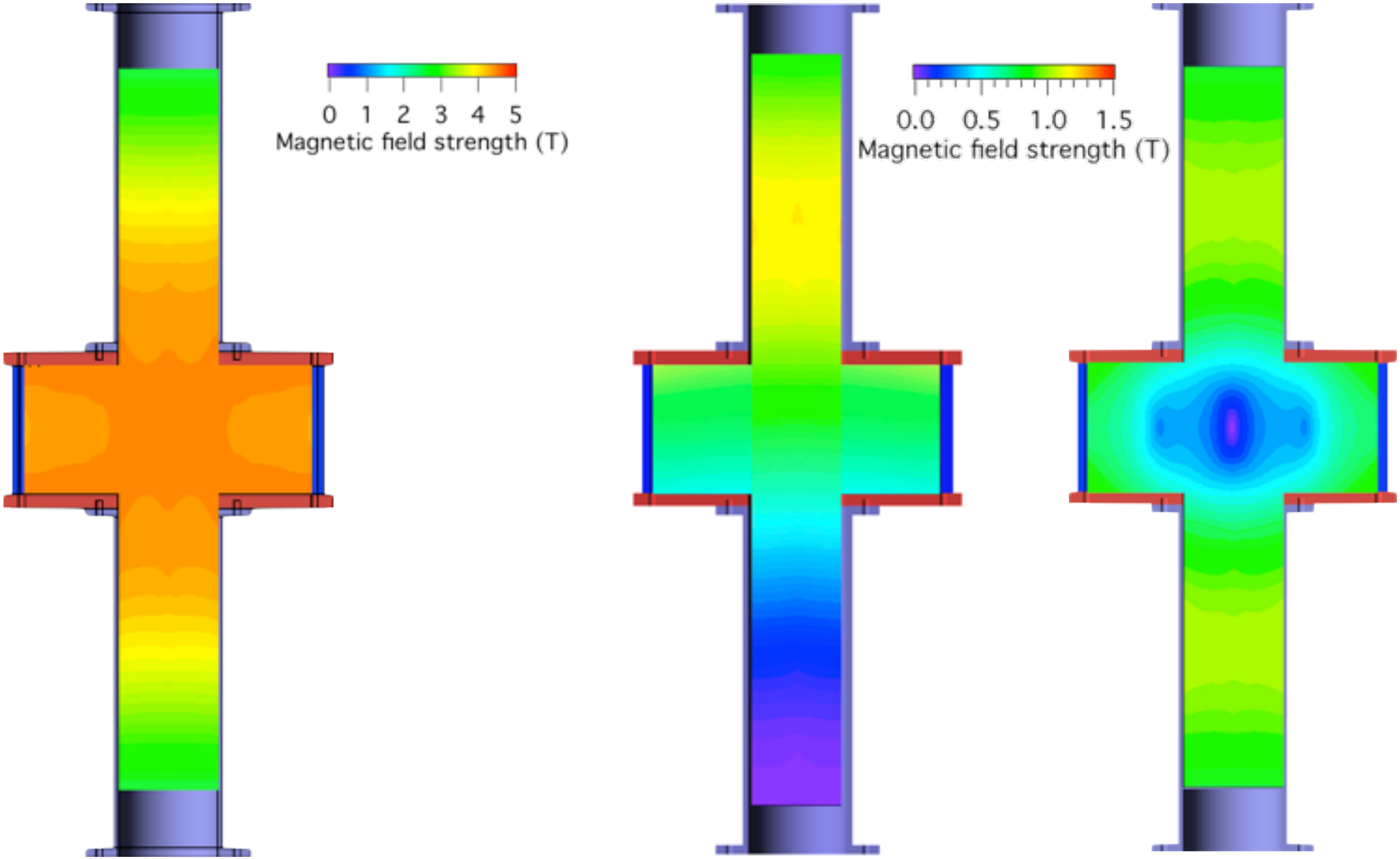
MDPX configurations

Mode	Configuration
1	Uniform field
2	Linear gradient
3	Quadrupole

AUPSL

AUBURN UNIVERSITY

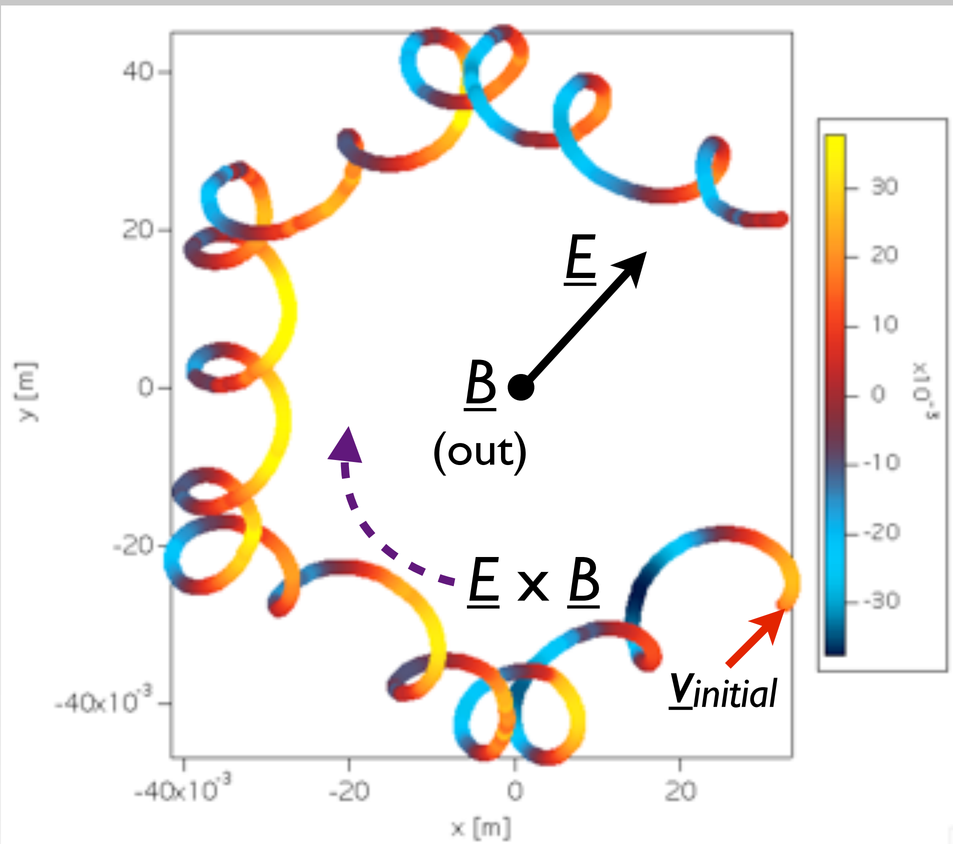
MDPX capabilities: Flexible magnetic configuration



