A proposed Magnetized Dusty Plasma User Facility

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ABSTRACT:

As the experimental study of dusty (complex) plasmas has advanced over the last two decades, a great deal of new insight has been gained on the complex interaction between the background plasma and charged microparticles. Even through the charged dust grains in a typical experiment can acquire several thousand elementary charges, the large mass of the grains ensures that the charge-to-mass ratio is quite low. As a result, it has been considered experimentally challenging to design an experiment that can achieve full magnetization of ions, electrons, and the charged dust grains. However, with continuing improvements in magnet design and sub-micron particle imaging technologies, it is now possible to contemplate the development of a Magnetized Dusty Plasma Facility. This presentation discusses the design, experimental parameters, and scientific motivation for a flexible, superconducting, 4 Tesla magnetic field user facility for the study of magnetized dusty plasmas.

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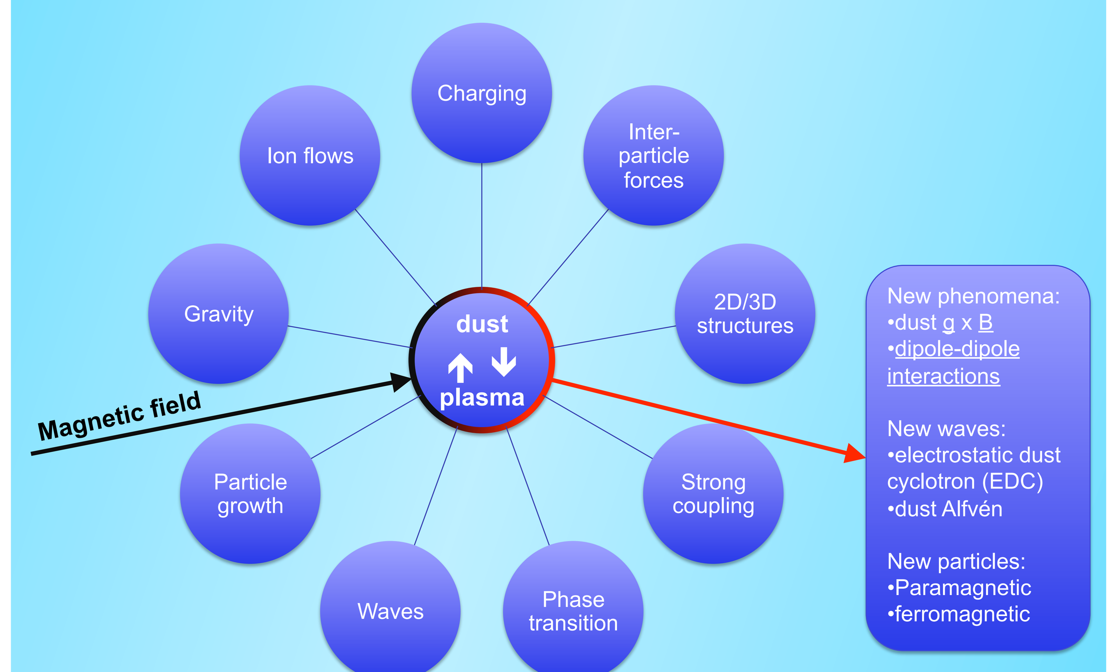
Motivation: Why a magnetized dusty plasma?

- Naturally occurring plasmas at all scales – from noctilucent clouds at the top of Earth's atmosphere to proto-stellar and proto-planetary disks - have both magnetic fields and charged dust.
- Because the addition of the charged dust modifies the properties of the plasma, current experiments have all focused on the dust – plasma interaction.
- Almost all of these experiments are operated in regimes without magnetic fields or with magnetized electrons only.
- With the knowledge gained from the last two decades of research, it is now possible to explore the true behavior of a dusty plasma in nature – a system that includes both charged microparticles and magnetic fields.
- **Therefore, to advance the complete understanding of dusty plasmas, it is necessary to study fully magnetized plasmas – where first the electrons, then the ions, and finally the charged dust are confined by the magnetic field.**
- The presence of the magnetic field modifies all of the properties of the plasma by adding an additional degree of freedom; a magnetized dusty plasma will, likewise, be completely transformed by the magnetic field – leading to an entirely new regime of dusty plasma physics.



