Introduction to the physics of complex/dusty plasmas

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Outline

- Why dusty plasmas?
- Basic properties
  - Fundamental parameters
  - Charging
  - Forces and transport
- Dusty plasma studies
  - Statistical mechanics of non-equilibrium systems
  - Dust acoustic / dust density waves
  - Magnetic field effects
- Outlook
  - Outstanding problems and opportunities
- More information
  - Institutions
  - References

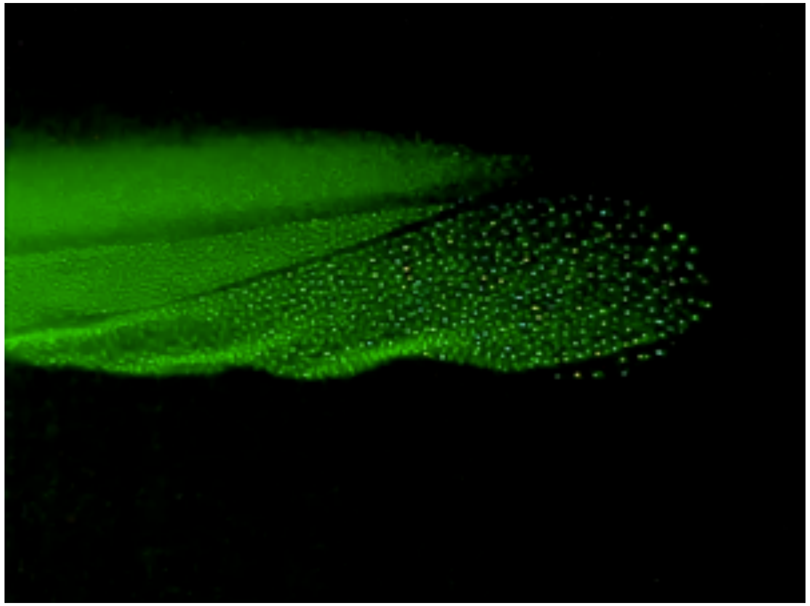
WHY DUSTY PLASMAS?

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
  - Ubiquitous in natural and man-made plasmas

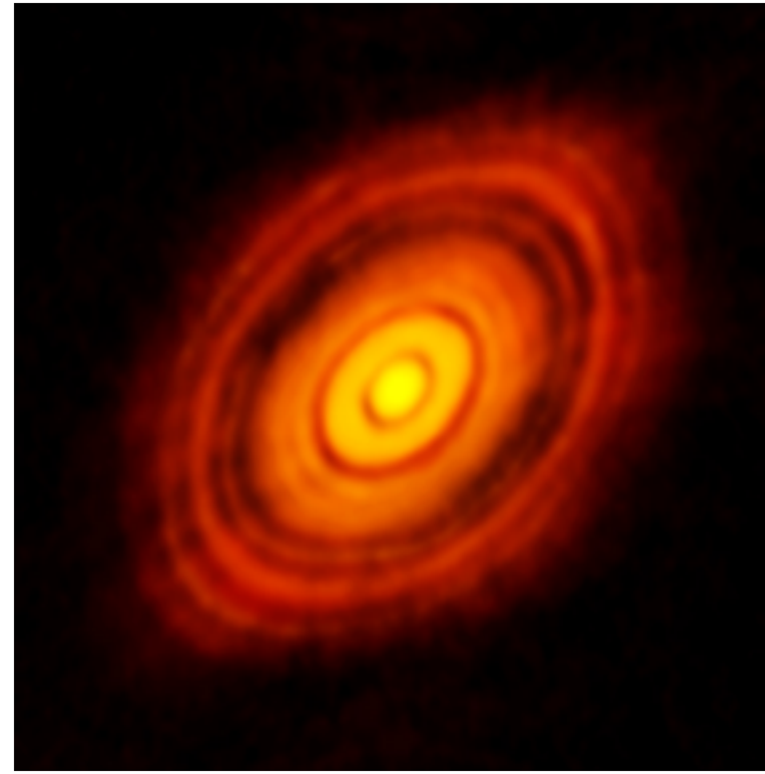


- Measurements of dust particles:
  - Forces
  - Electrostatic potential
  - Velocity distributions

Dusty plasmas in astrophysical environments

http://hubblesite.org/newscenter/archive/releases/2007/16/image/f/format/large_web/

Image: Star formation in Carina Nebula

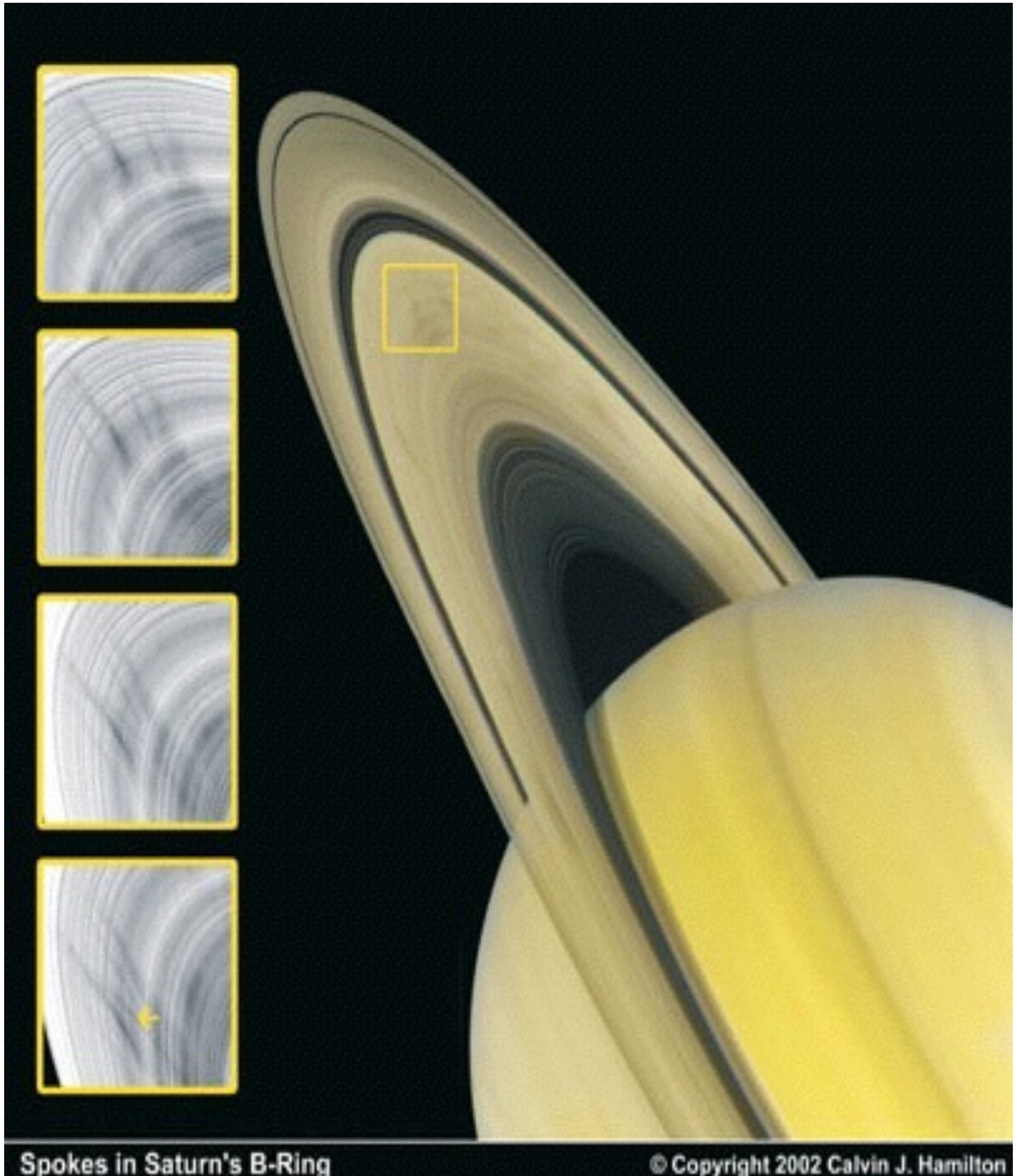


http://www.almaobservatory.org/en/press-room/press-releases/771-revolutionary-alma-image-reveals-planetary-genesis

Image: HL Tau (2014)

Photoionization from stellar material charges the dust in the nebula. The presence of charged dust may lead to enhanced coagulation of small particles AND to repulsion between larger particles. [F. Verheest, PPCF, **41**, A445 (1999)]

Dusty plasmas in the solar system



- Discovered by Voyager 2 in 1980
- Spokes seen in forward scattered light –> composed of micron-sized dust and ice
- Spokes exhibit dynamical behavior on timescales of minutes.

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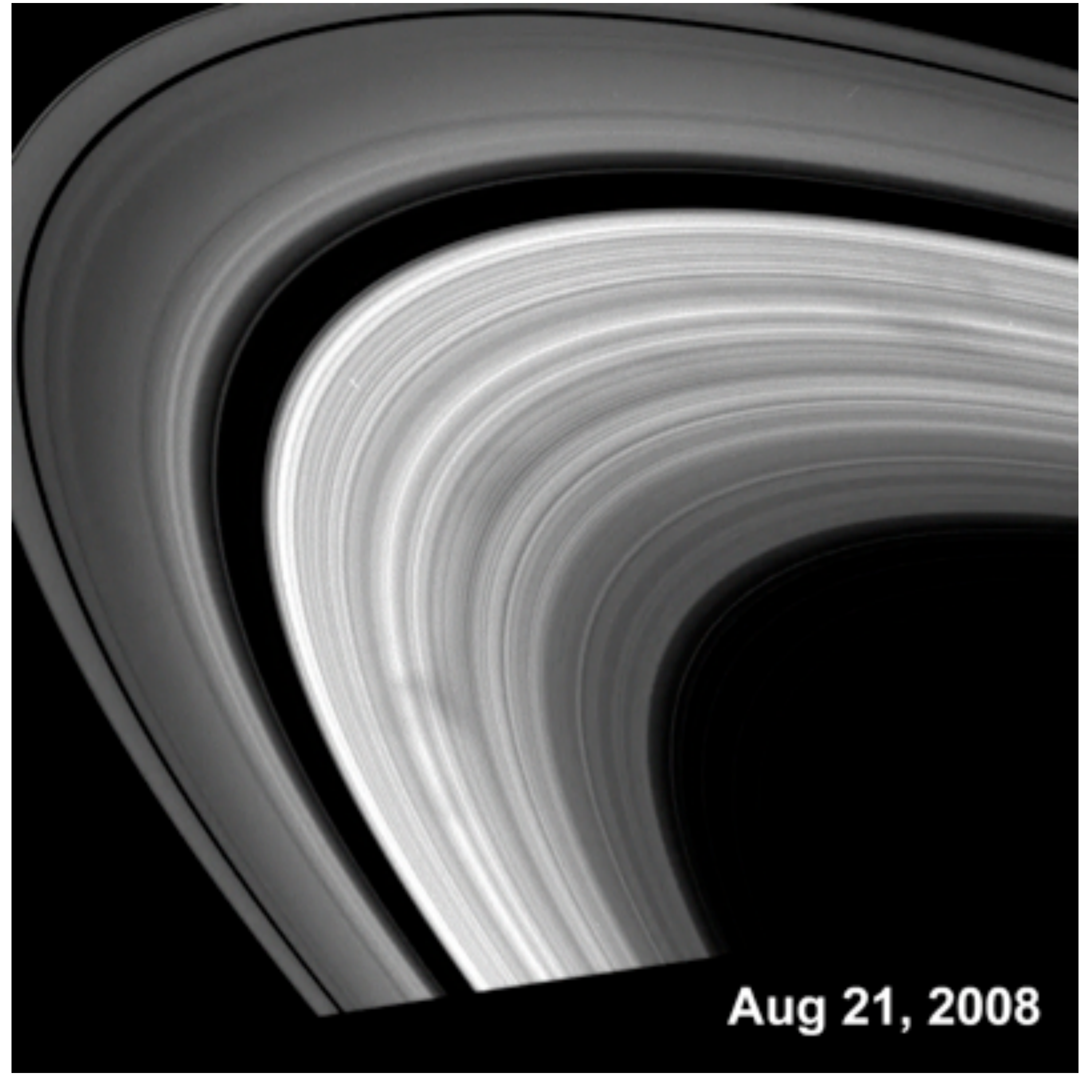
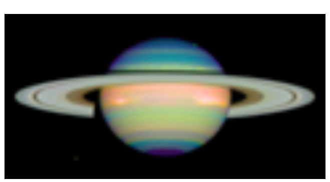
Dusty plasmas in the solar system

- Cassini (2004) - initially, no spokes observed!
- Re-evaluation of the Voyager data to understand changes in plasma environment.
- Cassini (2006) reappeared – as predicted by updated models.
- Spoke formation correlated to opening angle of Saturn's rings.

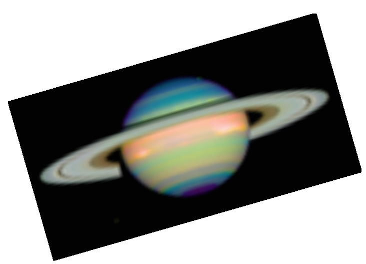


Cassini observation of spokes

C. J. Mitchell, et al., Science, **311**, 1589 (2006)



1980, $B = 6^{\circ}$



2004, $B = 27^{\circ}$

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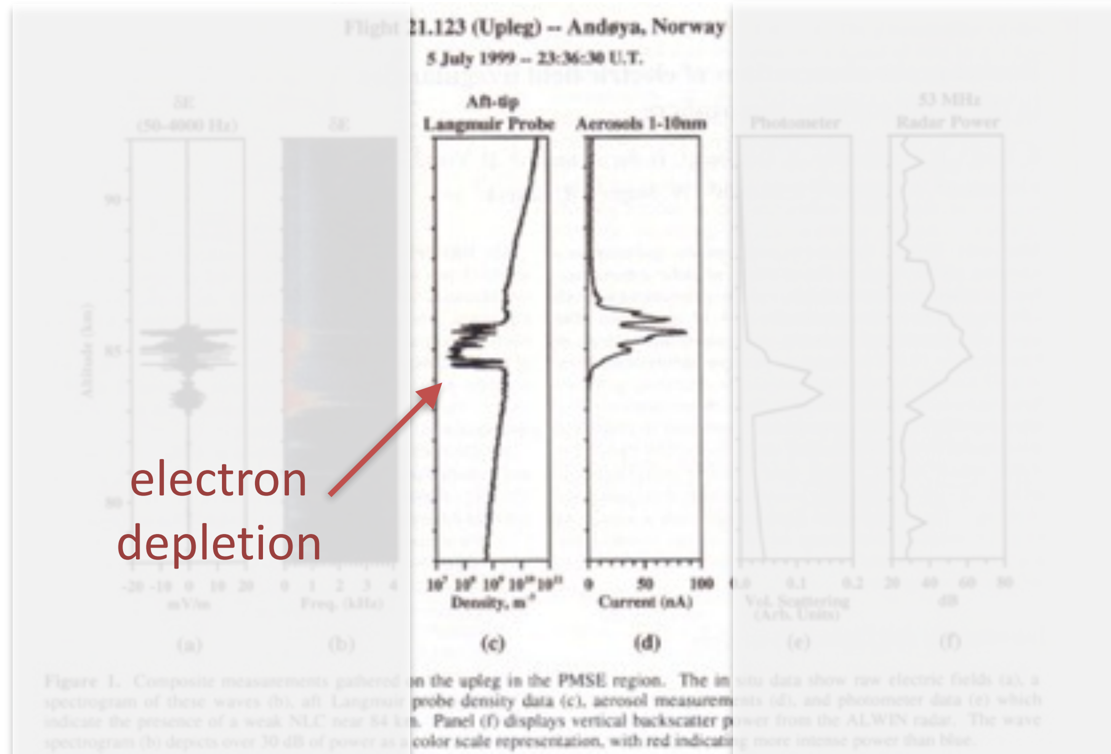
Dusty plasmas in terrestrial environments

- Noctilucent clouds (NLC’s) form at extremely high altitudes, about 85 km, that “shine at night”.
- They form in the cold, summer polar mesopause and are believed to be charged ice crystals.
- They are believed to be associated with radar backscatter phenomena (PSME’s) observed during the northern summers.

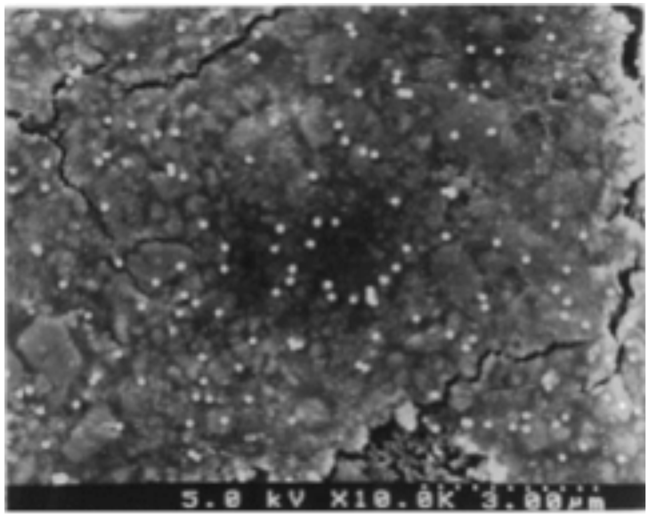


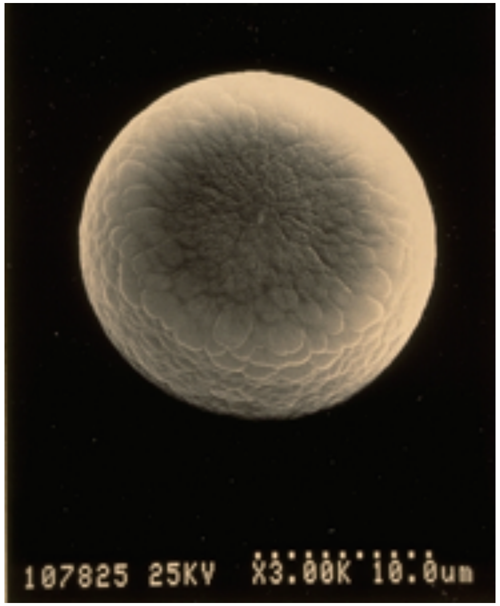
From: http://lasp.colorado.edu/noctilucent_clouds/

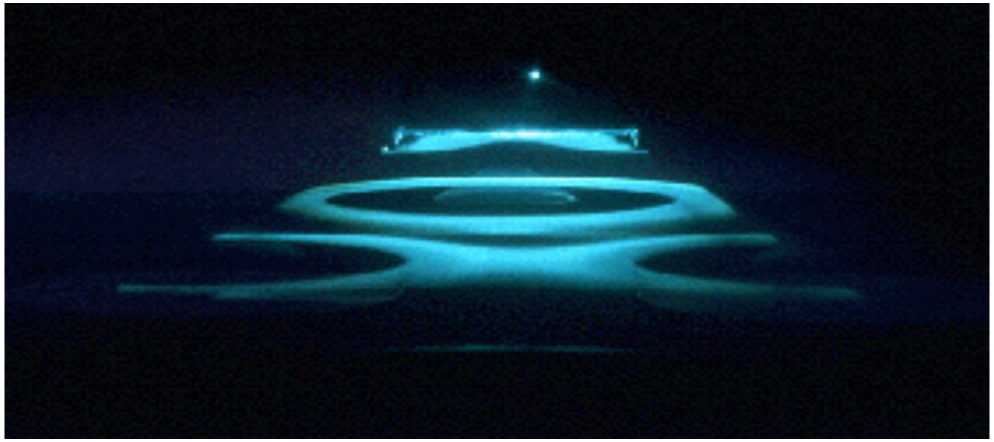
Dusty plasmas in industrial applications

Dust contamination:

- During the 1990s research was driven by the formation of microparticles in plasma processing reactors.
- Here, microparticles up to several microns in diameter can be grown in the plasma.
- "Killer" particle size has diameter, $d \leq 20$ nm.