Uniform   Linear gradient   Quadrapole

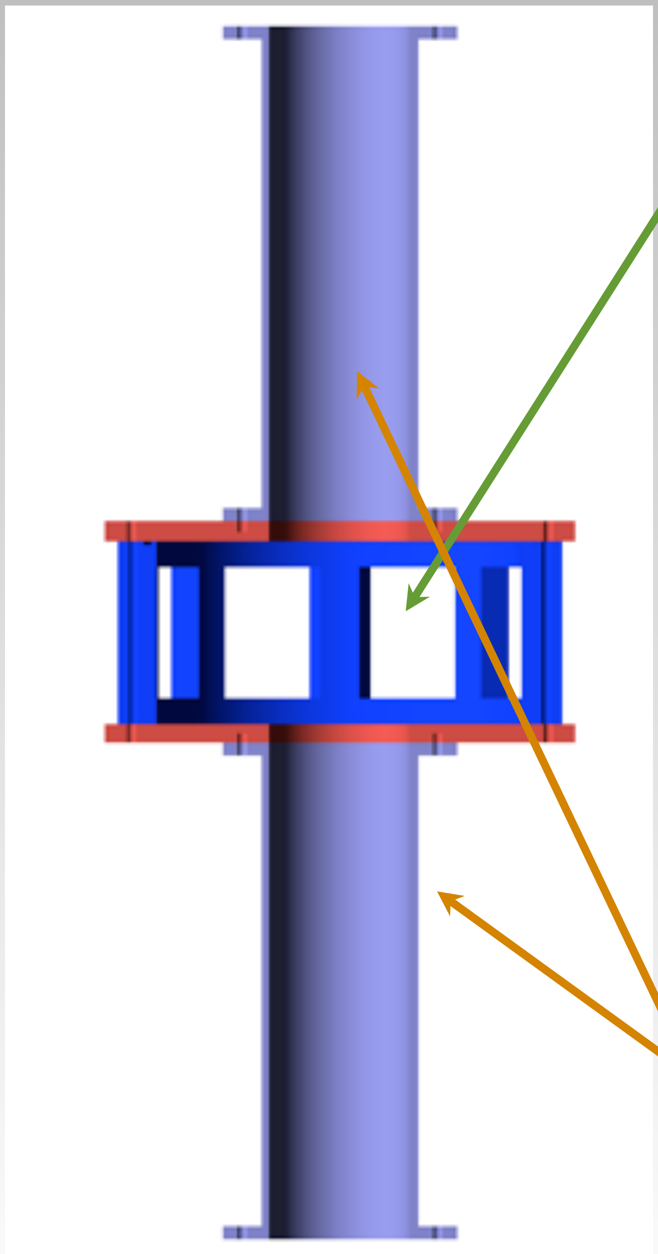
MDPX capabilities: confinement of charged dust

Preliminary simulations of dust particle trajectories in MDPX



Simulations using DEMON
[Dynamic Exploration of Microparticle clouds Optimized Numerically,
R. Jefferson, et al., Phys. Plasmas, 17, 113704 (2010)]

MDPX: Vacuum Chamber

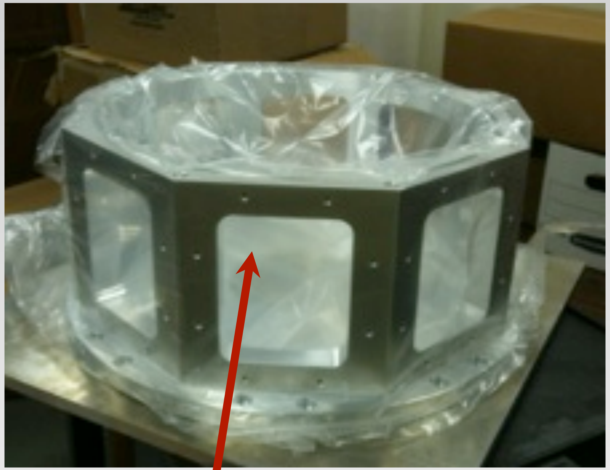


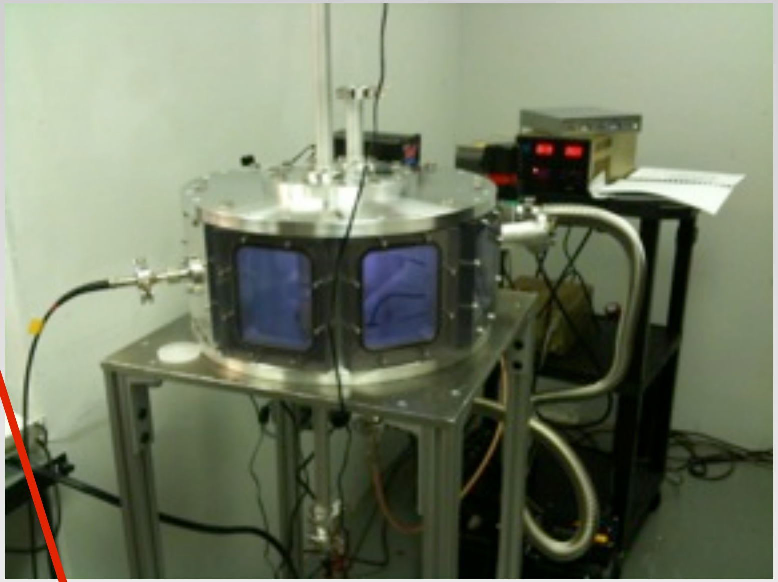
Main chamber:

- Octagonal frame
- 14 inch (35.56 cm) inner diameter
- 8 ports, 6.5 in x 7 in (16.5 cm x 17.8 cm)

Diagnostics:

- LIF
- PIV
- High speed imaging
- Probes
- Spectroscopy





Extensions:

- Cylindrical
- 5.5 inch (14 cm) inner diameter
- 18 inch (45.7 cm) long

Probe

RF argon plasma

AUPSL

AUBURN UNIVERSITY

Upcoming studies in the area of magnetized dusty plasmas

- Fundamental studies:
  - Dust transport
  - New dust waves, dust-modified plasma waves
  - Dust **g** x **B** drift
  - Wakes structure formation
  - Charge equilibrium and variable charging*
  - Anisotropic Coulomb shielding
  - Dust cyclotron motion
  - Dynamics of non-spherical dust grains*

- Strongly-coupled phenomena:
  - Plasma crystal formation*
  - Modified lattice waves
  - Phonon propagation
  - Dust string formation*

AUPSL

* Studies proposed by collaborators/users

AUBURN UNIVERSITY

Upcoming studies in the area of magnetized dusty plasmas

- Magnetic field gradients:
  - Behavior of paramagnetic, super-paramagnetic particles
  - Dust grad-**B** drifts
  - Phase transition experiments*

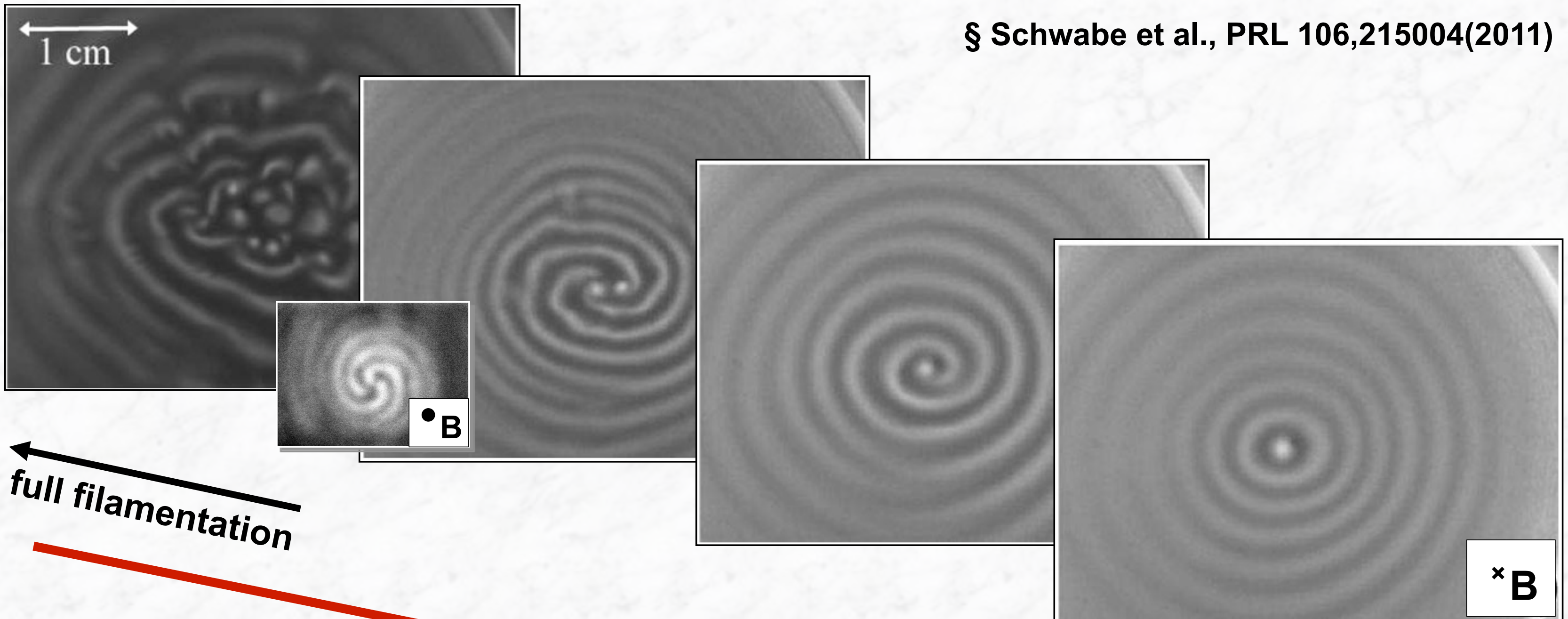
- Studies beyond dusty plasmas (via collaborations/users):
  - Physics of highly magnetized, steady-state plasmas
  - Plasma filamentation
  - Plasma source development*
  - Particle imaging [high speed, plenoptic,* Mie ellipsometry*]
  - Plasma-surface interactions in large magnetic fields*
  - Development of novel MRI-based diagnostics*
  - Technology of steady-state superconducting magnet systems
  - Development of cyber-infrastructure systems

* Studies proposed by collaborators/users

Technical challenge: filamentation in rf generated plasmas

The observed plasma glow (rings/spirals/filaments)

§ Schwabe et al., PRL 106,215004(2011)