Motivation: What are the guiding research questions?

Magnetization is defined as the condition where the magnetic force on a particle is comparable to the other forces acting upon the particle (electric, gravitational, etc.) and when the gyroradius is substantially smaller than the scale size of the experiment.

For these studies, we not only want to consider the condition of fully magnetized dust grains but also how strongly magnetized electrons and ions affect the properties of the dusty plasma.

The central research questions of this work are:

- As a dusty plasma is taken from an unmagnetized system through a progression of regimes where first the electrons, then the ions, and then the charged dust become magnetized - how do the structural, thermal, charging, and instability properties of the dusty plasma evolve?
- If a dusty plasma is composed of microparticles that have paramagnetic or ferromagnetic properties, how do the properties of the dusty plasma evolve in the presence of uniform and non-uniform magnetic fields?

- Relevance and applications of magnetized dusty plasmas:
  - Charged microparticle transport in fusion edge plasmas.
  - Modification of charged fractal agglomeration in proto-planetary and proto-stellar clouds.
  - Phase transitions in para- and ferro- magnetic systems
  - Development of new technologies for nanoparticle detection and the generation of high magnetic fields.

Previous experiments on magnetized dusty plasmas

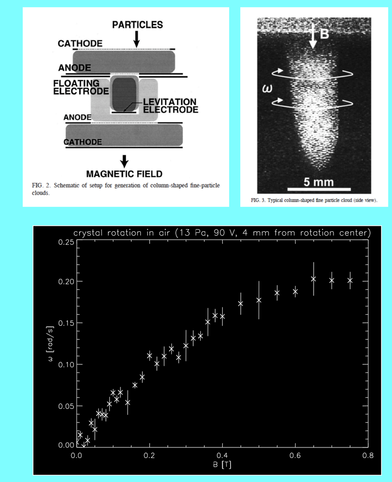
Some Earlier Studies

Oxford group (J. Allen, et al.):
- Small magnet below the lower electrode showed an influence on the particle dynamics (kind of vortex flow).

Sendai group (N. Sato et al.):
- First rotation experiments using a vertical magnetic field (shown at conference)

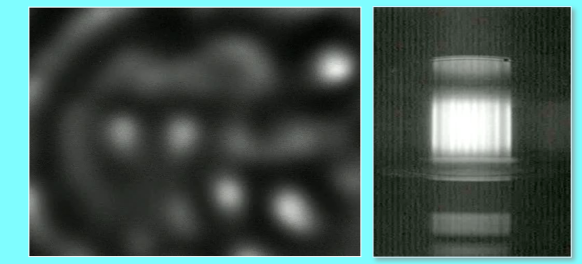
MPE group (U. Konopka et al. (also J. Goree)):
- First rotation experiments at MPE using a permanent magnet below the electrode (detailed study of the dynamic behavior with changes in confinement,..)

MPE Group (D. Samsonov, et al.)
- First studies of a dusty plasma composed of diamagnetic particles in a non-uniform magnetic field.