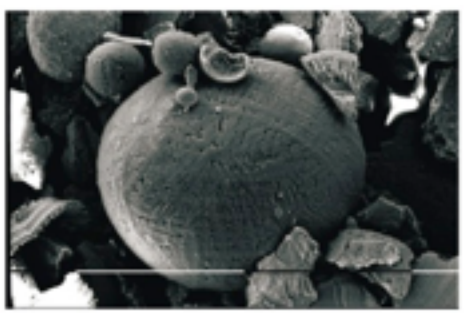


From: http://fjwsys.lanl.gov/bpw/contamination.html - G. Selwyn, LANL

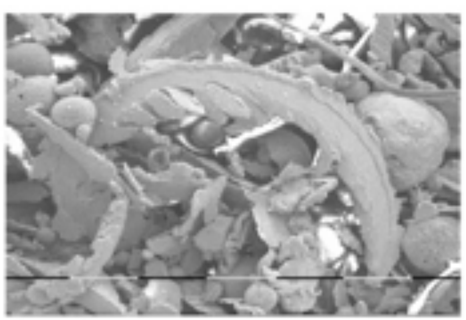
Dust in fusion devices

- Microparticles (d ~ 10 nm) entering the main plasma of a toroidal device can degrade plasma performance and possibly induce disruptions.

- Photographs show micron-sized dust particles formed in TEXTOR-94.



0.1 mm

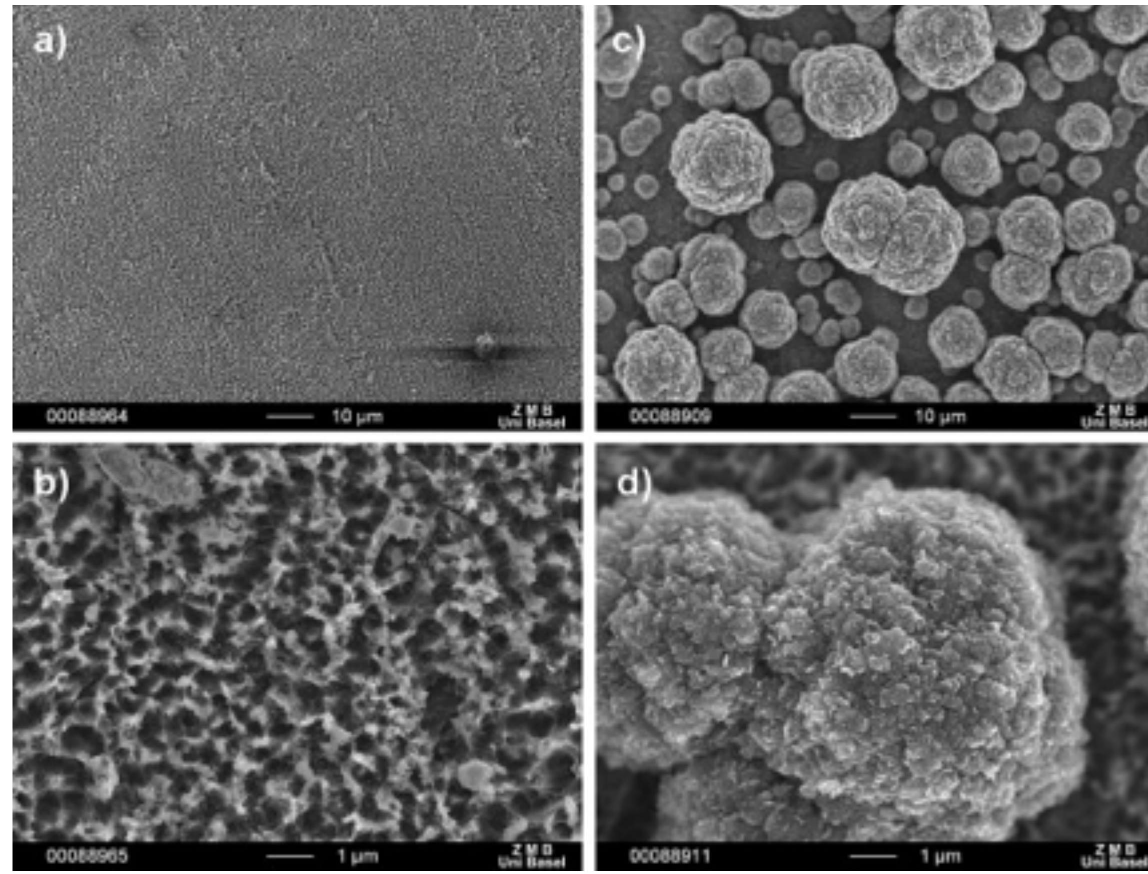


0.1 mm

J. Winter, PPCF, **40**, 1201 (1998)
S. I. Krasheninnikov, et al., PPCF, **53**, 083001 (2011)

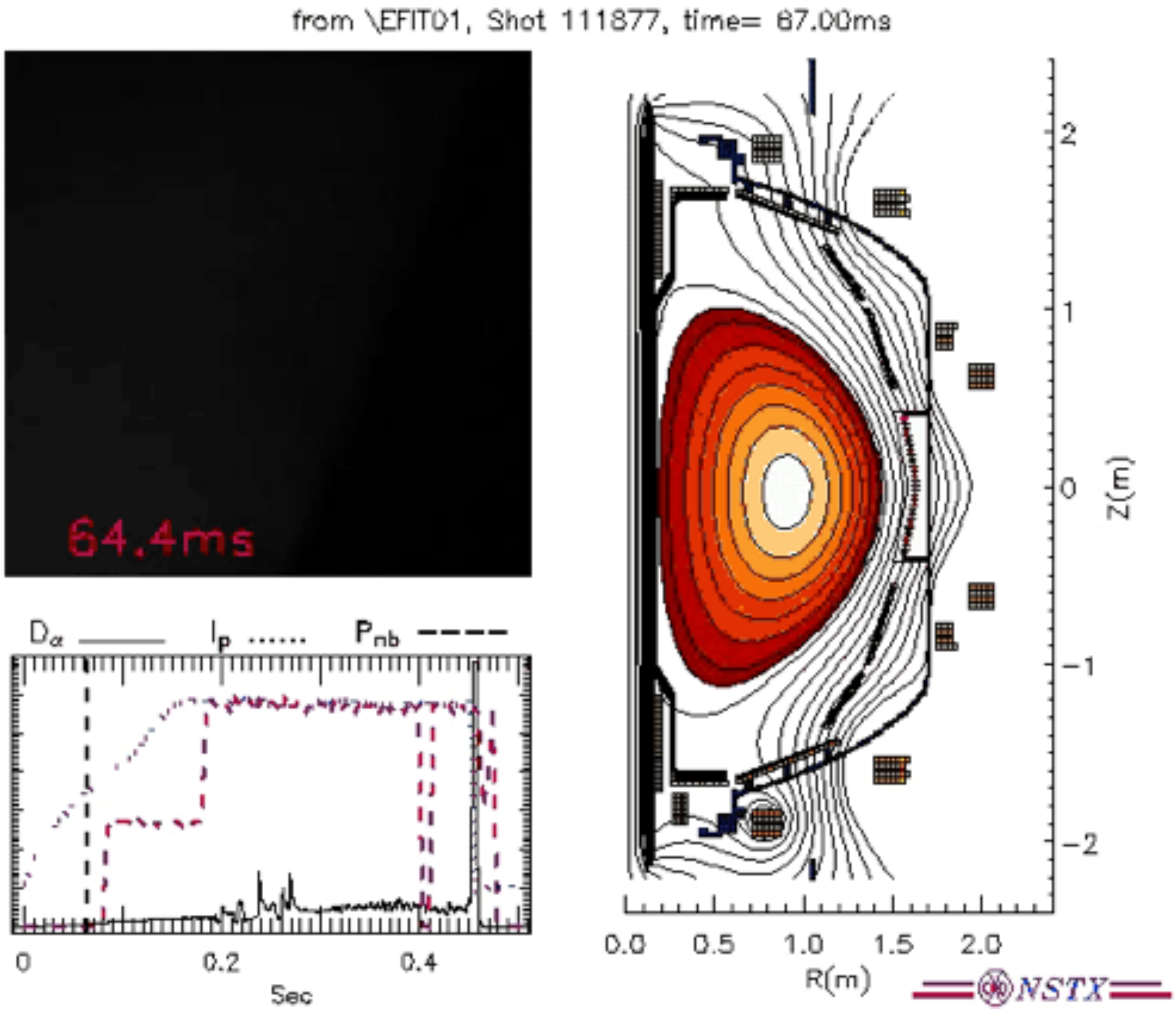
Modification of carbon surface by hydrogen plasma

Before *After*



From: Dutch Institute for Fundamental Energy Research (www.differ.nl/node/2921)
Ref: K. Bystrov, et al., J. Nucl. Materials, 415, S149 (2011)

Dust in fusion devices

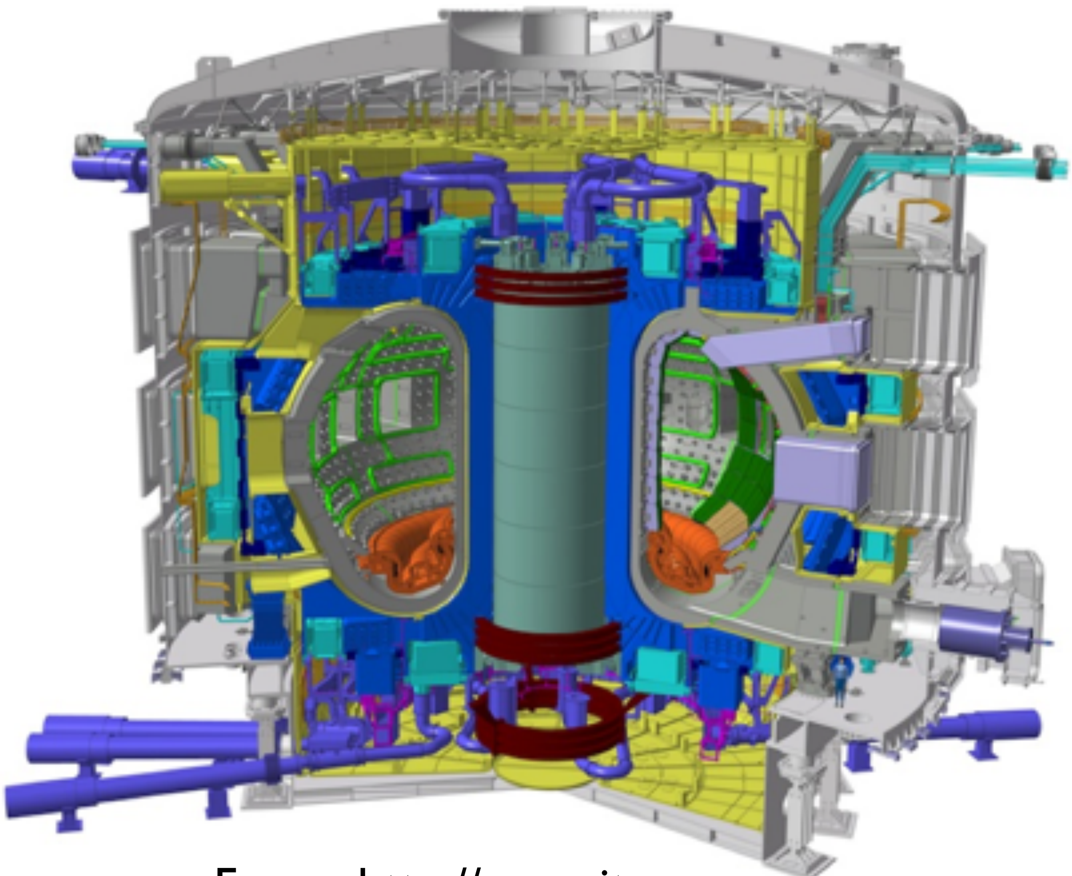


- Dust in fusion plasmas was often not considered a major issue.

- Recent studies do indicate that uncontrolled dust injection can have detrimental impacts on fusion plasmas.

• Dust production of up to several kg's / day could occur in a large scale, ITER-like fusion device.

Dust contamination in ITER

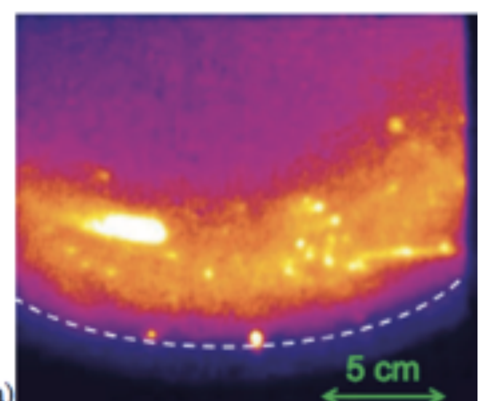


From: http://www.iter.org

There are a number of operational and safety issues associated with the formation of dust in ITER.

- Tritium retention in "dust"
- Reduction of density control
- Degradation of first wall material
- Radiated power losses
- Health and safety hazards
  - fire hazard
  - radiation safety limits
  - safe removal

(a)



Dust trajectories in TJ-II stellarator
E. de la Cal, et al., PPCF, 55, 065001 (2013)

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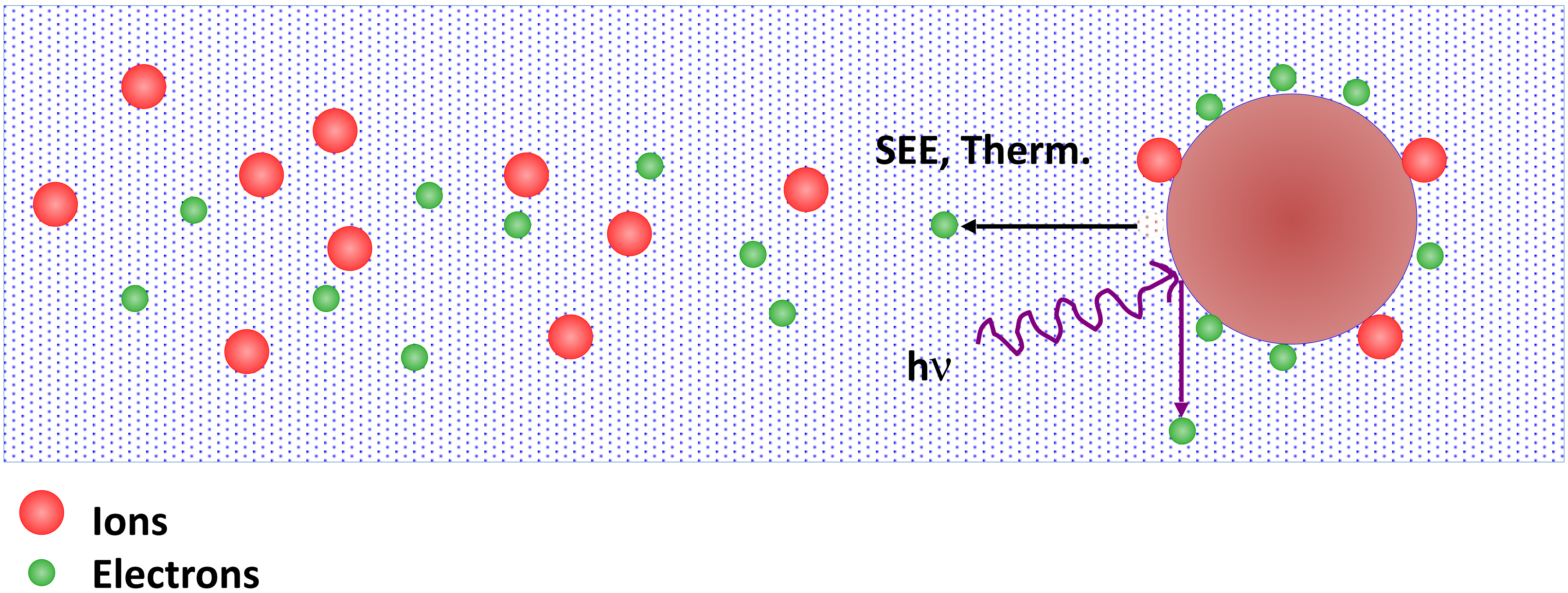
FUNDAMENTAL PROPERTIES

Fundamental properties of dusty plasmas

- Charge
- Basic parameters
- Forces

Fundamental Parameters (I) – Dust grain charge is a dynamic variable



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

Estimating dust grain charge (1)

- For laboratory studies, ions and electrons are the dominant charging mechanisms.
- We assume dust behaves as an electrically floating probe and estimate the flux to the grain surface using orbit motion limited (OML) theory.

$$I_e = 4\pi a^2 \left(\frac{en_e}{4}\right)\left(\frac{8kT_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eU}{kT_e}\right)$$ **electron**

a – grain radius
T_s – temperature
k – Boltzmann's constant
U – grain surface potential

$$I_i = 4\pi a^2 \left(\frac{en_i}{4}\right)\left(\frac{8kT_i}{\pi m_i}\right)^{1/2} \left(1 - \frac{eU}{kT_i}\right)$$ **ion**

Estimating dust grain charge (2)

- Assume grains are conducting.
- Assume grains are spherical capacitors: $Q_d = \pm eZ_d = 4\pi\varepsilon_0 aU$
- Assume quasineutrality: $en_i = en_e + Q_d n_d$
- Solve the balance equation: $I_e + I_i = 0$

$$\left(1+\frac{Q_d n_d}{en_0}\right)\left(\frac{m_i T_e}{m_e T_i}\right)^{1/2}\exp\left(\frac{eU}{kT_e}\right)=1-\left(\frac{eU}{kT_i}\right)$$

- Solve numerically for the grain potential U to get the charge, Q_d.