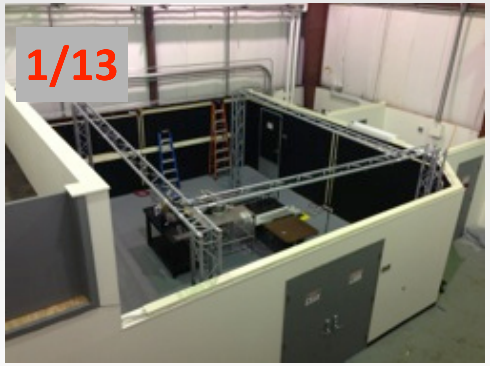
full filamentation

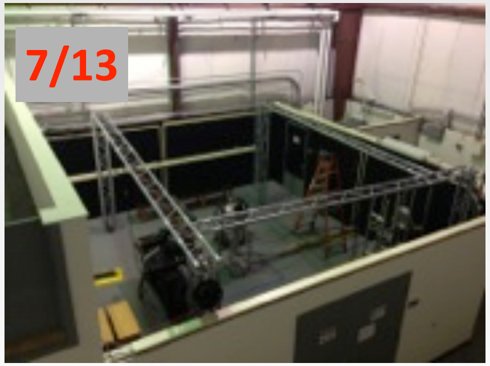
decreasing magnetization

homogeneous plasma

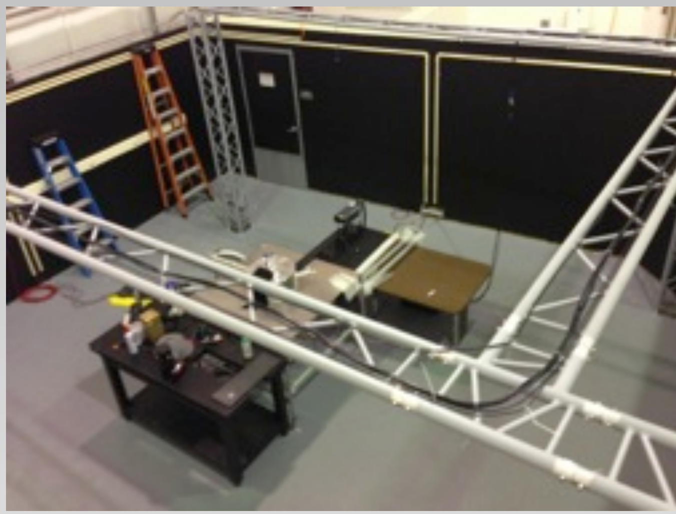
With increasing field the plasma more and more develops inhomogeneous plasma structures.