Measurements of cloud rotation due to ion E x B drifts

Above: Sato, et al., PoP, 2001
Below: MPE experiments



Plasma filamentation

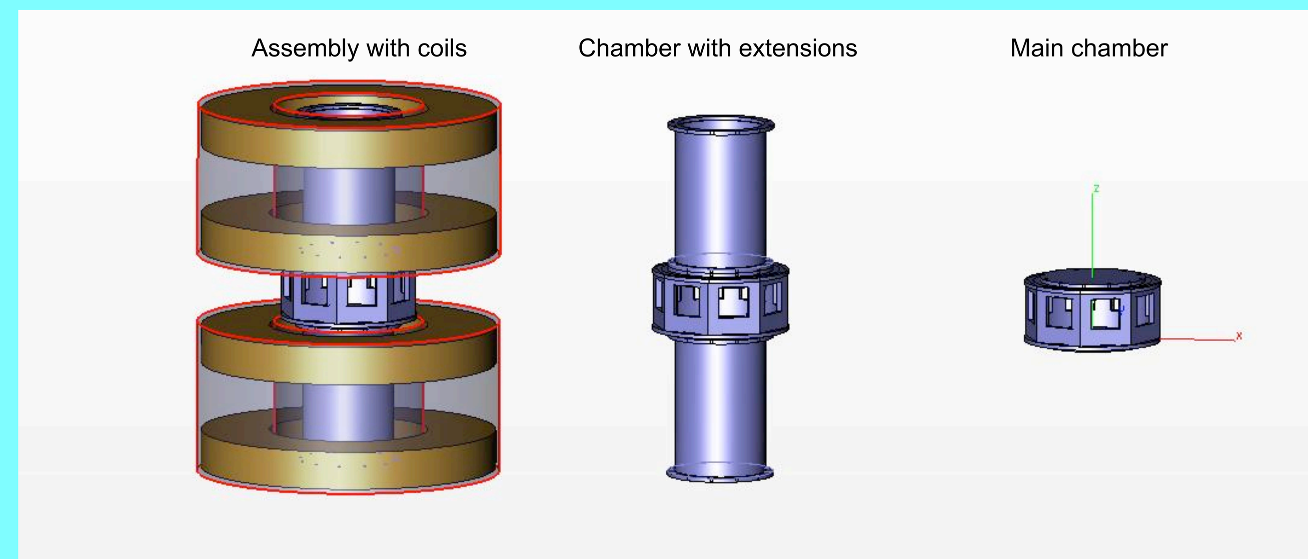
- An issue that arose with the MPE experiments.
- The filaments radial size and separation (without dust particles) weakly depends on power.
- Increasing power the filament structure changes from spots to ring-shaped plasma columns.
- Filaments appear at low pressures (typ. a few Pa), low discharge powers, and high magnetic fields (about 0.8 T and higher).
- They disappear after increasing power, pressure or decreasing the magnetic field strength.
- The micro particles rotate around the filaments -> Ion drag?

MPE superconducting magnet system

Magnetized Dusty Plasma Experiment

Design Philosophy

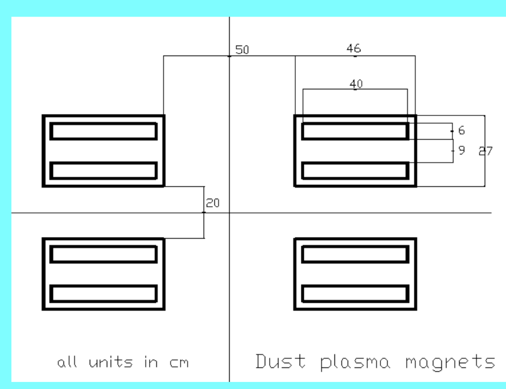
- Magnetic field strength that meets or exceeds parameters of previous experiments.
- Ability to have large, uniform magnetic fields over a volume at least 2x larger than previous experiments.
- Allow excellent diagnostic access to the plasma volume.
- Ability to independently control the current to each coil to allow magnetic fields with "user-defined" gradients to be made.
- Maintain the option to rotate the magnets to perform experiments with the magnetic field either parallel or perpendicular to gravity.
- To have an option to use "extensions" to substantially expand the plasma volume to allow experiments on magnetized dust waves (e.g., electrostatic dust cyclotron wave) to be performed.