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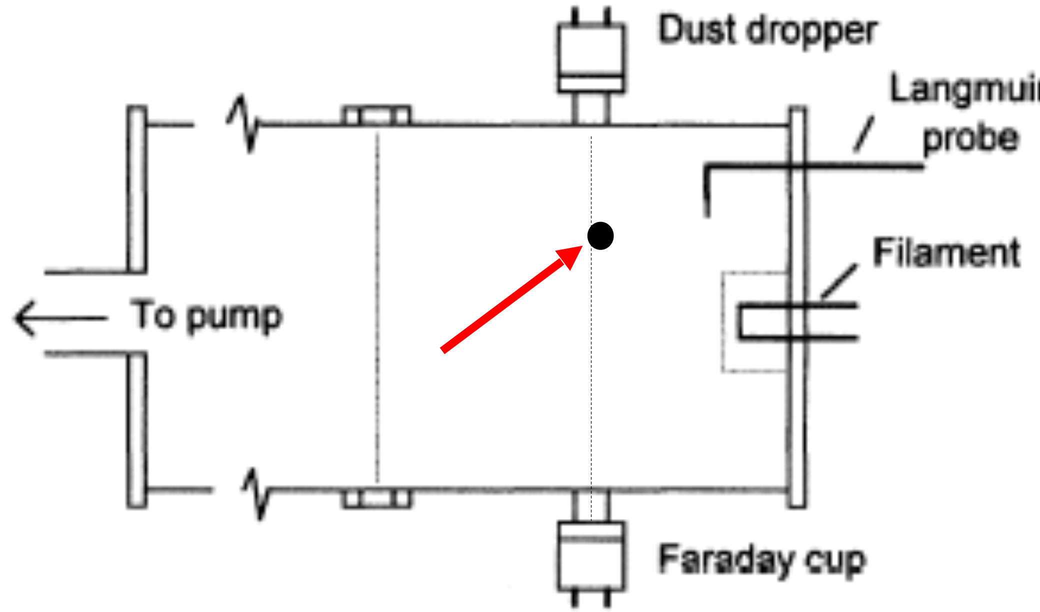
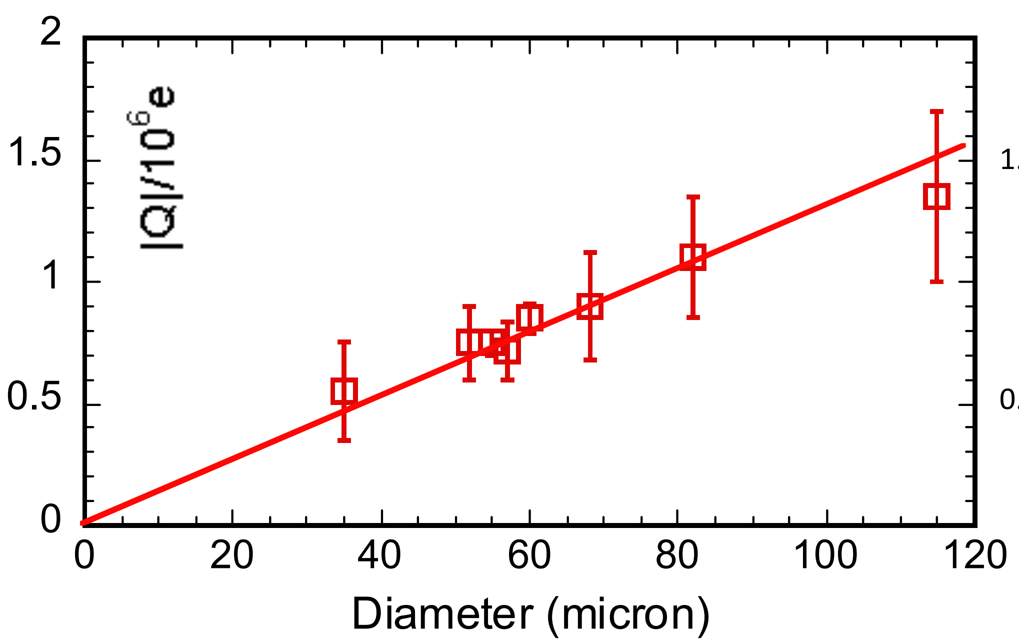
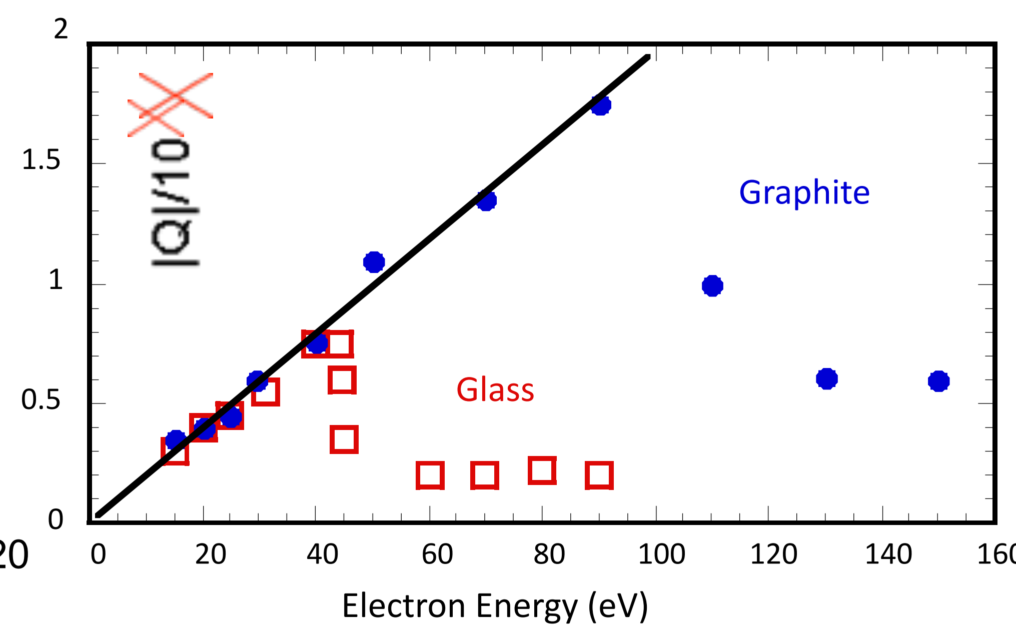
Charging experiments (1)

- Individual grains are dropped through a hot filament plasma.
- Grains are captured in a Faraday cup.







Walch, et al., Phys. Rev. Lett. 75, 838 (1995)

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Charging experiments (2)

Barkan experiment uses a Q-machine to generate the plasma
-> Here, $T_i \approx T_e \sim 0.2$ eV

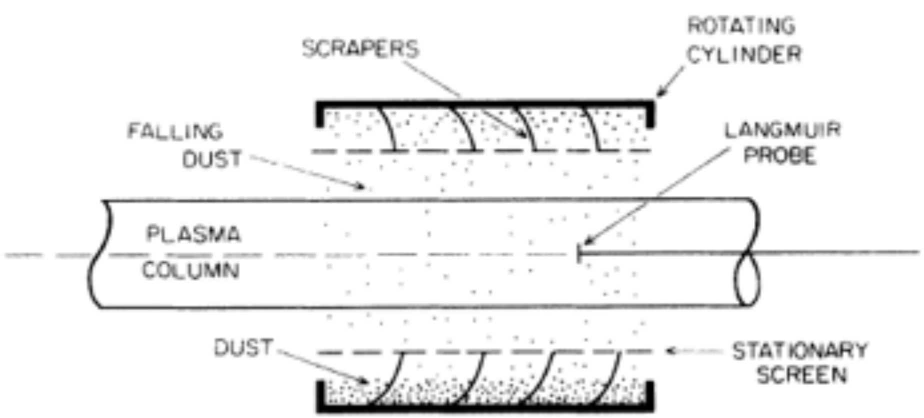


FIG. 2. Schematic diagram of the device used to disperse dust into the plasma column.

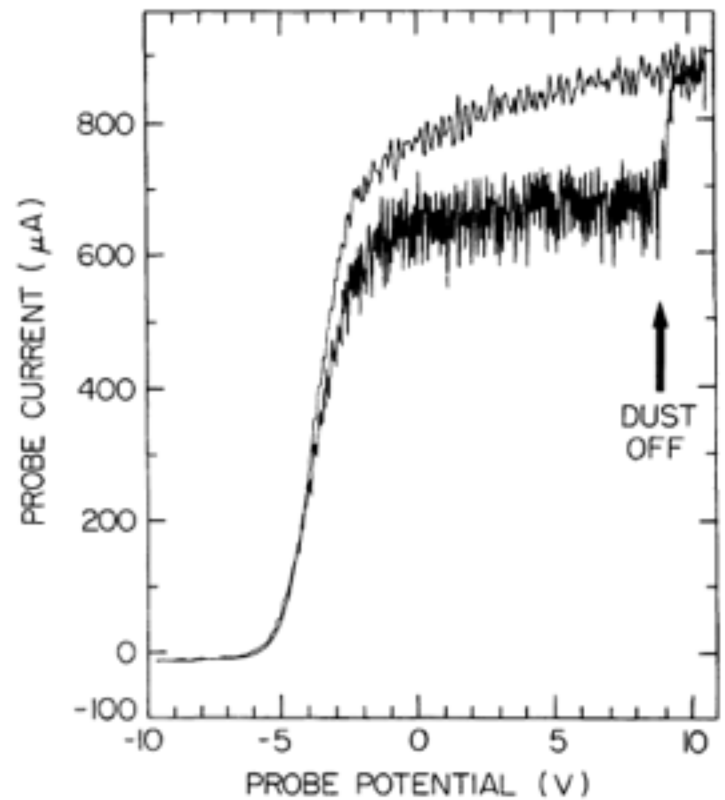
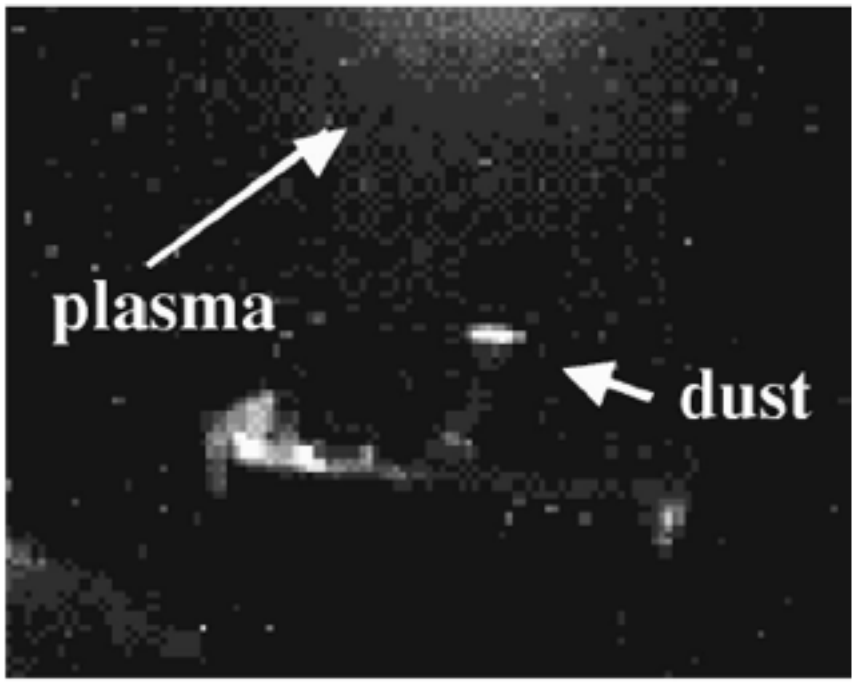


FIG. 3. Langmuir probe characteristics obtained under identical conditions, except for the absence (upper plot) or presence (lower plot) of kaolin dust. In the lower characteristic, the dust dispenser is abruptly turned off near the end of the trace to check that the electron current returns to the no-dust value.

A. Barkan, et. al., Phys. Rev. Lett., **73**, 3093 (1994)

Charging experiments (3)

Grain charging in a dc glow discharge plasma
-> Here, $T_i << T_e$



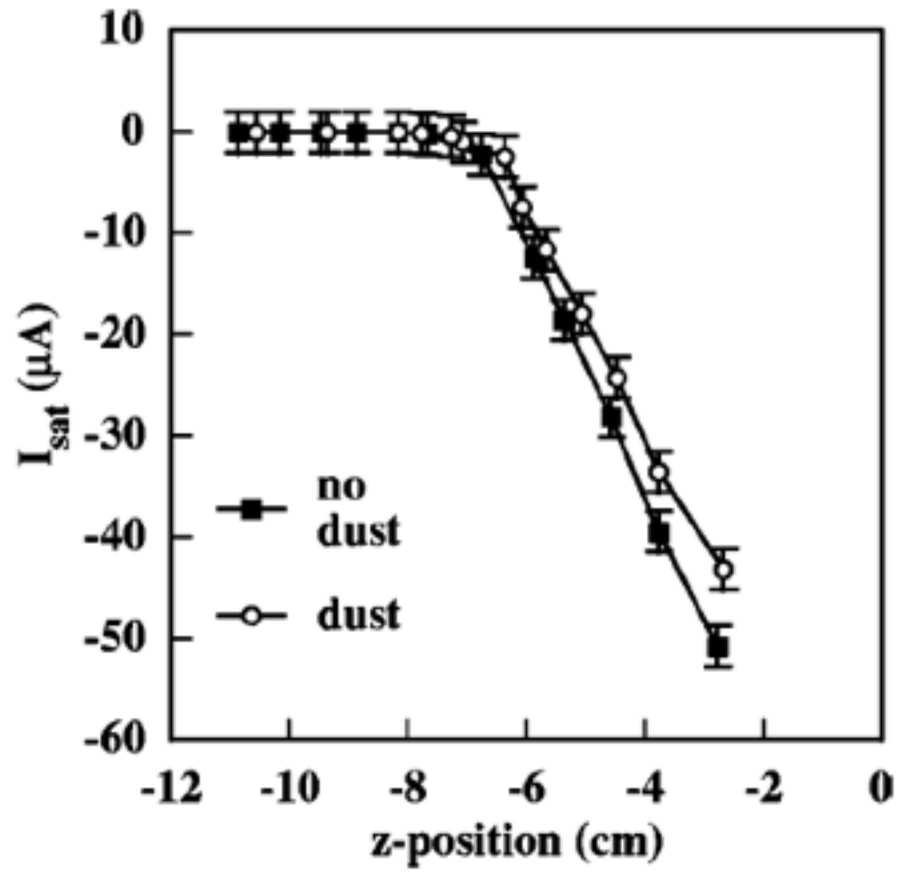


FIG. 3. Electron saturation current measurement as a function of axial position in the FPS device. The open circles indicate measurements of the electron saturation current in the absence of the silica dust and the closed squares indicate measurements of the electron saturation current in the presence of the silica dust particles.

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E. Thomas and M. Watson, Phys. Plasmas, **7**, 3194 (2002)

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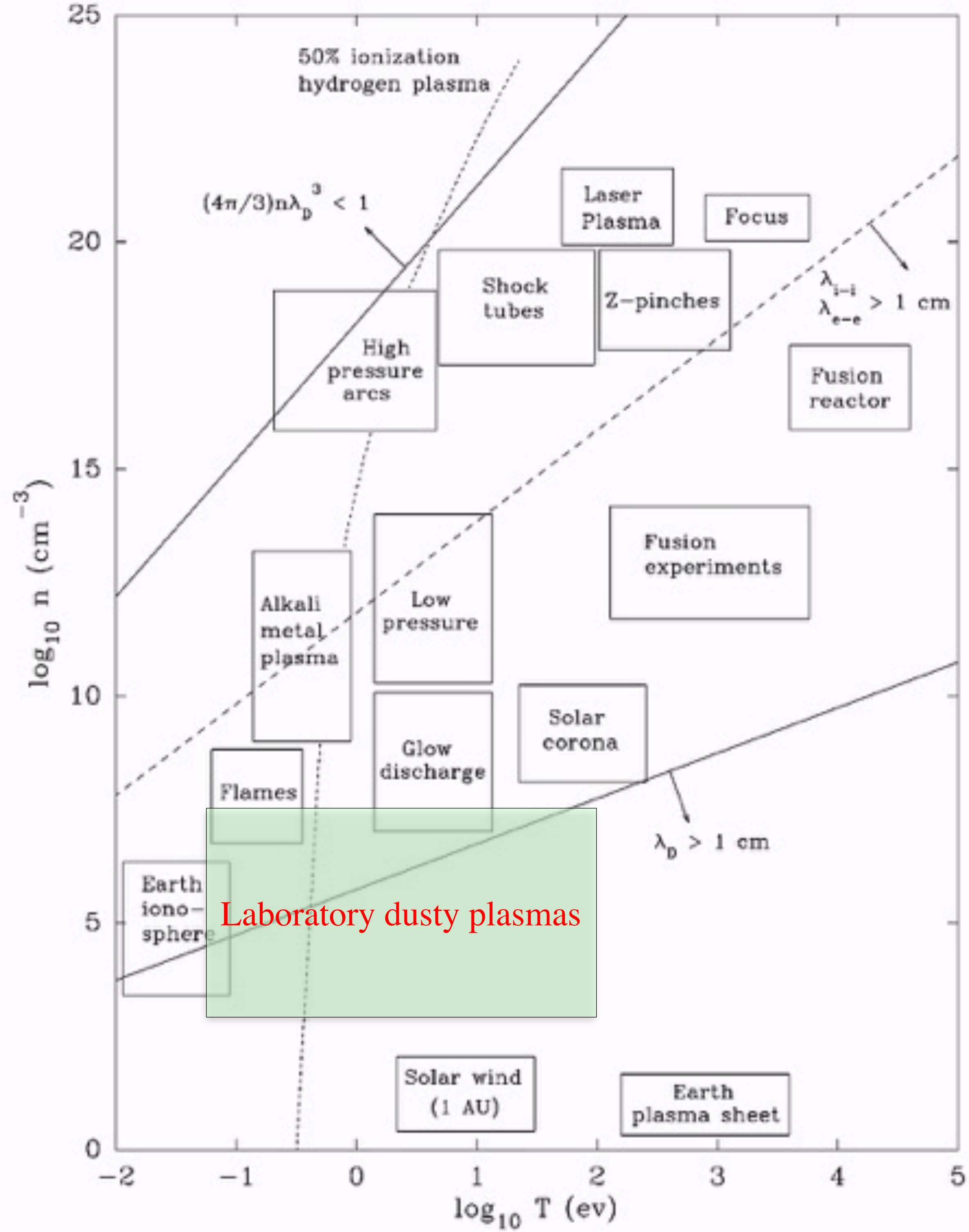
Fundamental properties of dusty plasmas

- Charge
- Basic parameters
- Forces

What are the parameters of a dusty plasma?