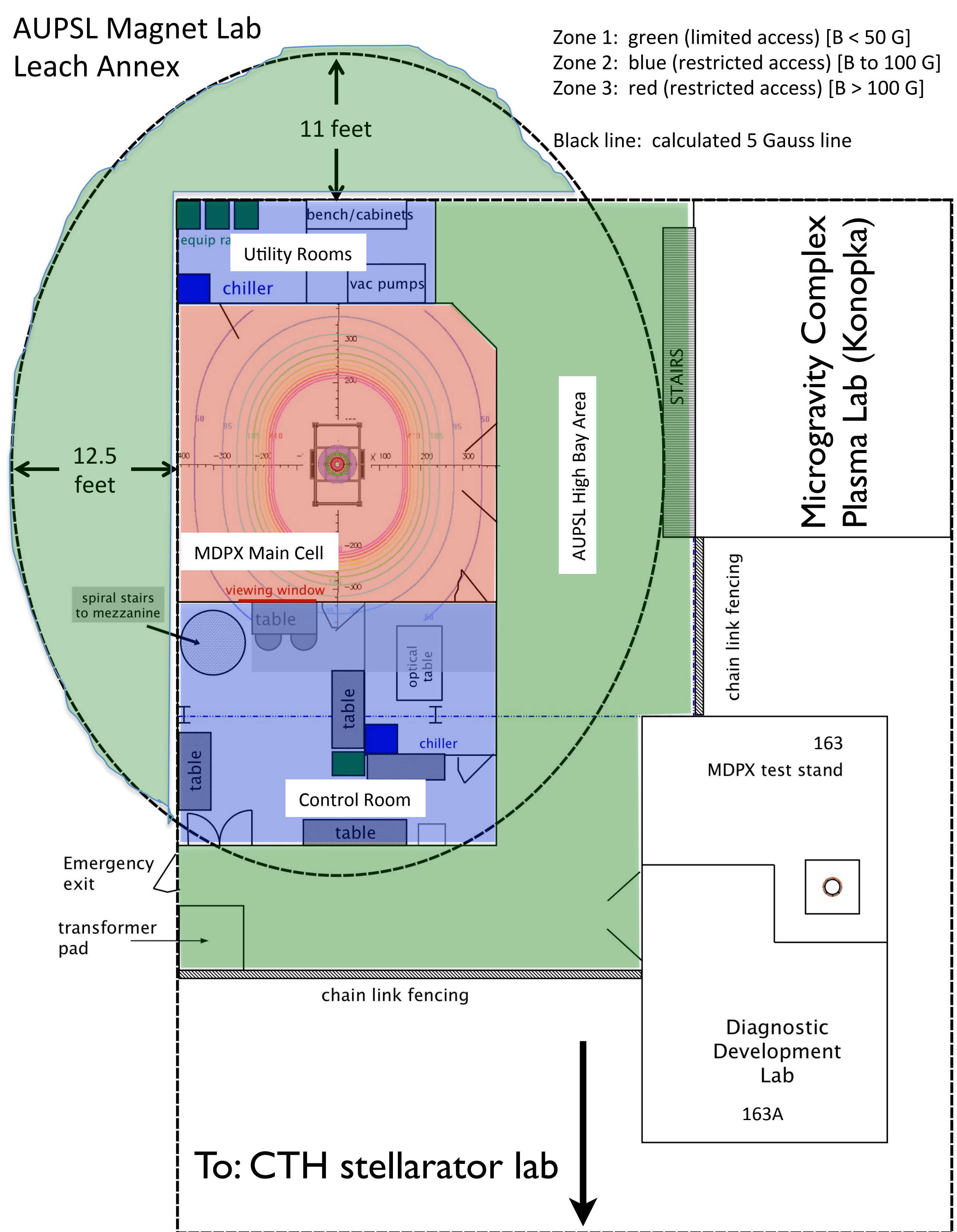
MDPX Laboratory Construction





MDPX: Laboratory Facility

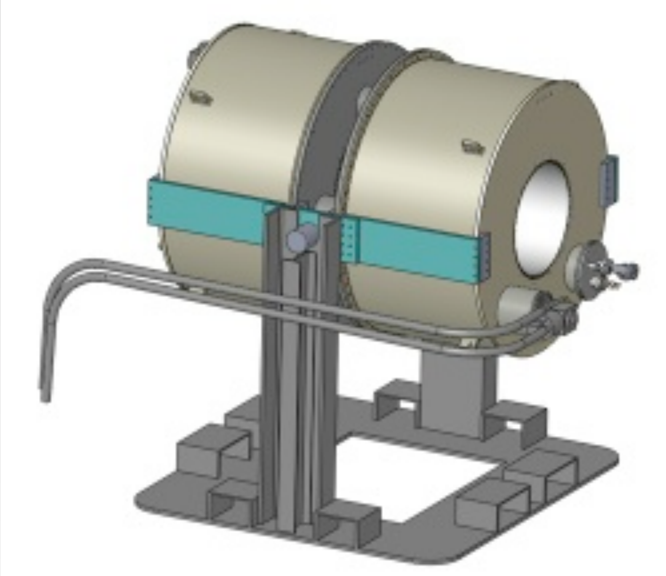


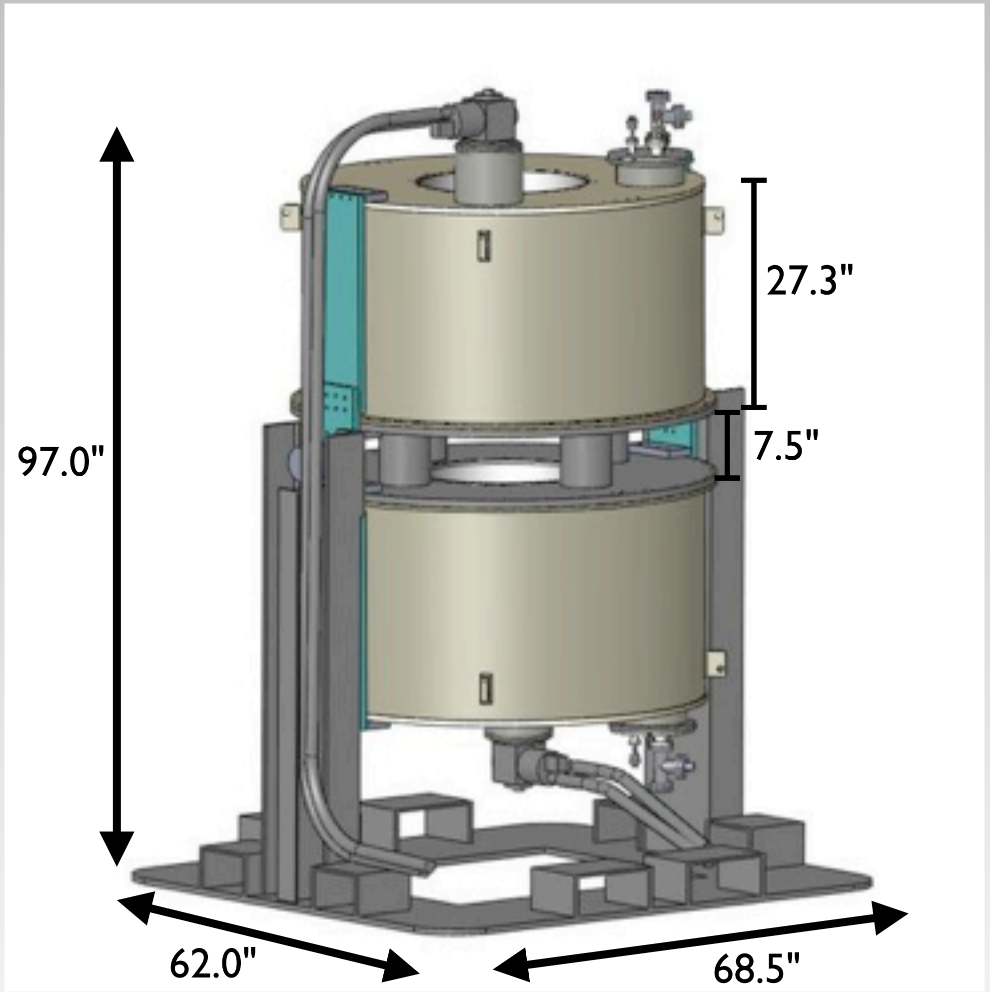


AUPSL

AUBURN UNIVERSITY