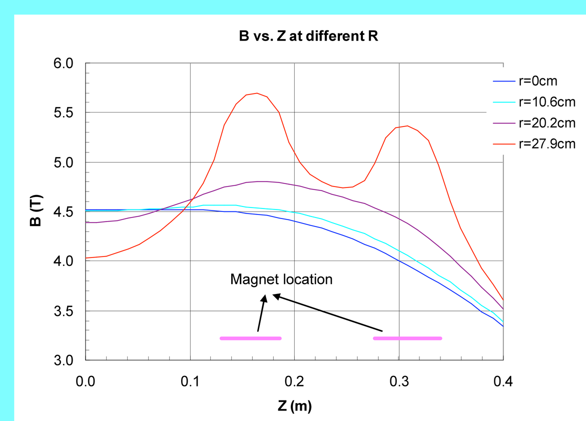


Conceptual design for the Magnetized Dusty Plasma Experiment

Target Experimental Configuration

- Four superconducting magnet coils, grouped as two pairs.
- Magnetic field coil assembly should have a 50 cm (~19.6") bore.
- Separation between coil pairs: 20 cm (~7.8")
- "Day one" configuration:
  - Magnetic field: 4 Tesla
  - Orientation: vertical field (i.e., B || g)
  - Plasma volume: 40 cm diameter x 20 cm axial
  - Uniform B region: 20 cm diameter x 5 cm axial
  - Plasma source: parallel plate rf electrodes
  - Particles: 1 micron diameter (monodisperse)
  - Diagnostics: laser diodes (visible) + fast cameras (>200 fps)



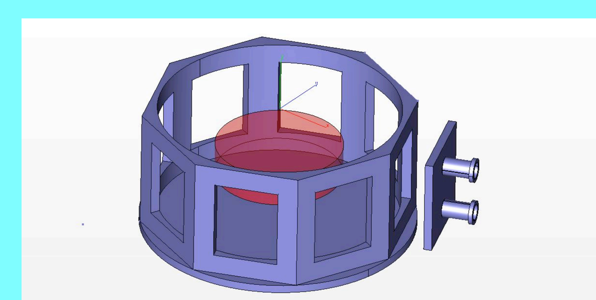


Design of the superconducting magnets

- One of the most challenging aspects of this project is the design of the magnetic field coil system.
- The dusty plasma community has partnered with the MIT Fusion Technology and Engineering group to leverage their expertise on the design and construction of high field superconducting magnets.
- The MIT group has provided a preliminary model for the magnets with estimates of the magnetic field strength based upon the experimental configuration provided above.
- Preliminary model gives:
  - Using Nb-Ti superconducting conductor
  - Uniform region: ~22 cm diameter, ~18 cm axial
  - Predicted magnetic field: 4.5 Tesla
  - Parameters exceed preliminary design criteria
- Additional work remains to be done on the cooling system and support structure – particularly, force and stress calculations.

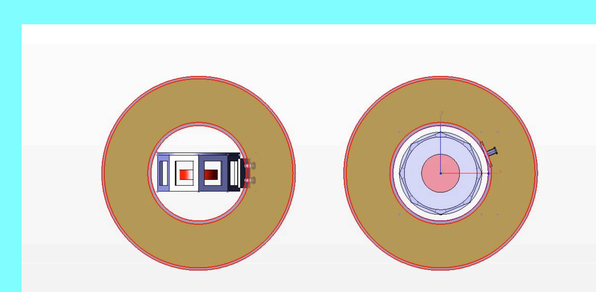
Development of diagnostic systems

- For micron sized particles (down to a ~ 500 nm), the visible laser / video camera combination used extensively in the dusty plasma community will be the primary diagnostic system.
- However, smaller particles (a ~ 50 to 100 nm) may be needed in order to observe some magnetic effects. Some approaches include:
  - Using the surface plasmon resonance to have enhanced light scattering or absorption of metallic or metallic coated nanoparticles.
  - Using UV light sources with UV sensitive cameras for detection of particles down to a ~ 100 nm.
  - Using multi-pass extinction techniques to detect the presence of clouds of nanoparticles.
  - Using PMT's to detect fluctuations in clouds of nanoparticles.



Vacuum vessel design

- Main vacuum vessel is an octagonally shaped chamber.
- Shape is chosen to allow perpendicular viewing of injected laser sheets from numerous orientations.
- The chamber has an overall dimensions of:
  - Diameter: 43 cm (17.0")
  - Height: 19 cm (7.5")
  - Ports: 12.7 cm x 8.9 cm (5.0" x 3.5")
- The red cylindrical region in the center of the vacuum vessel is the 20 cm x 5 cm uniform magnetic field region (at full field).
- Extensions are available to increase the length of the chamber to over 80 cm long; this is important for wave studies.