Fundamental Parameters (2): The basic equations

- Objective: To define the relevant temporal and spatial scales for a dusty plasma
- Use continuity and momentum equations
  - Assume no zero-order gradients or flows
  - Assume only electrostatic oscillations
  - Close the set using Poisson's equation

Parameters:
s – ion, elec, dust
a – dust radius
q_s – charge; $q_d = -Z_d e$
n_s – density
m_s – mass
v_s – velocity
ϕ - potential

- Continuity: $$\frac{\partial n_s}{\partial t} + \nabla \bullet \left(n_s \vec{v}_s\right) = 0$$
- Momentum: $$\frac{\partial \vec{v}_s}{\partial t} + \left(\vec{v}_s \bullet \nabla\right)\vec{v}_s = -\frac{q_s}{m_s}\nabla\phi$$
- Poisson's: $$\nabla^2\phi = -\frac{1}{\varepsilon_0}\sum q_s n_s$$

Fundamental Parameters (3): Large mass extends the time scales

- Linearize the equations using: $a = a_0 + a_1 \exp[i(kx-\omega t)]$

- Derive a result that gives the time scales of plasma oscillations:

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

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

- 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

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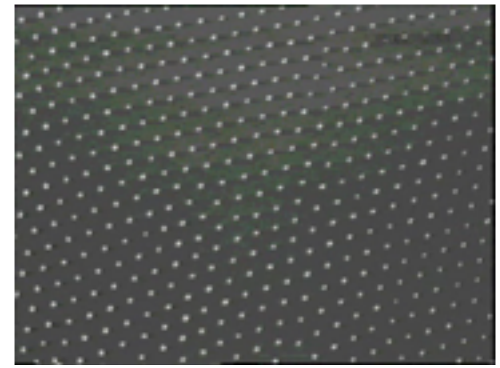
Fundamental Parameters (4) – Coupling parameter is a measure of self-organization

- 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):

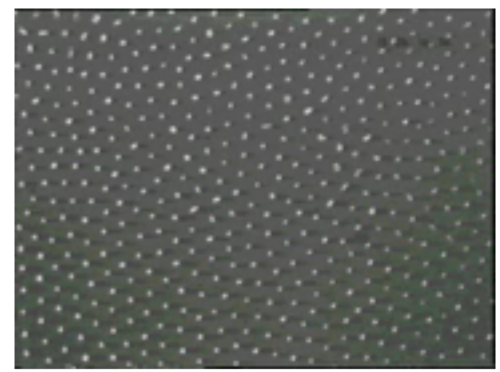
$$\varphi \sim \frac{\exp\left(-r / \lambda_D\right)}{r}$$

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

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



$\Gamma >> 1$
"solid"



$\Gamma \sim 1$
"liquid"

$\Gamma < 1$
"gas"

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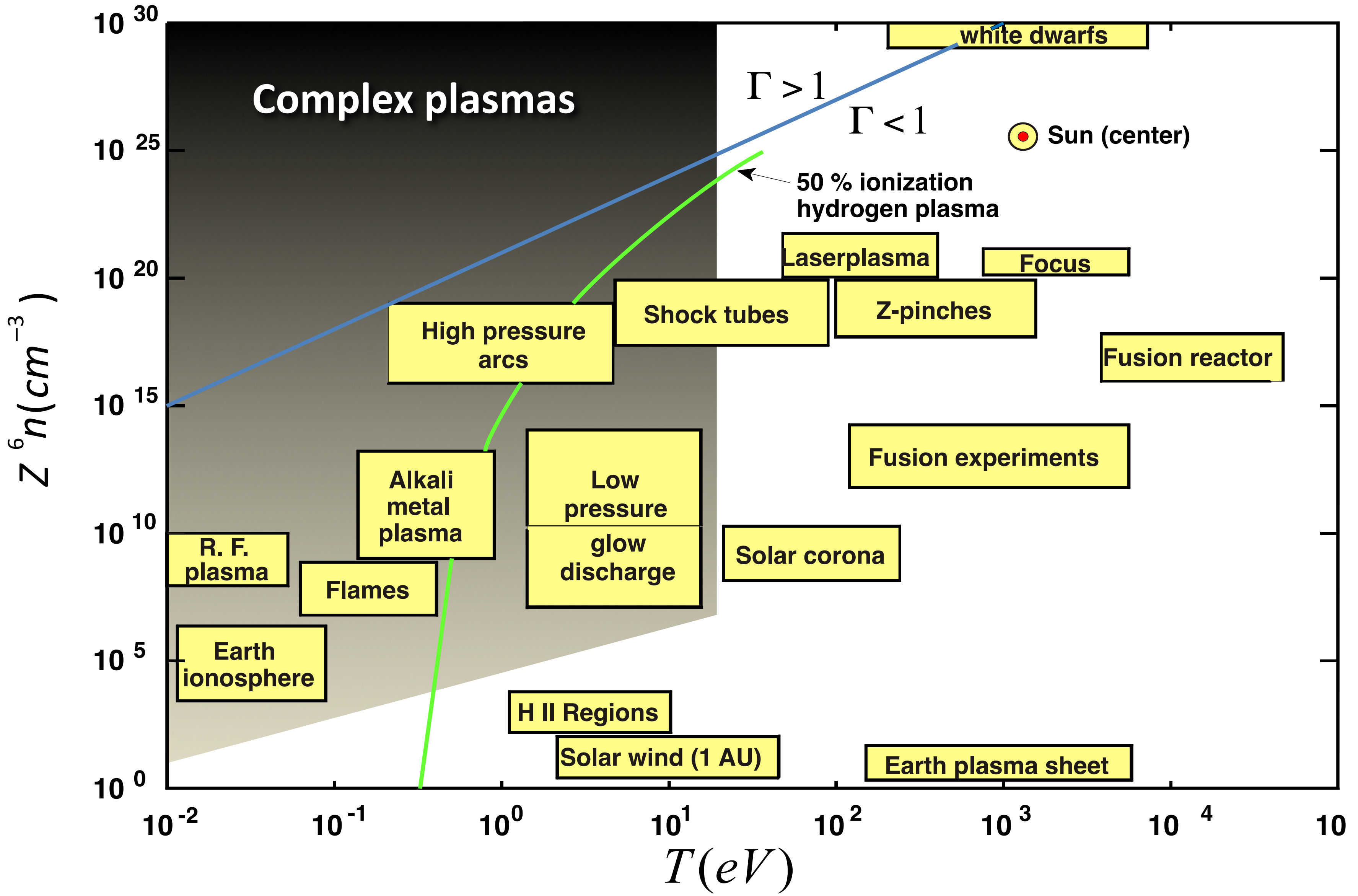
Redefining the parameters of a dusty plasma

$$\Gamma \equiv \frac{(Ze)^2}{kT} n^{1/3}$$



G. Morfill, et al., PoP, **6**, 1769 (1999).

Fundamental properties of dusty plasmas

- Charge
- Basic parameters
- Forces

Summary of dominant forces in dusty plasmas

Force	Origin	Size dependence
Weight	Gravity	a^3
Neutral drag	Streaming neutrals	a^2
Ion drag	Streaming ions	a^2
Thermophoretic	Temperature gradient	a^2
Electric	Electric field	a^1
Magnetic	Magnetic field	a^1

These forces give rise to the majority of the phenomena observed in laboratory and microgravity dusty plasma experiments

a = dust grain radius

Adapted from textbook *Plasma Physics* by A. Piel, Table 10.2 (Springer-Verlag, 2010)

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Gravitational force

- Relevant for dusty / complex plasmas since the particles need to be suspended in the plasma.
- $\vec{F}_{\mathrm{g}} = m_{\mathrm{d}}\vec{g} = \frac{4}{3}\pi a^3 \rho_{\mathrm{d}}\vec{g}$
- Gravitational force can also play an important role in astrophysical environments (e.g., Saturn's rings).

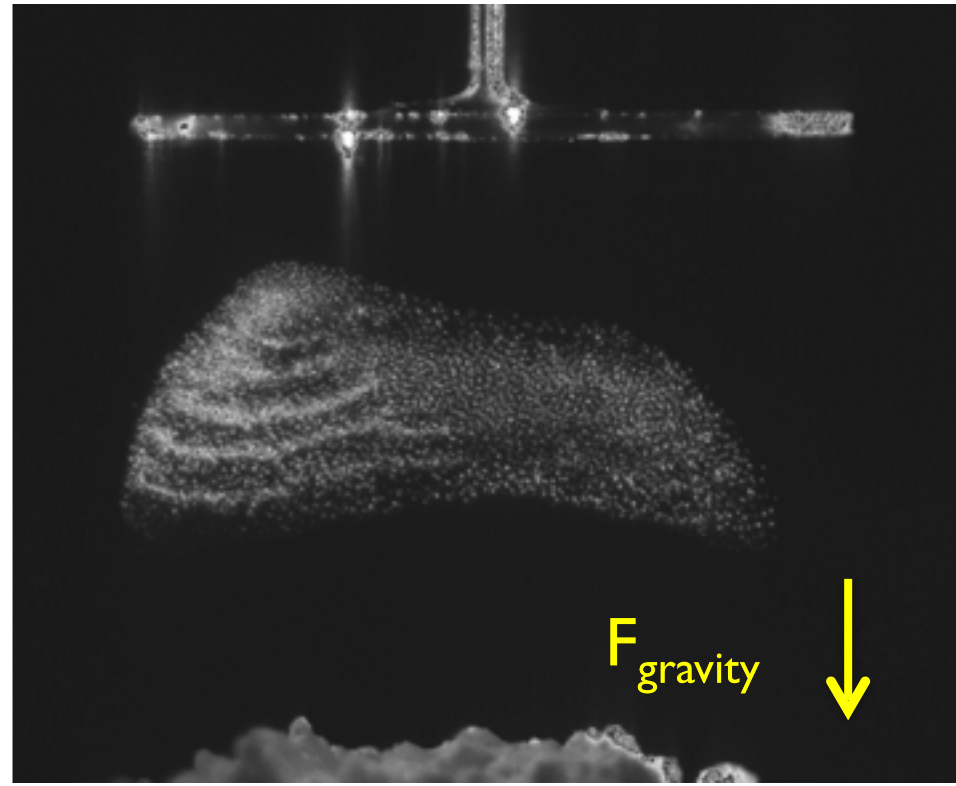


Image from Auburn University

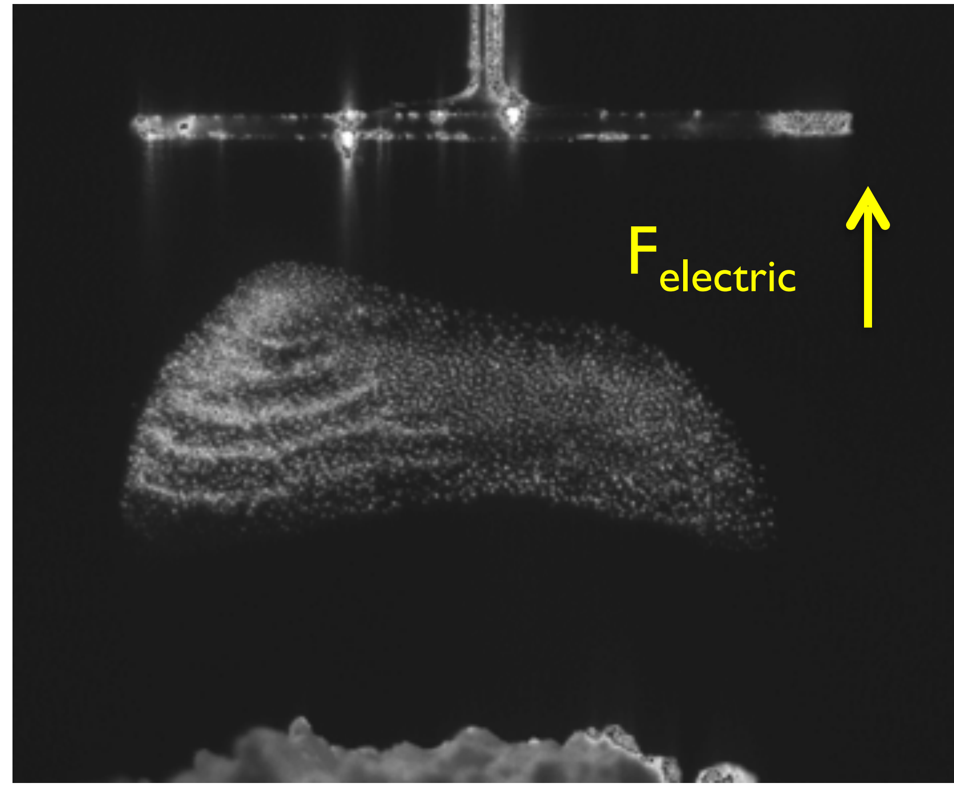
Electric force

- Because the dust grains are charged, they respond to the internal electric fields within the plasma.

- $\vec{F}_{\mathrm{E}} = Q_{\mathrm{d}}\vec{E} = 4\pi\epsilon_0 a \phi_{\mathrm{fl}}\vec{E}$

- Ion flows can cause the shielding cloud around dust grains to become distorted, leading to a dipole-like charge distributions.

- $\vec{F}_{\mathrm{dip}} = \vec{\nabla}(\vec{p}\cdot\vec{E})$



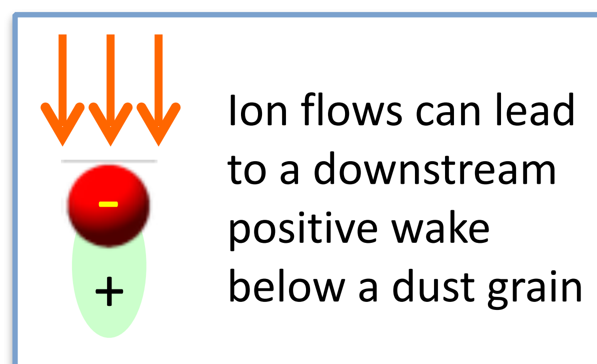


Image from Auburn University

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Balancing gravitational and electric forces: A zero-order equilibrium in laboratory dusty plasmas

- For most ground-based experiments: $F_{gravity} \sim F_{electric}$
- Defines zero-order equilibrium
- Typical values:
  - ➡ a = 1.5 μm
  - ➡ $m_d = 2.8 \times 10^{-14}$ kg
  - ➡ Z_d = 4600 electrons
  - ➡ **E = 3.8 V/cm**

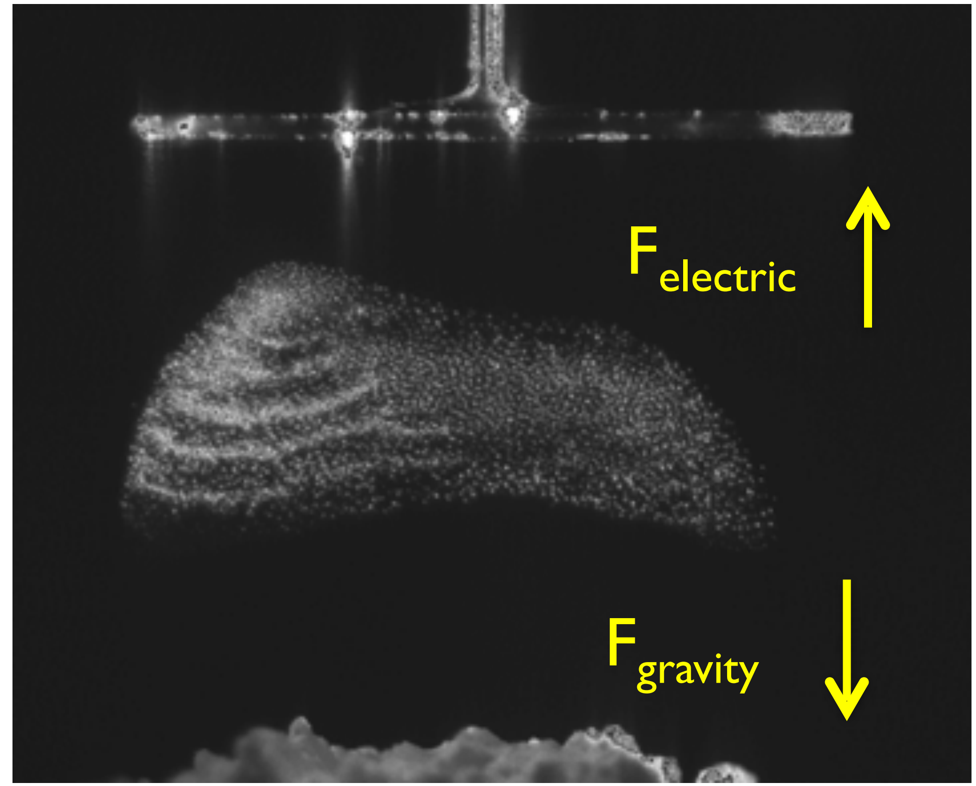
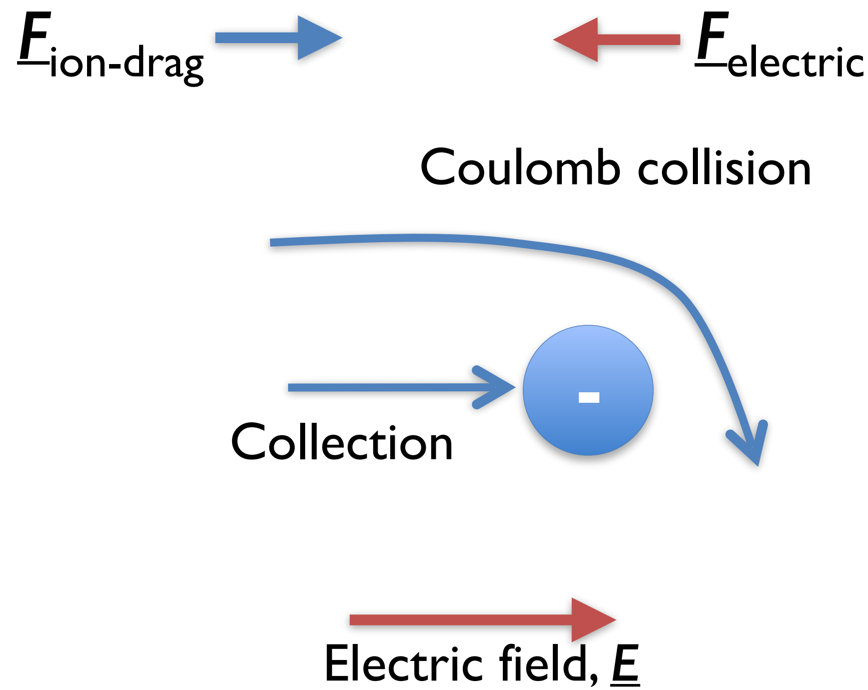


Image from Auburn University

Ion drag force - origin

- Positive ions can flow in a plasma in the direction of the electric field.
- Arises from the momentum transfer from ion-dust interactions: the collection of ions and Coulomb collisions.
- $F_{ion\text{-}drag} = F_{collection} + F_{collision}$
- Critically depends upon the screening length of the dust particle.