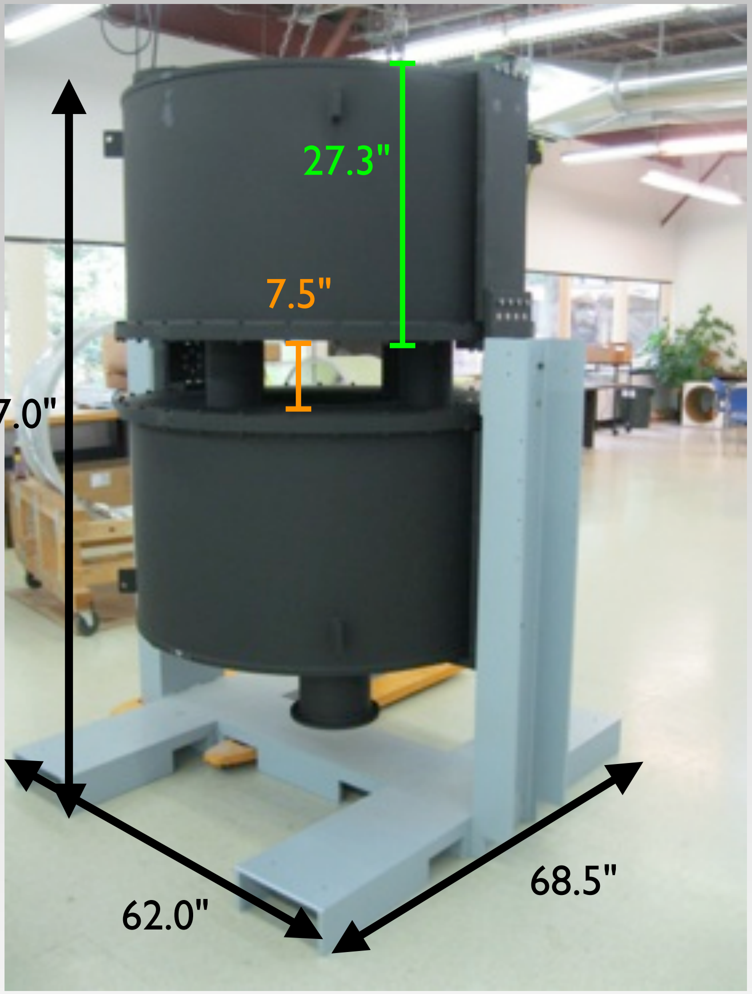
MDPX status: magnets under construction





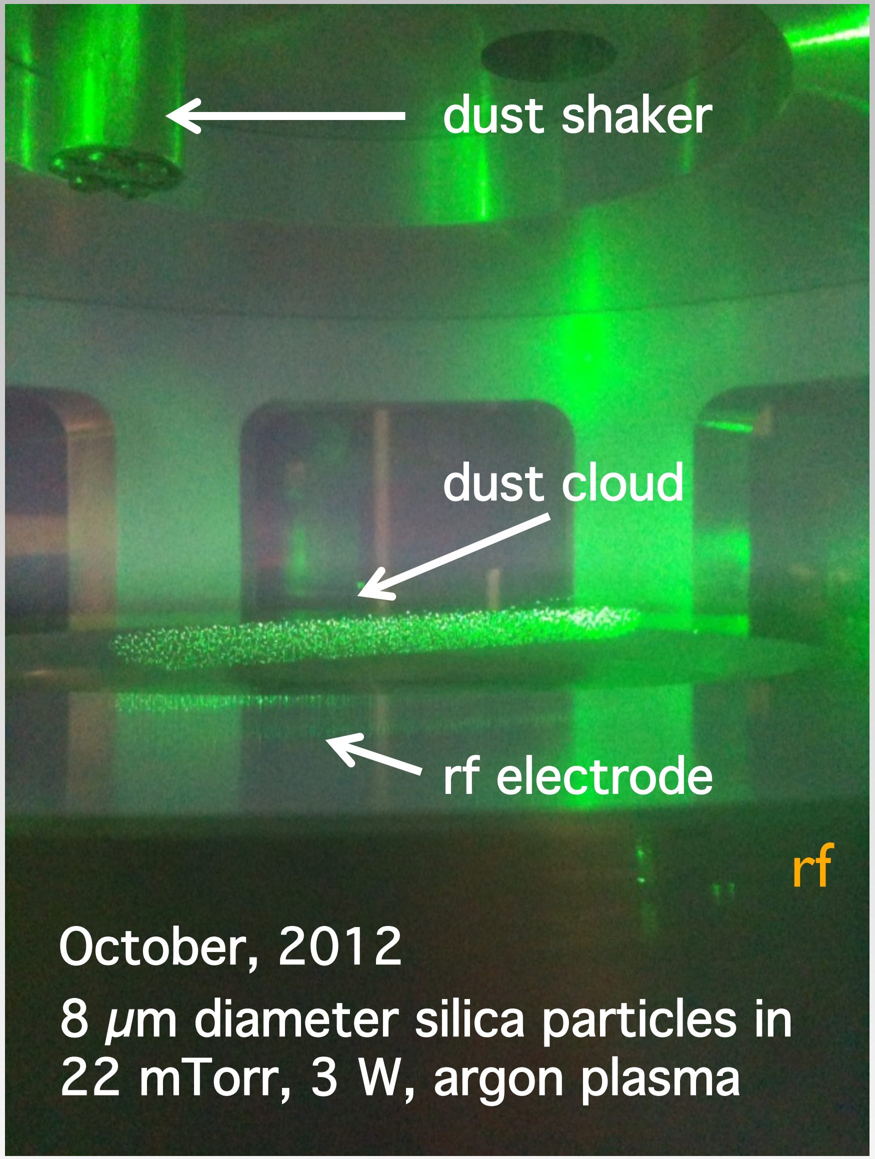
From: Superconducting Systems, Inc. and MIT Fusion Engineering Group