Orientation of magnets

- A critical feature of this experiment is the capability to orient the experimental such that the magnetic field can be either parallel or perpendicular to gravity.
- The figure above shows that the vacuum chamber – without the extensions, can be made to fit within the central bore of the magnets in either configuration.

Physics studies using a Magnetized Dusty Plasma

- The addition of the magnetic field represents a new degree of freedom for the plasma and its coupling to the charged dust particles.
- Experiments will focus not only on the phenomenon of a magnetized, charged grain in a plasma, but the progression of phenomena that occur as the electrons, then the ions, and then the charged dust become magnetized.
- **Fundamental studies of dusty plasmas:**
  - How does charging and screening of charge evolve as a function of magnetic field strength?
  - Can the dust g x B drift be observed for a horizontally oriented magnetic field?
  - What happens to a dusty plasma when the magnetic force becomes the dominant force in the system (i.e., $F_m \geq F_e, F_g$)?
  - Is it possible to observe dust dipole-dipole interactions at large magnetic fields?
- **Waves: Magnetized ions / Unmagnetized dust:**
  - Dust modified E x B driven instabilities (Hall current)
  - Dust modified diamagnetic drift instabilities
  - Some theoretical work has been done, but no experiments have been performed.
- **Waves: Magnetized ions / Magnetized dust:**
  - Electrostatic dust cyclotron instability
  - Modified longitudinal and transverse waves in plasma crystals
- **Paramagnetic, super-paramagnetic and ferromagnetic dust**
  - Can the behavior of dust acoustic waves be tuned using attractive forces along B and repulsive forces perpendicular to B?
  - Can binary crystals be formed by using electric and magnetic forces to levitate one type of grain, and electric forces to levitate other type?
  - Can a large enough magnetic field gradients be created to use the magnetic packing force ($F \sim \nabla B$) to levitate particles directly?
- **Plasma crystals and strongly-coupled phenomena**
  - Can crystals and other strongly-coupled structures (Coulomb balls, clusters, etc.) be formed in a strong magnetic field?
- **Other topics**
  - Can the growth/coagulation of nanoparticles and charged fractal particles be modified by a strong magnetic field? [astro/materials]
  - Is the ablation cloud around heated dust affected by a strong magnetic field? [fusion/materials]

Feasibility of a magnetized dusty plasma facility

Experimentally, two key conditions must be satisfied:

1. dust gyroradius << transverse plasma dimension

$$r_{cd} << \ell_{\perp}$$

2. dust gyrofrequency >> dust-neutral collision frequency

$$\omega_{cd} >> \nu_{dn}$$

In addition to satisfying these conditions, it is important to understand how they will be affected by the properties of the dust particles, the plasma, and the magnetic field.

Experimental parameters:
- dust radius – a
- neutral pressure – P
- magnetic field strength – B
- dust kinetic temperature – T_d

$$m_d = \frac{4\pi\rho a^3}{3} \sim a^3$$

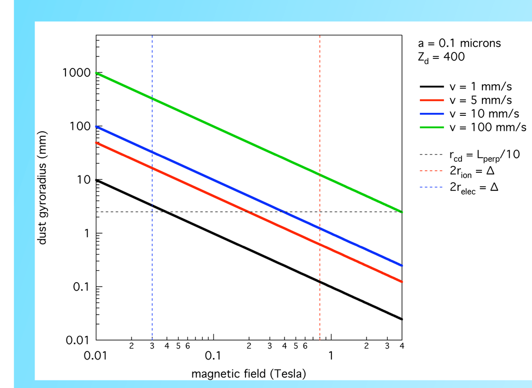
$$q_d = eZ_d = 4\pi\varepsilon_0 a\phi(T_e, T_i, n_e) \sim a$$