Refs: M. Barnes, et al., PRL, **68**, 313 (1992)
S. Khrapak, et al., PRE, **66**, 046414 (2002)
A. Ivlev, et al., PRE, **71**, 016405 (2004)
I. Hutchinson, et al., PPCF, **48** 185 (2006)
S. Khrapak, et al., IEEE TPS, **37**, 487 (2009)

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Evidence for ion drag force: voids in space

- In rf plasmas in microgravity experiments, a void appears.
- Enhanced ionization at the center: provides a source of ions and outward electric field.
- Boundary determined by the force balance: $F_{elec} = F_{ion\text{-}drag}$

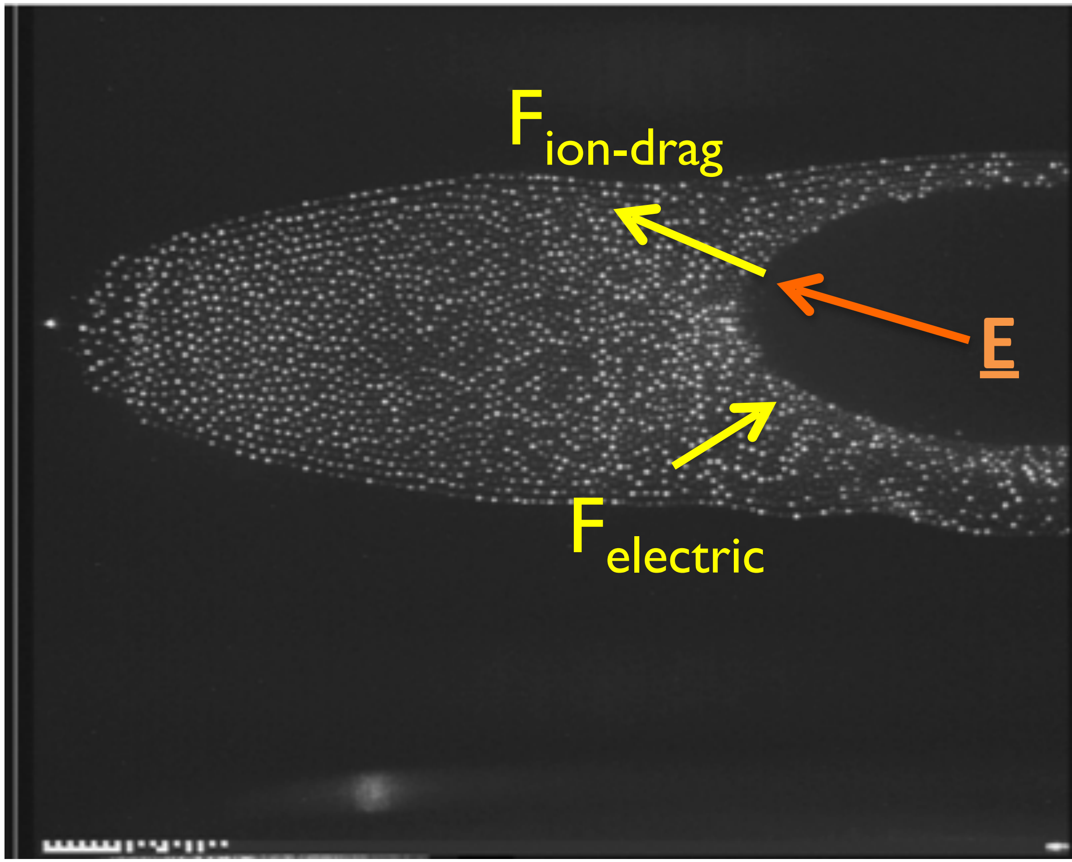
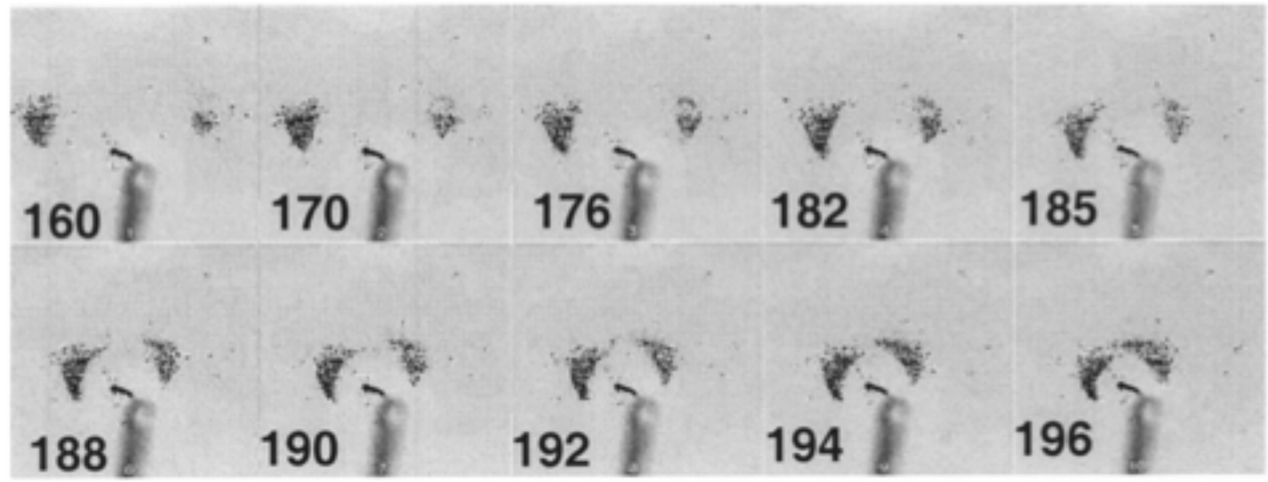


Image from Max Planck Institute, PK-3

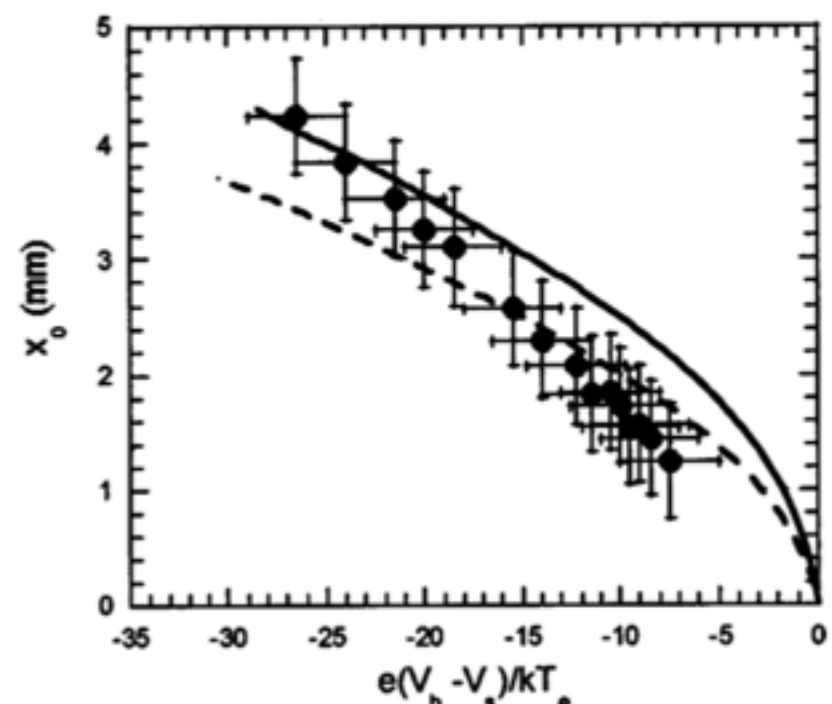
Evidence for ion drag force: voids in the lab

- Control size of the void region using different potentials on a probe tip.



- Estimate the void size, x_0, using different electric field estimates.

  Dashed: 25 V/cm
  Solid: 17 V/cm

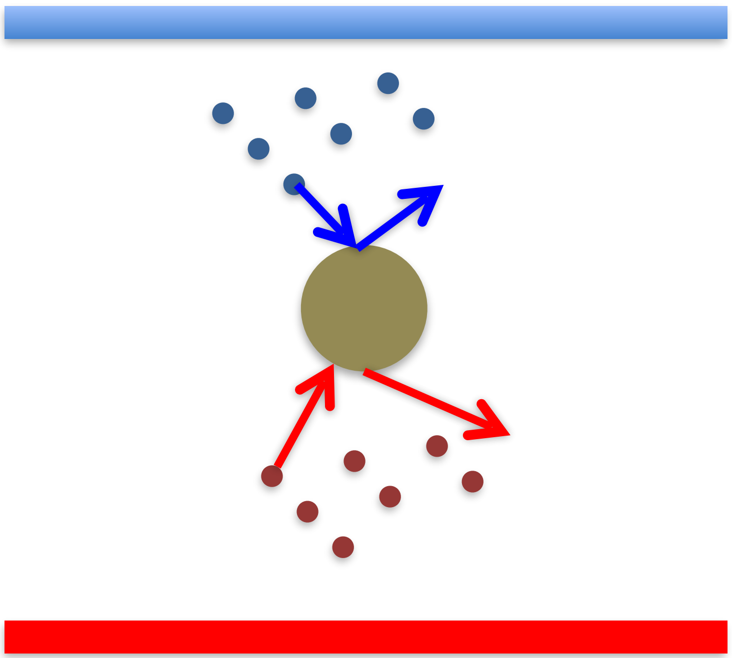


E. Thomas, Jr., et al., PoP, **11**, 1770 (2004)

Thermophoretic force

- Arises from the momentum transfer from neutral-dust interactions.
- Neutral atoms from "hot" side provide more momentum than those from "cold" side.
- $$F_{thermo} = -\frac{8}{3}\frac{a^2}{v_{tn}}\Lambda\frac{dT_n}{dz}$$

v_{tn} – neutral thermal velocity
T_n – neutral gas temperature
Λ – thermal conductivity



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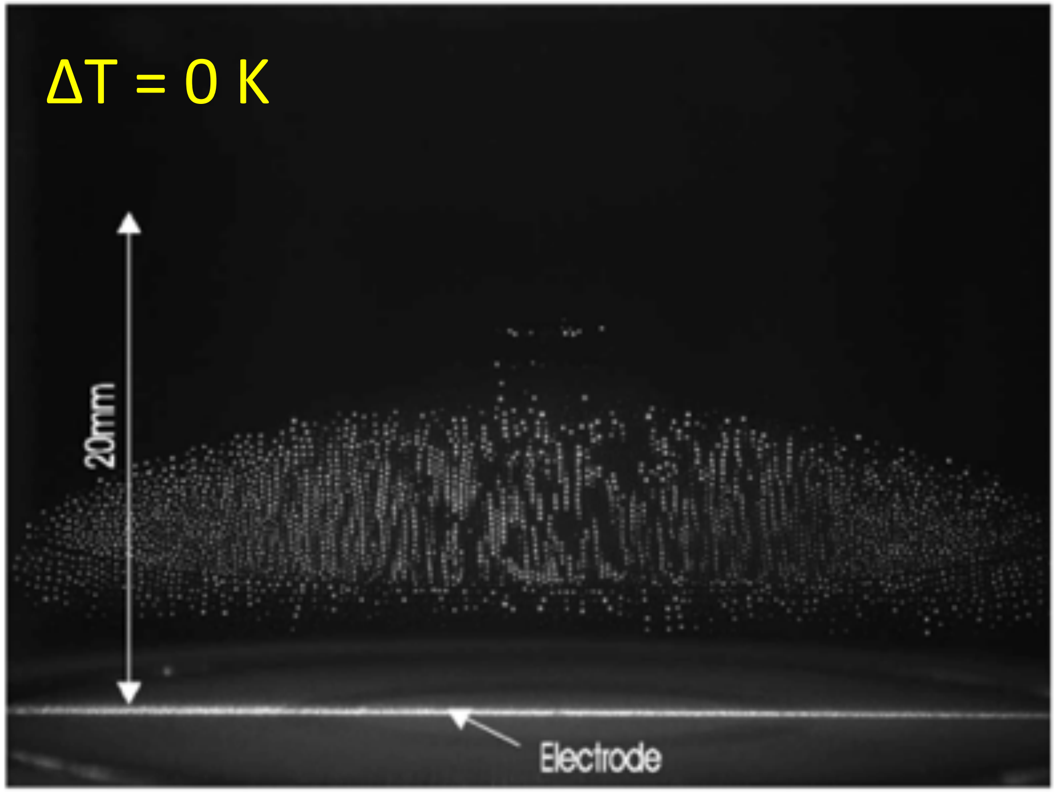
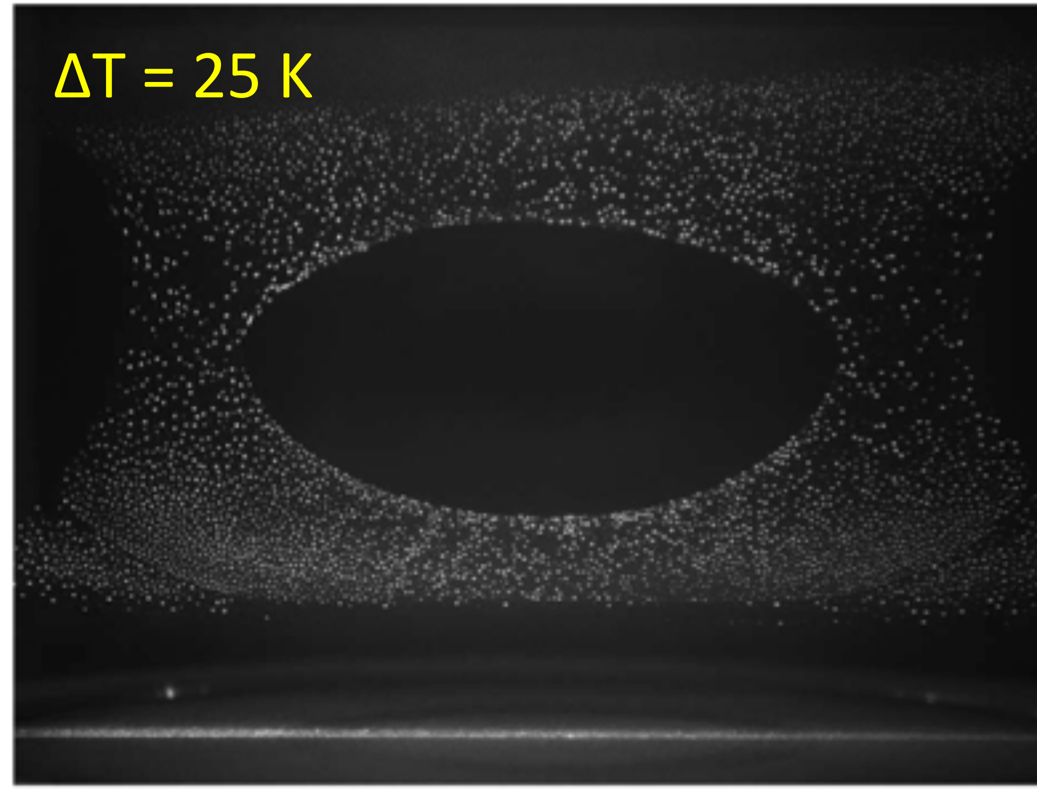
Evidence for thermophoretic force: simulated voids





- Dusty plasma of 3.4 μm melamine formaldehyde particles
- Applied temperature gradient of ~1200 K/m
- ΔT = 25 K over 20 mm
- Lower electrode is heated using a Peltier element

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H. Rothermel, et al., PRL, **89**, 175001 (2002)

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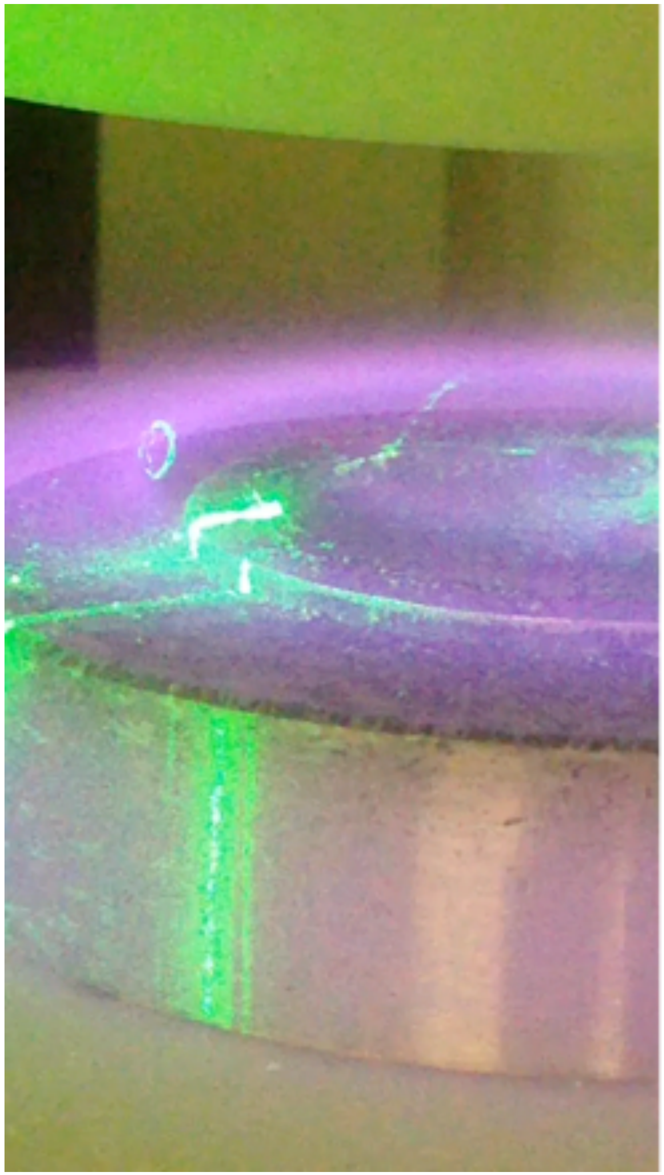
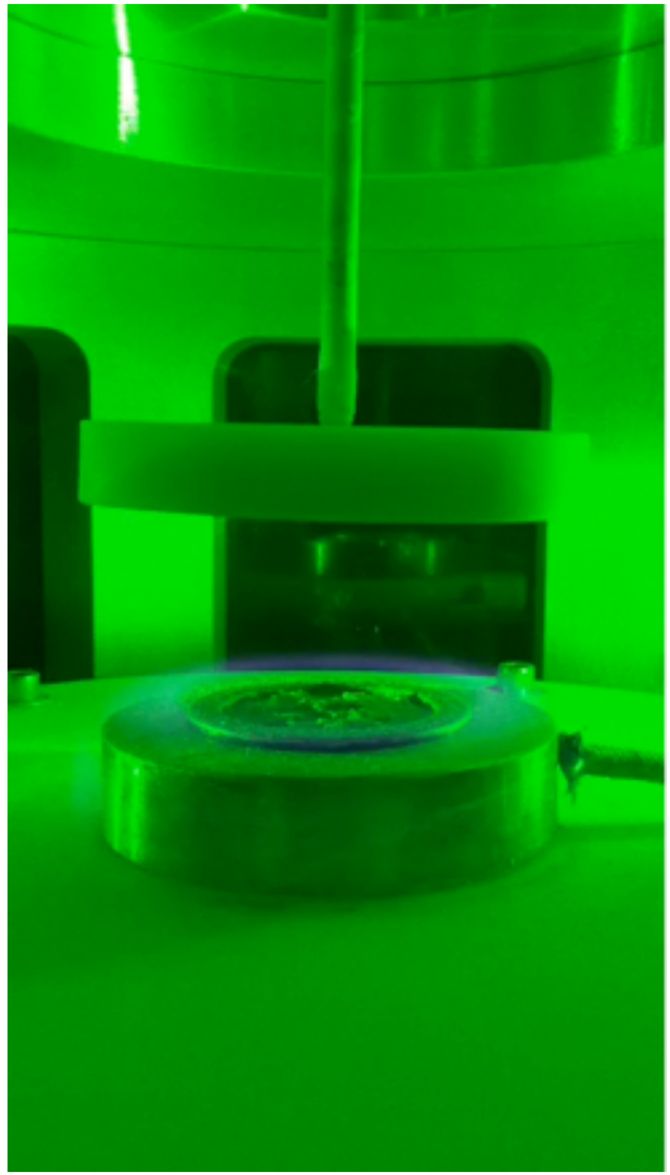
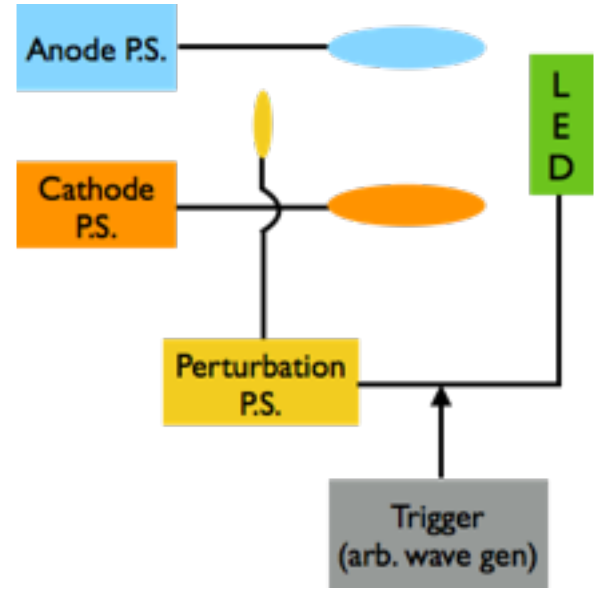
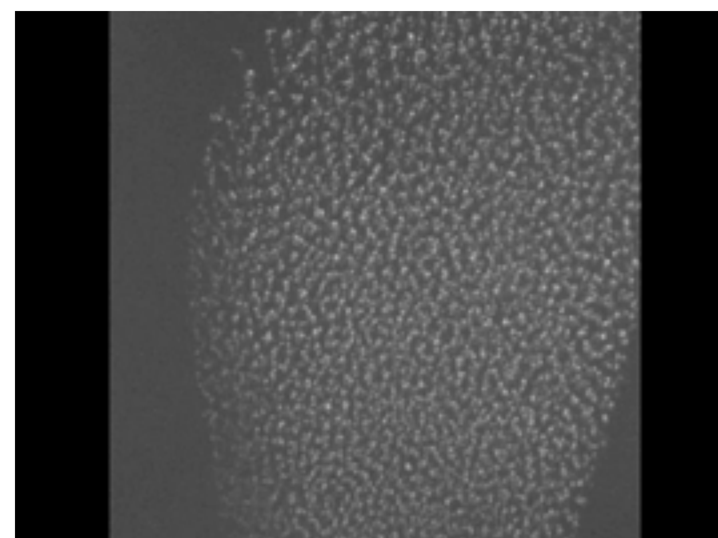
Combinations of these forces give rise to transport phenomena in dusty plasmas