MDPX status: magnets under construction



From: Superconducting Systems, Inc. and MIT Fusion Engineering Group

MDPX status: dust cloud formation

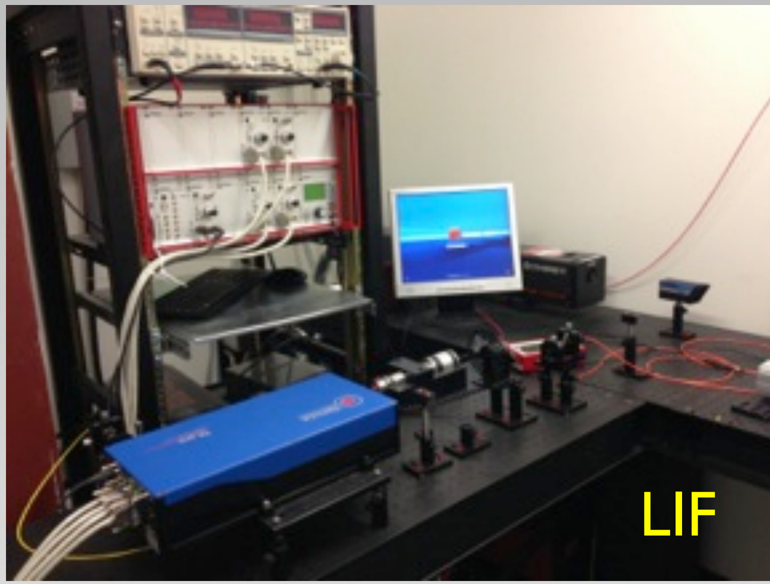


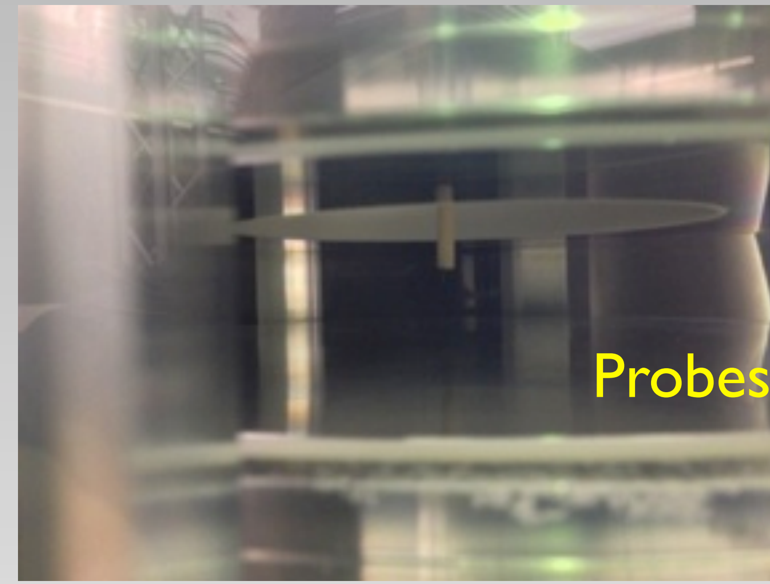
Preliminary tests of dusty plasma confinement

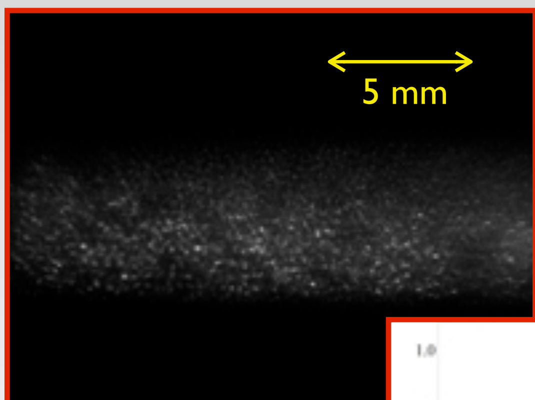
AUPSL

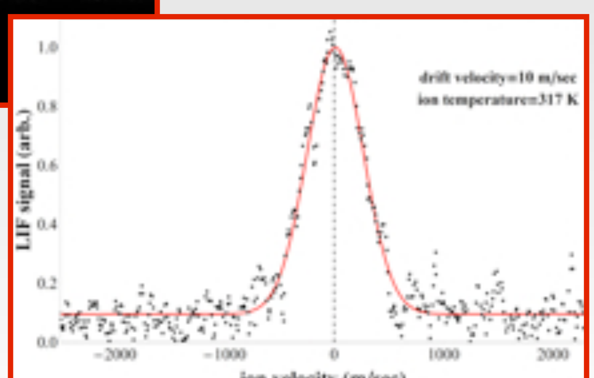
AUBURN UNIVERSITY

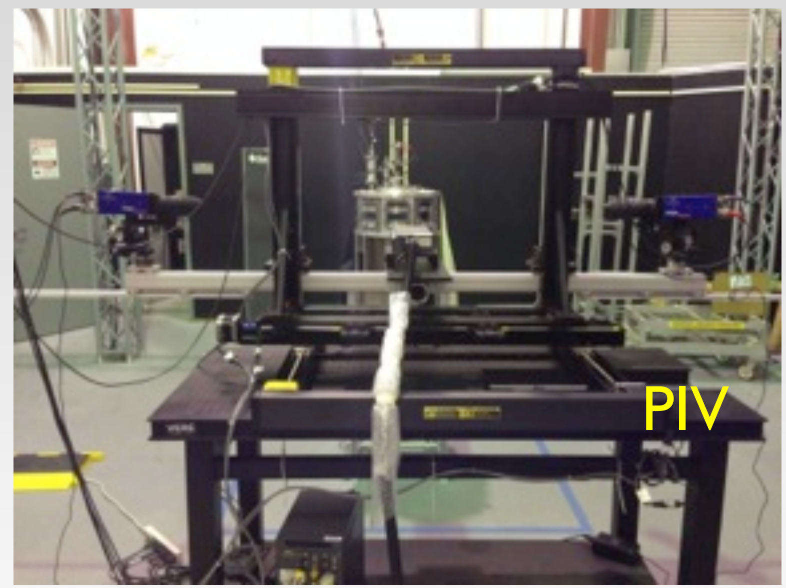
MDPX status: diagnostic development is in progress