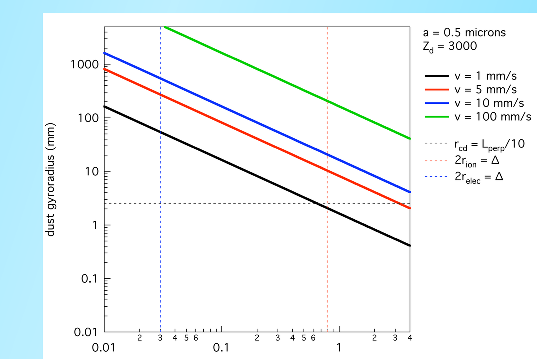
$$\frac{\text{dust cyclotron freq.}}{\text{dust - neutral coll. freq.}} = \frac{\omega_{cd}}{\nu_{dn}} \sim \frac{B}{aP}$$

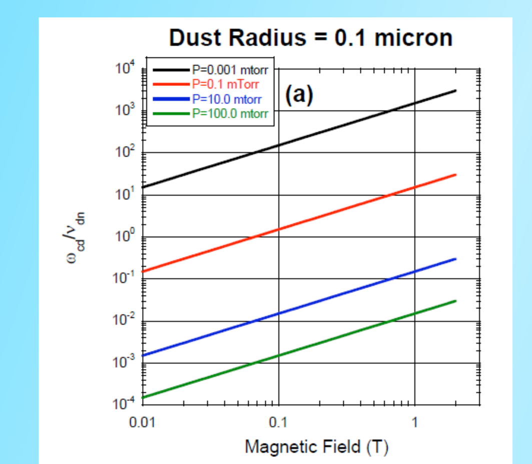
$$r_{cd} = \frac{v_{Td}}{\omega_{cd}} = \frac{(kT_d / m_d)^{1/2}}{eZ_d B / m_d} \sim \frac{a^{1/2} T_d^{1/2}}{B}$$

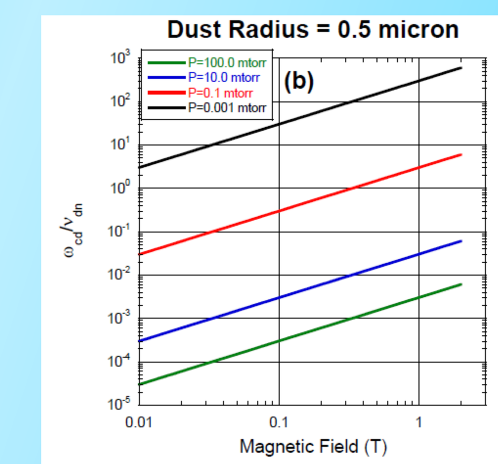
$$\frac{\text{magnetic force}}{\text{weight}} = \frac{F_m}{F_g} = \frac{eZ_d v_{Td} B}{m_d g} \sim \frac{T_d^{1/2} B}{a^{7/2}}$$

$$\nu_{dn} = \frac{4\pi m_n N v_{Tn} a^2}{3 m_d} \sim \frac{P}{a}$$









Balancing experimental needs

- To design the experiment to achieve our physics goal is dependent upon several competing conditions:
  - Condition 1: Weak magnetic fields ($) => large experimental volume ($$)
  - Condition 2: Large magnetic fields ($$) => smaller experimental volume ($)
  - Condition 3: Larger particles => Larger magnetic fields ($$) => easier diagnostics
  - Condition 4: Smaller particles => smaller magnetic fields ($) => new diagnostics ($$)
  - Condition 5: Plasma source development => low neutral pressure
  - Condition 6: Maximize plasma volume to carry out wave studies ($$)
- After extended discussions, the choice is made to pursue the high magnetic field strength path to a magnetized dusty plasma.
- We will also pursue the development of new plasma sources and advanced diagnostic approaches to allow the use of smaller (nanometer scale) particles.

Current Status

- Preliminary calculations suggest that the development and operation of a US magnetized dusty plasma user facility can be successful.
- Preliminary magnet designs show that the operating conditions needed for performing experiments are reasonable and achievable.
- Partner Institutions:
  Auburn, Baylor, Colorado, Iowa, LANL, MIT, MPE, NRL, PPPL, Wittenberg