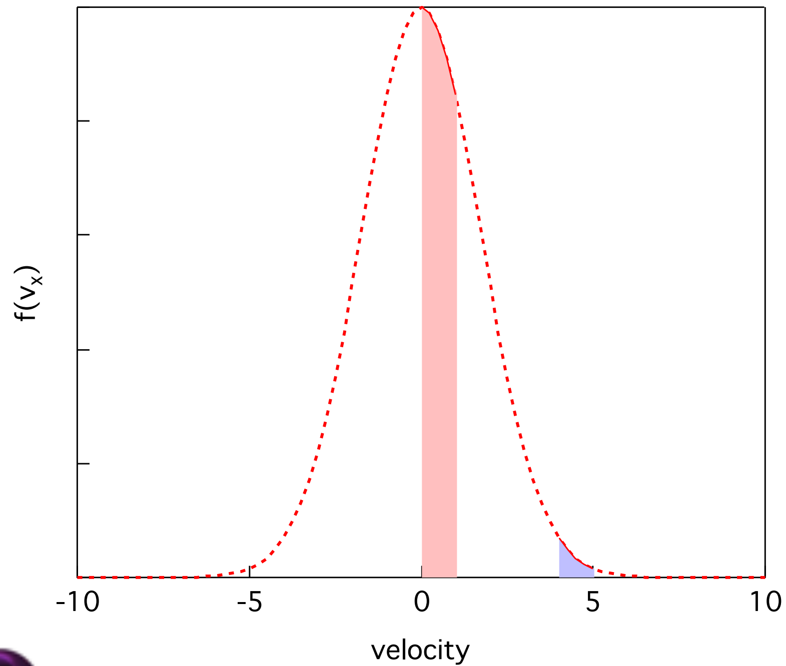






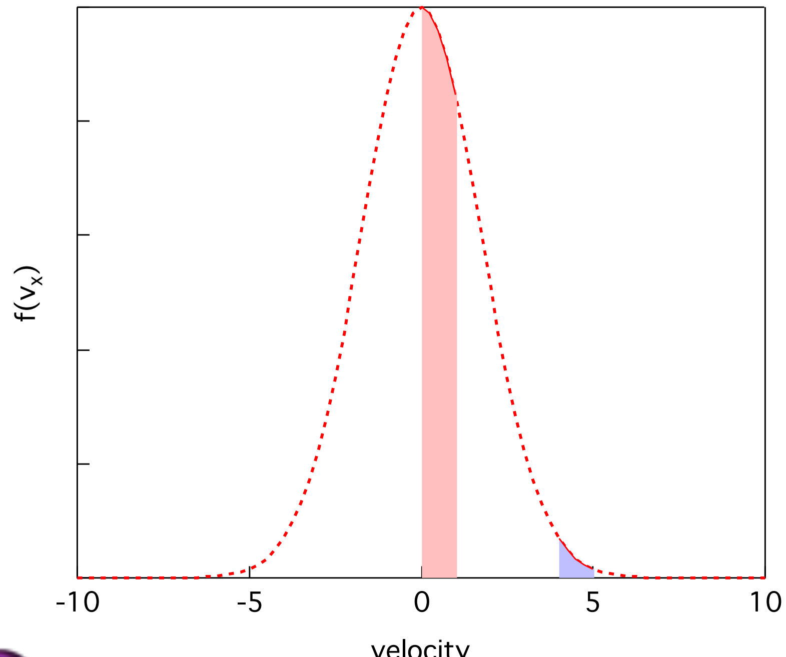
DUSTY PLASMA STUDIES:
STATISTICAL MECHANICS

A distribution function can represent the state of a system as it involves in time and space



- Assume that a measurement can be made of the position and velocity of each atom at time t_0.
- The distribution function represents the probability of finding a particle with position vector ($\underline{r}$) and velocity vector ($\underline{v}$).
- Distribution function: $f(\underline{v}, \underline{r}, t)$

A distribution function can represent the state of a system as it involves in time and space



- Integrating the distribution function (moments) can give macroscopic quantities:
- Number: $n(\vec{r},t) = \int f(\vec{r},\vec{v},t)d^3\vec{v}$
- Momentum: $n\vec{p} = \int m\vec{v}f(\vec{r},\vec{v},t)d^3\vec{v}$
- Kinetic energy: $\frac{1}{2}m\langle\vec{v}^2\rangle = \int \frac{1}{2}m\vec{v}^2 f(\vec{r},\vec{v},t)d^3\vec{v}$
- Time evolution:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + v \bullet \nabla f + \left(\frac{\vec{F}}{m}\right) \bullet \nabla_v f = \left(\frac{\partial f}{\partial t}\right)_{collisions}$$

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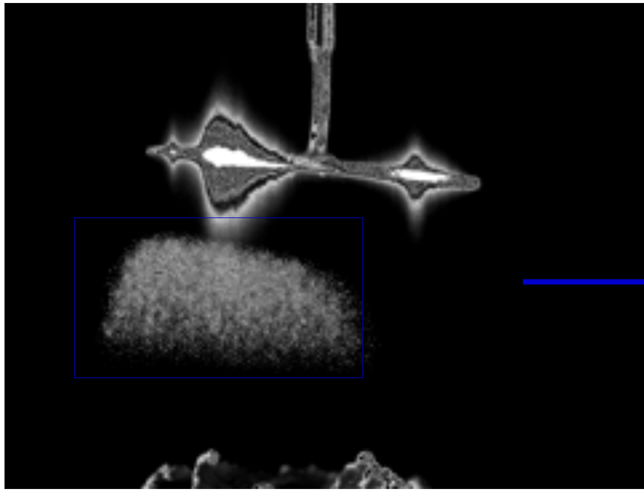
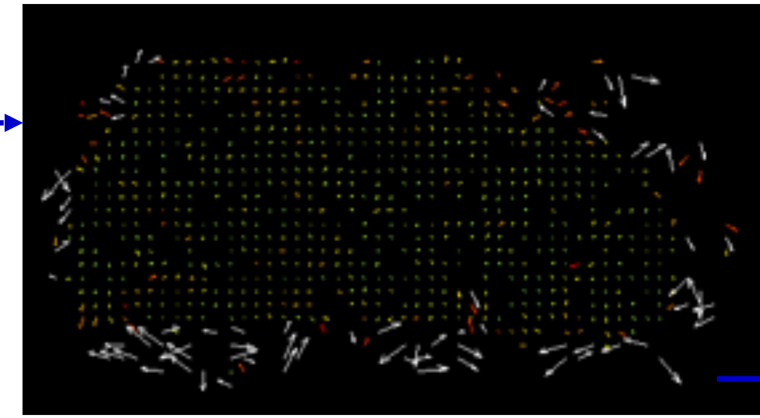
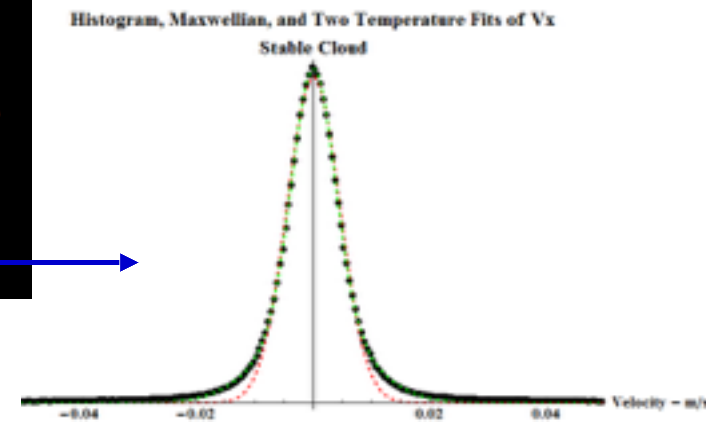
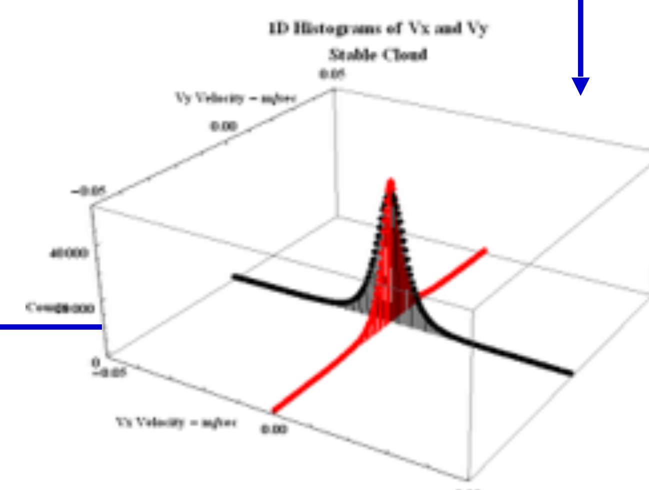
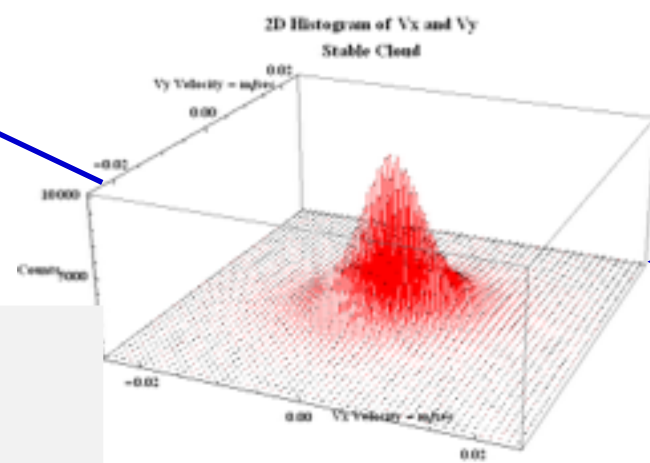
In a dusty plasma it is possible to directly measure the complete distribution function - f(r, v, t)

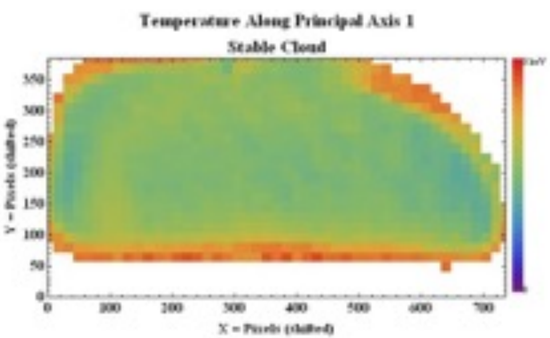












- 1500 velocity measurements
- Construct a velocity distribution
- Assume multi-normal distribution
- Construct covariance tensor

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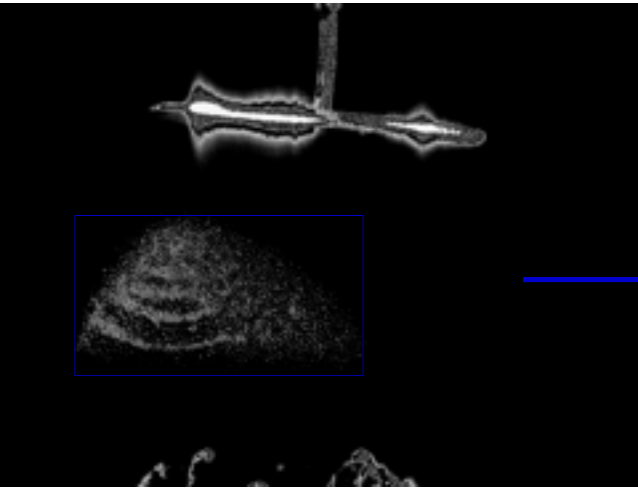
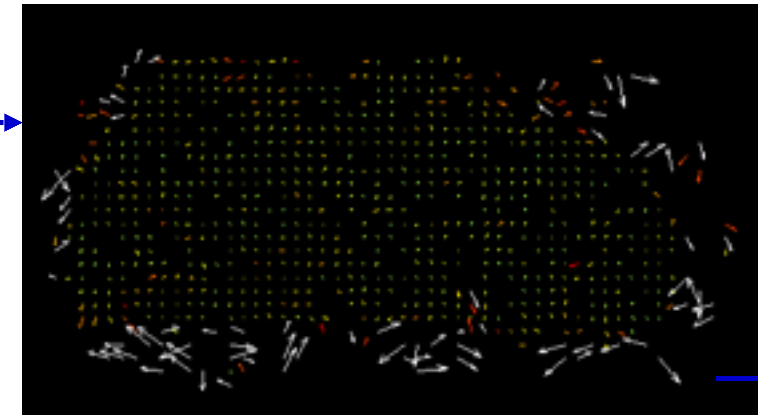
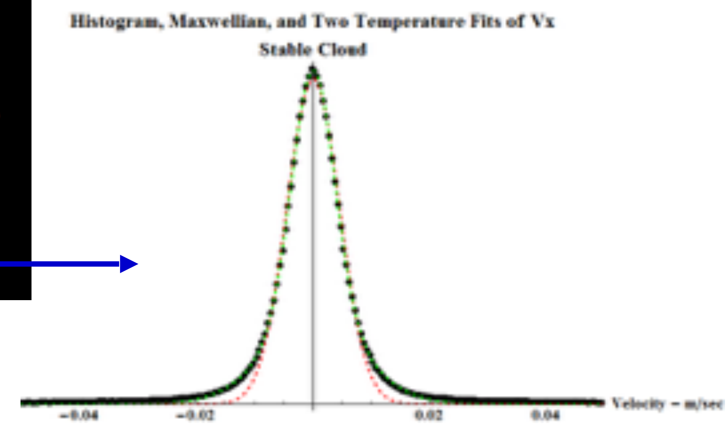
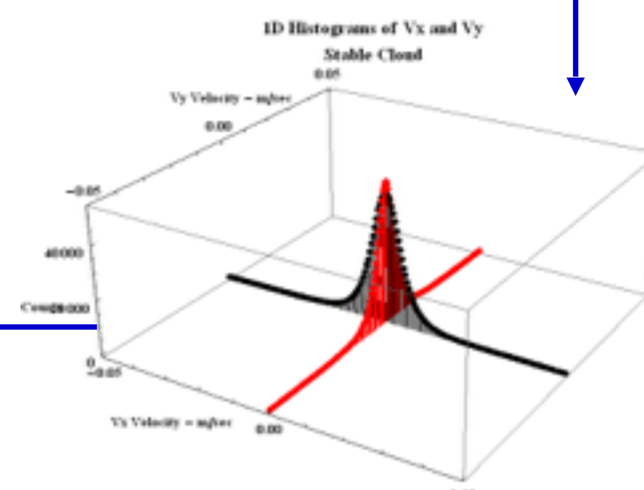
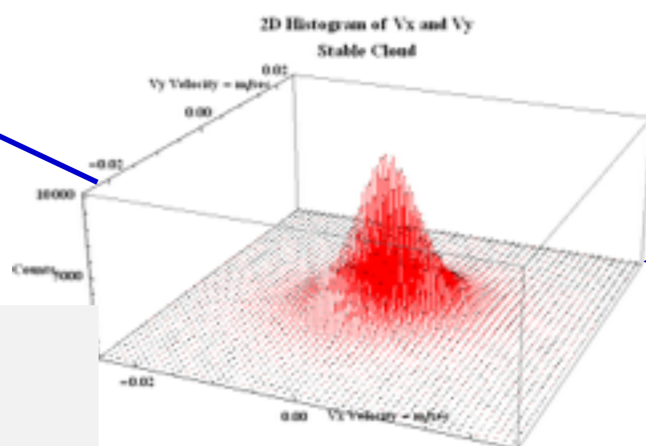
In a dusty plasma it is possible to directly measure the complete distribution function - f(<u>r</u>, <u>v</u>, t)