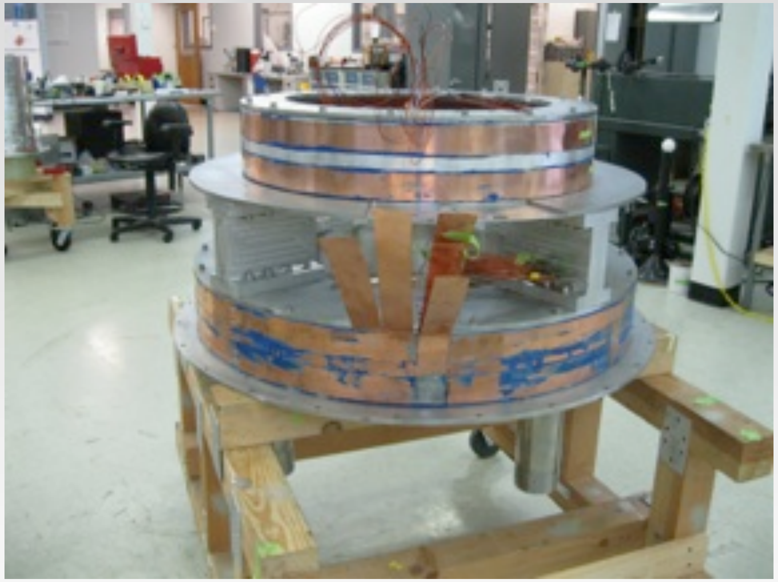


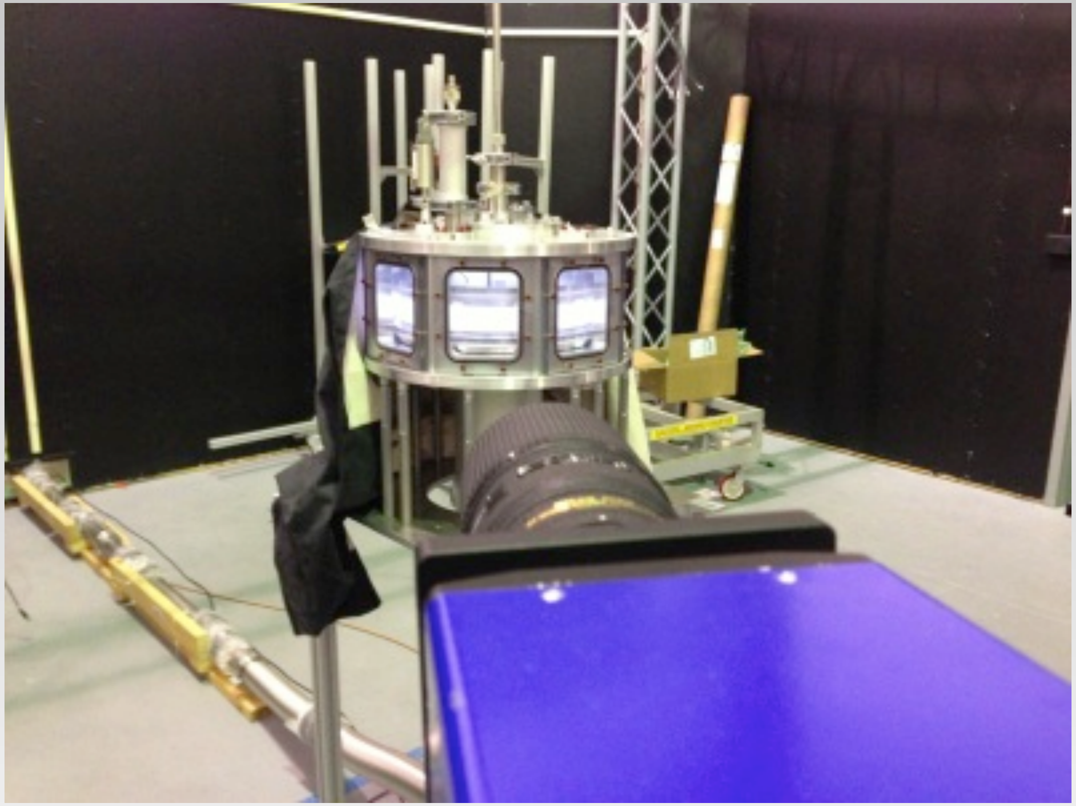


AUPSL

AUBURN UNIVERSITY

Status: magnets in final assembly, chamber is being tested





AUPSL

AUBURN UNIVERSITY

Initial research plans for MDPX

- MDPX Research Program
  - Goal 1: Magnetization in uniform fields
    - Phase 1: Dust particles in magnetized plasmas
      - Rigid body rotation
      - Dust gyromotion
    - Phase 2: Magnetized dusty plasmas in uniform fields
      - Grain charging
      - Inter-dust forces
      - Plasma waves and dust waves
  - Goal 2: Magnetization in non-uniform fields
    - Phase 3: Magnetized dusty plasma in field gradients
      - Gradients on magnetic particles
      - Strongly coupled effects

Summary

- Charged dust, magnetic fields, and plasmas co-exist in many laboratory, fusion, and astrophysical environments.
- The technical expertise is now available to develop a new, flexible, multi-user experimental facility for the study of magnetized dusty plasmas.
- The MDPX facility is under development at Auburn University.
  - Vacuum vessel (V1 and V2) have been built and tested.
  - Magnet construction is ongoing, expect delivery in late Fall, 2013.
  - Diagnostic development is ongoing.
  - Begin magnetic field operations before end of 2013.
- The modular design of MDPX enables a variety of scientific investigations beyond dusty plasmas: properties of magnetic materials, highly magnetized plasmas, etc.
- Open invitation to collaborators/users
  - Seeking proposals for a broad range of plasma and/or dusty plasma experiments that can make use of steady-state, high magnetic fields.
  - Begin first collaborative experiments by Summer/Fall, 2014.

AUPSL

AUBURN UNIVERSITY

The people who did the work!

MDPX team: Dr. Ross Fisher (post-doc), Mr. Darrick Artis (technician / master of all)
Stephen Adams, Spencer LeBlanc, Brian Lynch, Keith Wood (graduate students)

And a small army of undergraduates:
Matt Gill, Kevin Gilmore, Joseph Shaw, Robert Sutherland,
Taylor Hall, Shane Moorhead, Christian Polka, Daniel Robinson, James Schloss

Magnet design and construction:
MIT Fusion Engineering, Superconducting Systems, Inc. (MA)

With many thanks to world-wide dusty/complex plasma community:

Baylor, Colorado, Iowa, Middle Georgia, MIT, Ouachita,
UAH, UCSD, WVU, Wittenberg

LANL, NRL, PPPL

Kiel Univ., Univ. of Delhi, IPR (India), Max Planck Inst./DLR

AUPSL

AUBURN UNIVERSITY