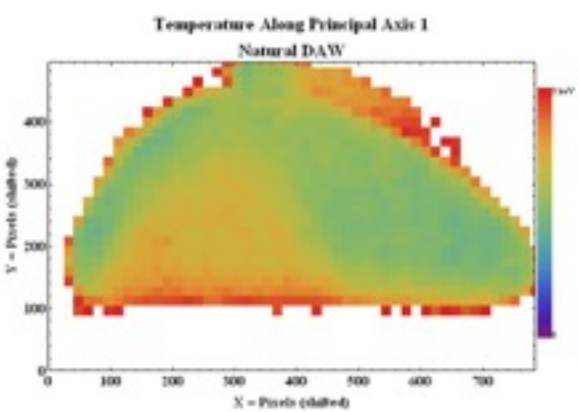












- 1500 velocity measurements
- Construct a velocity distribution
- Assume multi-normal distribution
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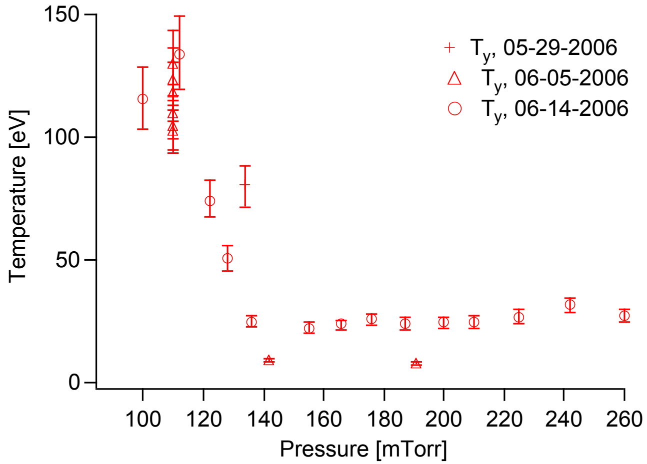
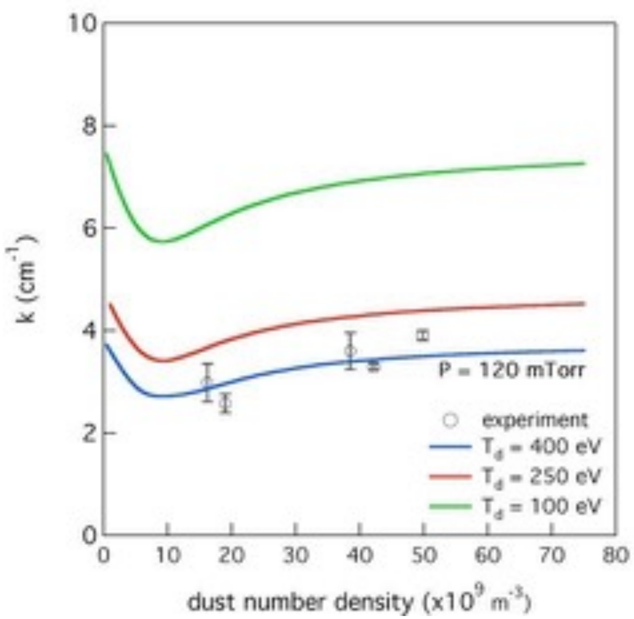
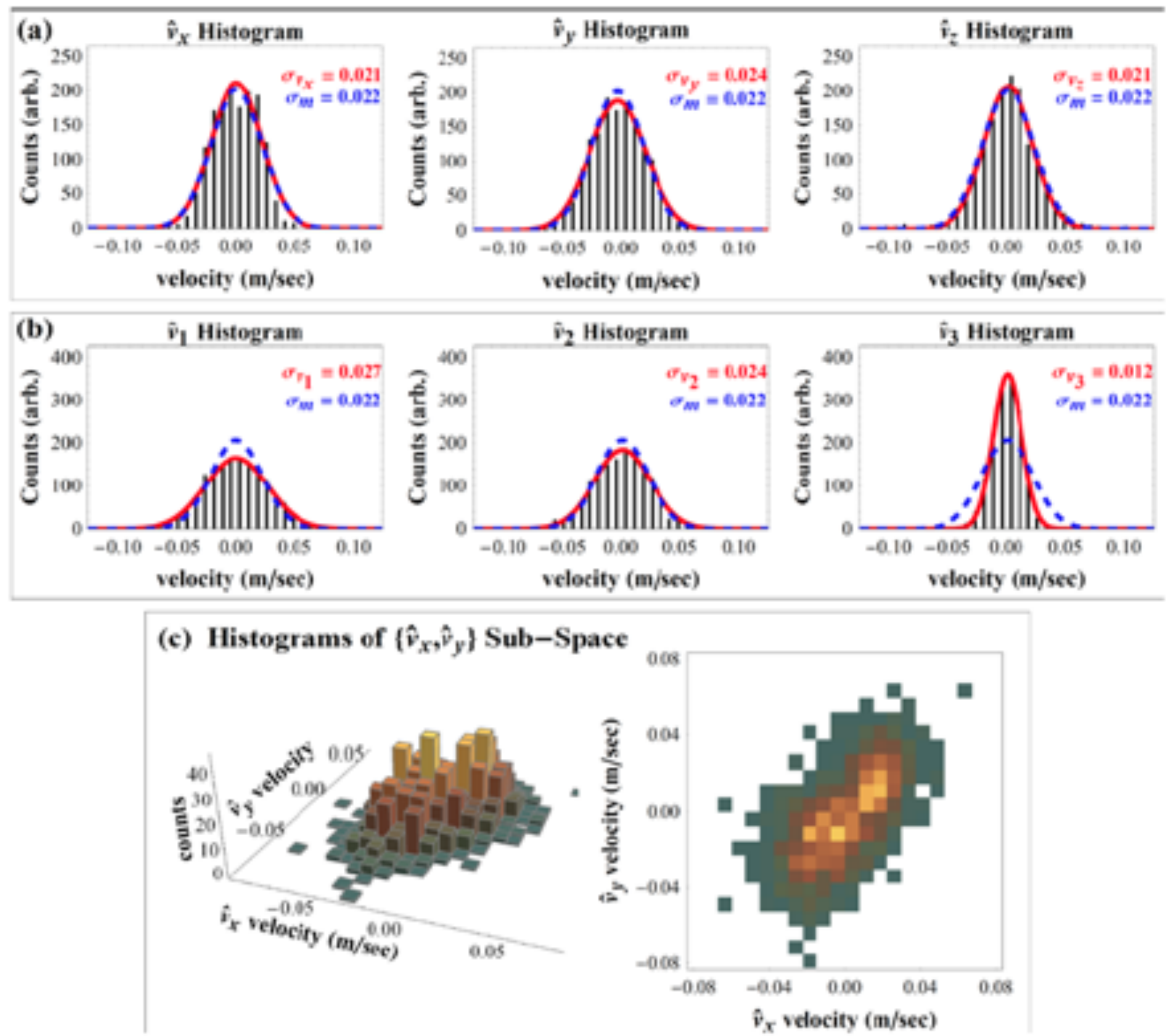
Studies of the thermodynamics of dusty plasmas







From Auburn University:
J. Williams dissertation (2006) and R. Fisher dissertation (2012)

Studies of statistical properties of dusty plasmas

Experiment	Reference
Melting of plasma crystals	Melzer, et al., PRE (1996)
Melting of plasma crystals	Quinn, et al., PoP (2000)
Dusty plasma liquids	Y.-J. Lai et al, PRL (2002)
Microstructures in 2d dusty plasma liquids	Y.-H. Huang, et al., PRE (2007)
Propagation of melting fronts	Williams, et al., PRE (2012)
Laser driven heating of plasma crystals	Nosenko, PoP (2006)
Superdiffusion	Liu, PRE (2008)
Viscoelasticity in 2-d liquids	Feng, PRL (2010)
Thermal properties of weakly-coupled system	Zhakhovskii, JETP Lett. (1997)
Thermal properties of weakly-coupled system	Williams, et. al., PoP (2007)
Thermal properties of weakly-coupled system	Thomas, et al., PoP (2007)
Anisotropic velocity distributions	Fisher, et al., PRE (2012)

- Since the coupling parameter, Γ, can be controlled, a dusty plasma is a model system for studying the statistical mechanics of solids, liquids, gases and plasmas.

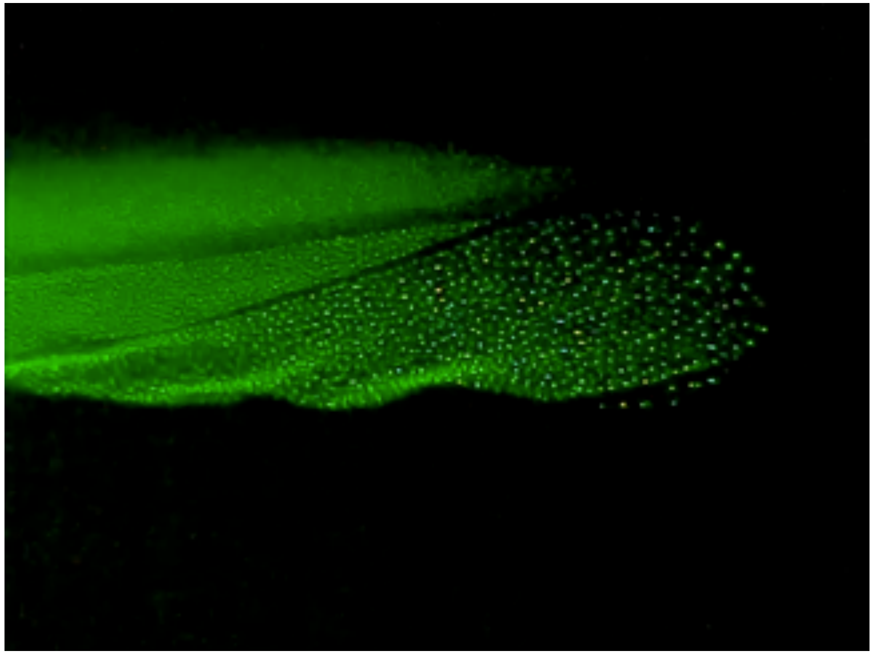
rf plasma laser excited dc plasma

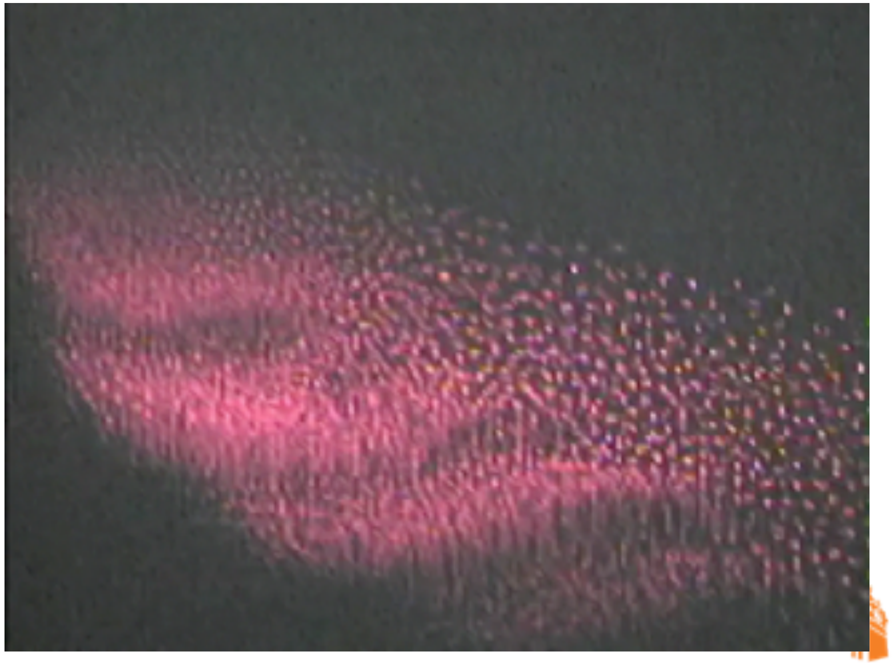
DUSTY PLASMA STUDIES:

DUSTY PLASMA WAVES

Waves in dusty plasmas

- In dusty plasmas, it is possible to visualize both collective motion and individual particle motion simultaneously.
- This enables a unique capability to study wave properties with incredible precision.
- Dusty plasma waves can be studied from "strongly-coupled" (solid-like) systems to "weakly-coupled" (fluid-like) systems.
- Excellent summary article:
  R. L. Merlino, "25 years of dust acoustic waves," *JPP*, 80, 773 (2014).





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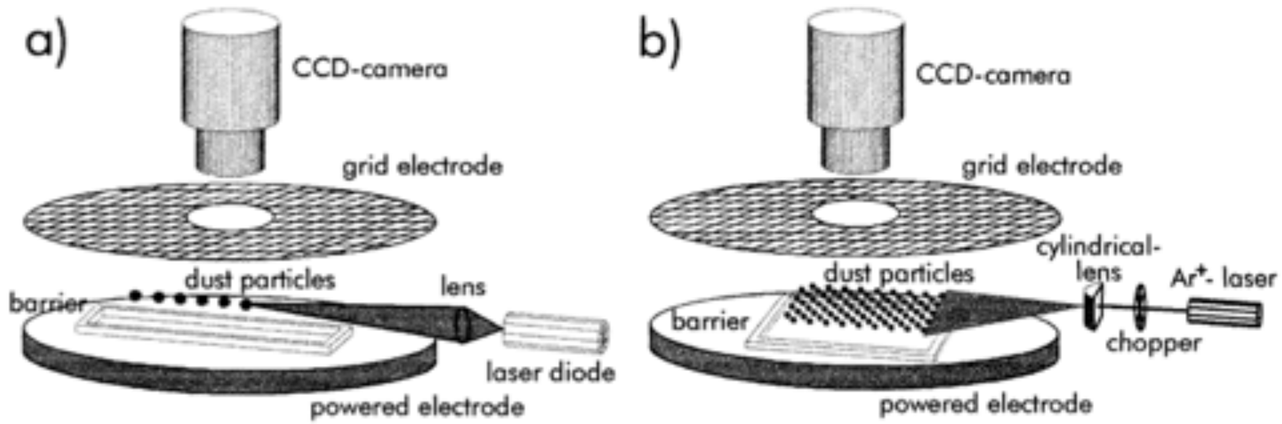
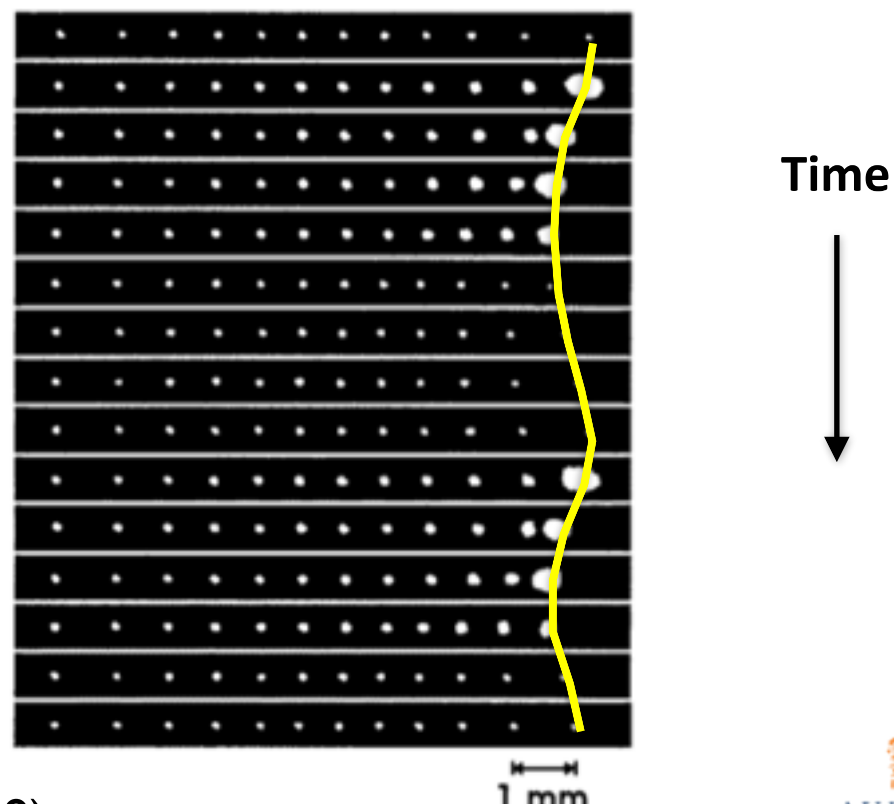
Dust wave in a strongly coupled dust lattice



Laser excited one-dimensional and two-dimensional lattice waves in a plasma crystal.



AUPSL A. Piel, et al., PPFC, **41**, A453 (1999)

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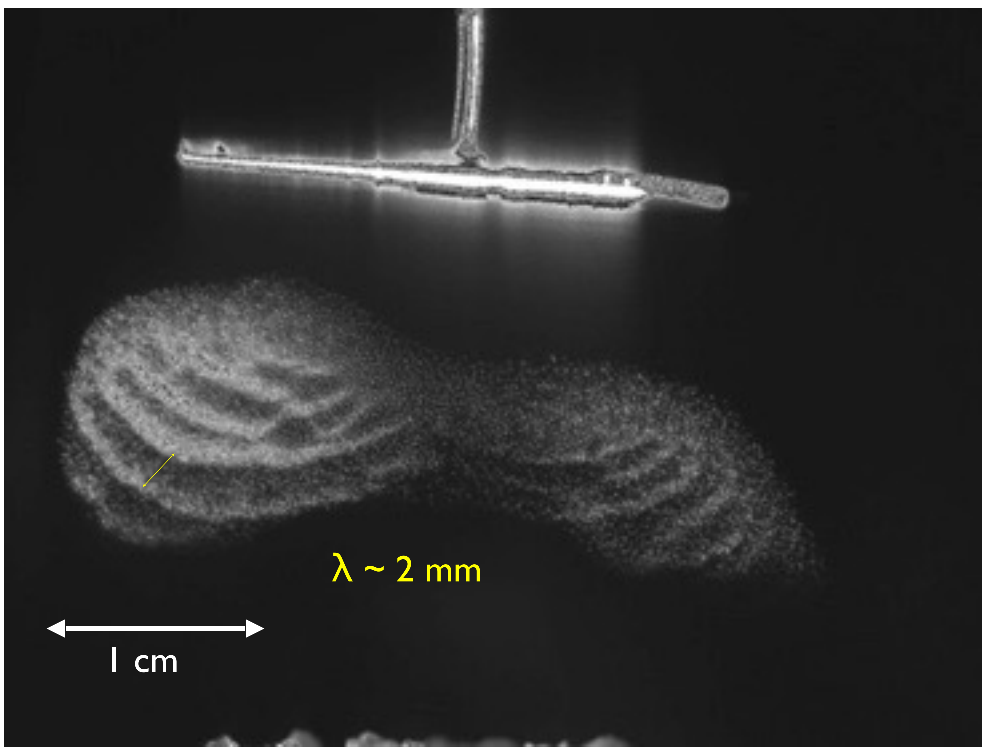
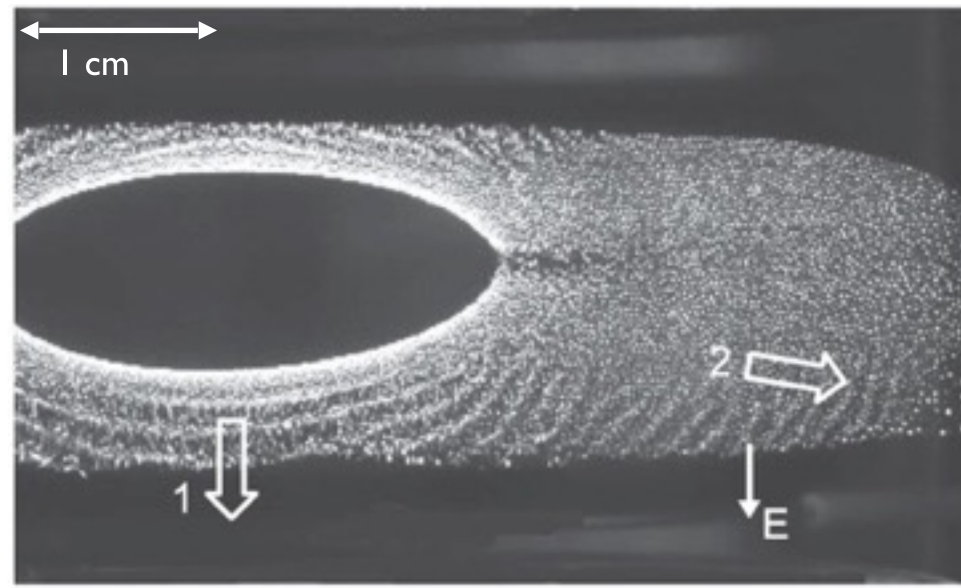
Dust density waves in laboratory and microgravity plasmas

Dust density waves refers to the general class of low frequency, often self-excited waves in a dusty plasma that are characterized by a modulation of the dust number density.





Left: DC glow discharge experiment (Auburn)
Above: RF microgravity experiment (Kiel)

Existence of a "dust sound wave" was one of the earliest predictions of dusty plasma theory

- Experiments on the **dust acoustic wave** have been ongoing since the earliest days of dusty plasma research.
- DDWs have been studied in RF and DC glow discharge plasmas, in Q-machine plasmas, in hot filament discharge plasmas, and under microgravity conditions.
- A wide variety of experiments have been performed:
  - Experiments on self-excited and driven waves
  - Shock-driven waves

Dust acoustic waves (DAW)

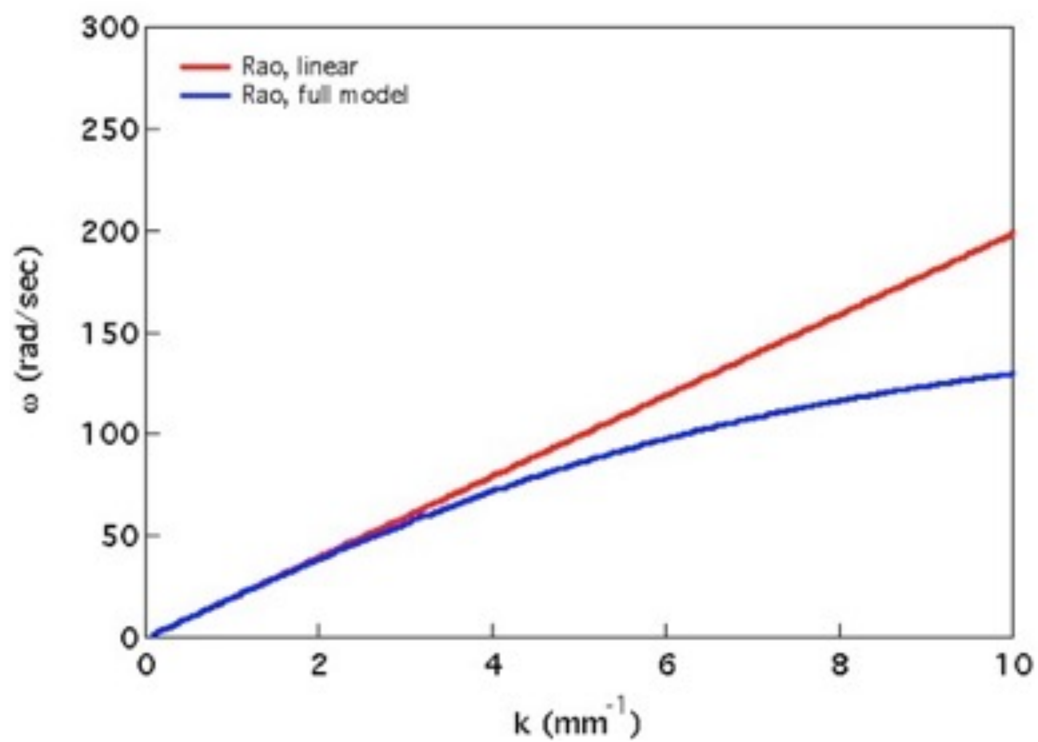
- The original derivation of the one-dimensional dust acoustic wave was given by N. N. Rao, et al., [PSS, (1990)].

$$\omega^2 = \frac{k^2 C_D^2}{\left(1 + k^2 \lambda_D^2\right)}; \qquad \text{where, } C_D = \left[\frac{\left(\frac{T_i}{m_d}\right)\varepsilon Z^2}{1 + \left(\frac{T_i}{T_e}\right)(1 - \varepsilon Z)}\right]^{1/2} \qquad \lambda_D^{-2} = \lambda_{De}^{-2} + \lambda_{Di}^{-2} \quad \text{and} \quad \varepsilon = \frac{n_d}{n_i}$$

For many laboratory experiments:
$T_i << T_e$

In the long wavelength limit:
$k\lambda_D << 1$

$$v_{phase} = \frac{\omega}{k} = c_D = \left[\left(\frac{T_i}{m_d}\right)\varepsilon Z^2\right]^{1/2}$$



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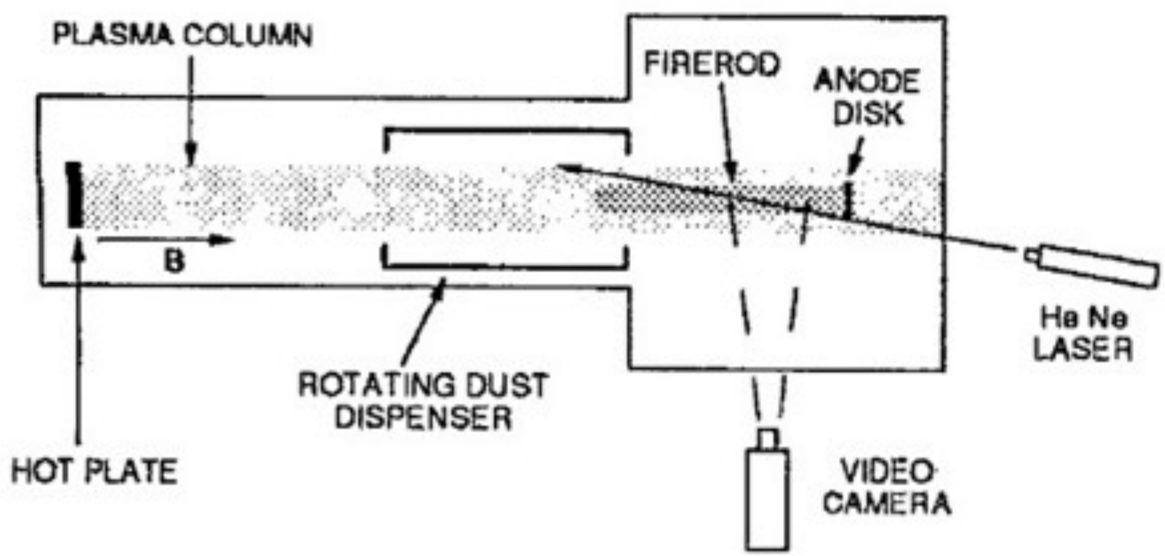
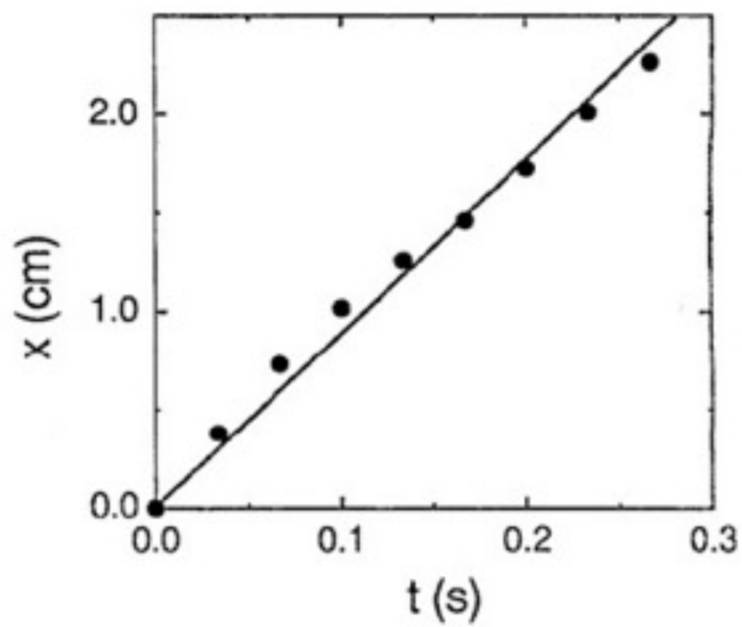
DAW/DDW basic properties

- Early experiments on DAWs focused on characterizing the basic properties of self-excited waves.
- The first experimental result was reported by Barkan, et al., PoP, 1995.



The displacement of single wavefront is recorded using a video camera and a He-Ne laser as the light source.



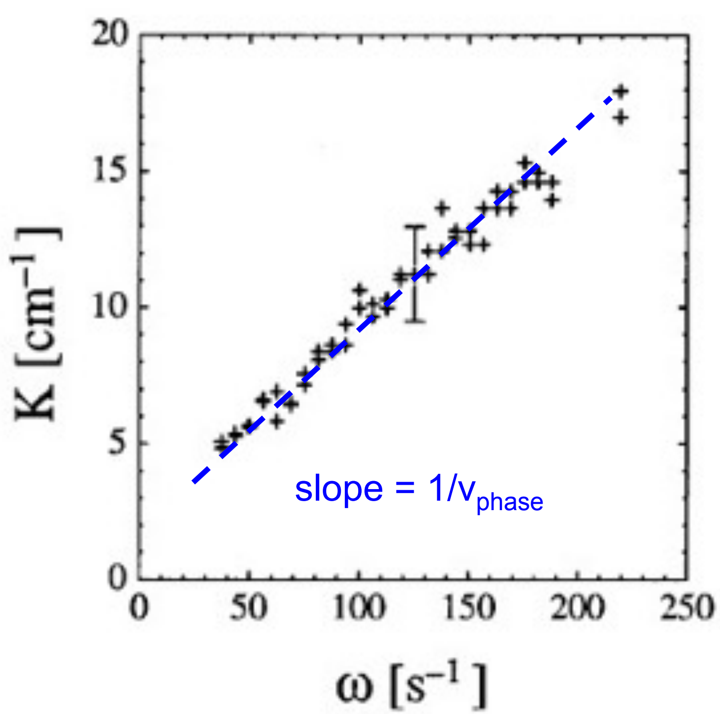
Measurement of the displacement of a wave front giving a velocity of: $C_D \sim 9$ cm/s.

Dust acoustic waves as a diagnostic for charge

In the long λ limit, phase velocity of DAW/DDW is:

$$\frac{\omega}{k} = \left[\left(\frac{T_i}{m_d}\right)\varepsilon Z^2\right]^{1/2}; \qquad \varepsilon = \frac{n_d}{n_i}$$

Use the phase velocity of the DDW, measured dust number density, and ion number density to estimate grain charge: $q_d = -Z_d e$



$r_d = 0.8\ \mu m$
$m_d = 6 \times 10^{-16}$ kg
$\varepsilon = 2$ to 5×10^{-4}
T_i (est.) = 0.03 eV
$v_{phase} \sim 12$ cm/s

➔ $Z_d \sim 1300$

C. Thompson, et al., PoP (1997)

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DUSTY PLASMA STUDIES:

MAGNETIC FIELD EFFECTS

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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: $q_d/m_d \ll e/m_{ion} \ll e/m_{elec}$

Key result:
Maximize B/a

- Key parameters:
  - gyroradius to exp. size: $\frac{\rho}{L} \sim \frac{a^2 v_d}{BL} \ll 1$
  - gyrofreq. to collision freq.: $\frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1$
  - magnetic to gravitational force: $\frac{F_m}{F_g} = \frac{Q_d v_d B}{m_d g} \sim \frac{v_d B}{a^2} \geq 1$

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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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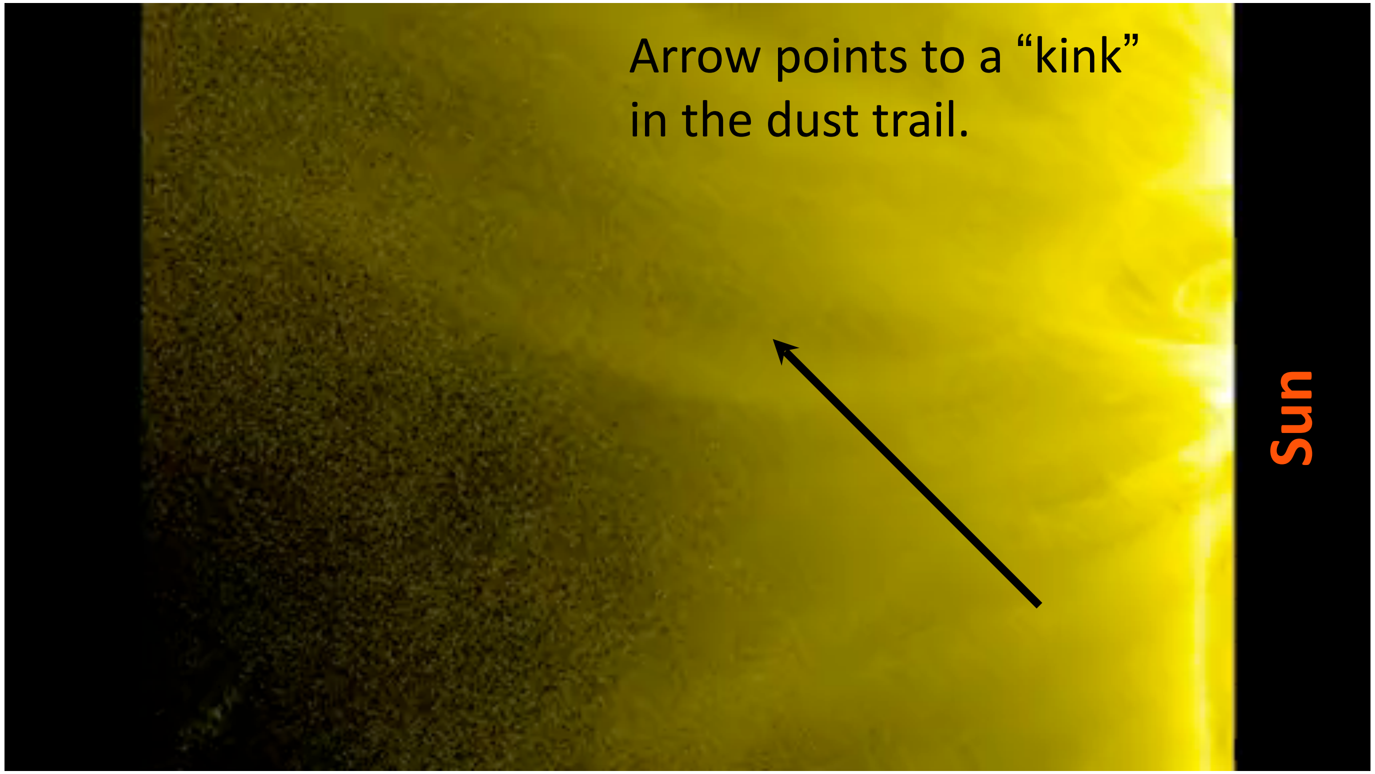
Modification of a comet's tail: an astrophysical example

- 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

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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?

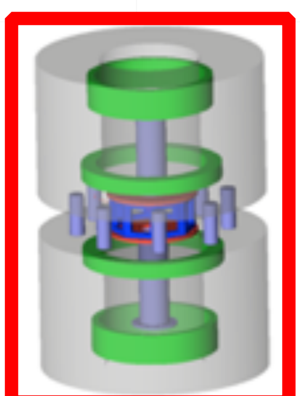
  - If a dusty plasma has magnetic particles - how does the system evolve in the presence of uniform and non-uniform magnetic fields?

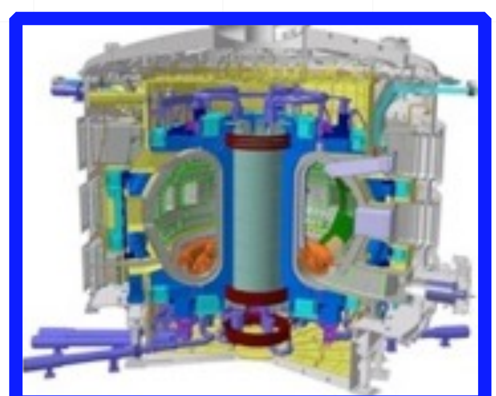
Parameter space for MDPX device

	dust spacing	dust radius	charge	magnetic field	dust velocity	electron Debye length	gyroradius		
	d	a	Z	B	v	L_{de}	D_g	d/L_{de}	d/D_g
	(m)	(μm)		(T)	(m/s)	(cm)	(m)		
Saturn's E-ring	2	1	10	5.0E-7	1000	2.35E+01	7.85E+13	**0.1**	**2.74E-14**
Interstellar molecular clouds	2	0.5	1	1.0E-8	1	7.43E+00	1.64E+12	**0.3**	**1.32E-12**
Star-forming region	0.01	0.01	2	0.0001	10	7.43E-03	6.54E+02	**1.4**	**1.53E-05**
Process plasma	0.0003	1	2000	0.005	0.01	1.92E-04	3.93E+01	**1.5**	**6.91E-06**
Fusion experiment	0.005	0.1	500	2	10	5.25E-05	3.93E-01	**100**	**1.18E-02**
MDPX - large dust	**0.0002**	**1**	**4000**	**1**	**0.01**	**4.07E-04**	**1.44E-01**	**0.5**	**1.50E-03**
MDPX - small dust	**0.001**	**0.25**	**500**	**4**	**0.005**	**4.07E-04**	**2.25E-03**	**2.5**	**4.45E-01**

$n \sim 10^{15}\ m^{-3}$
$T_e \sim 3$ eV

Not to scale





AUPSL Adapted from Mendis and Rosenberg, Ann. Rev. Astron. Astrophys., **32**, 419 (1994)

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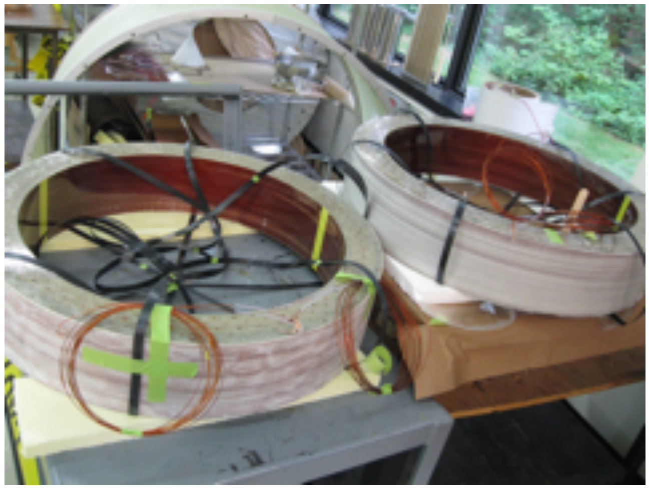
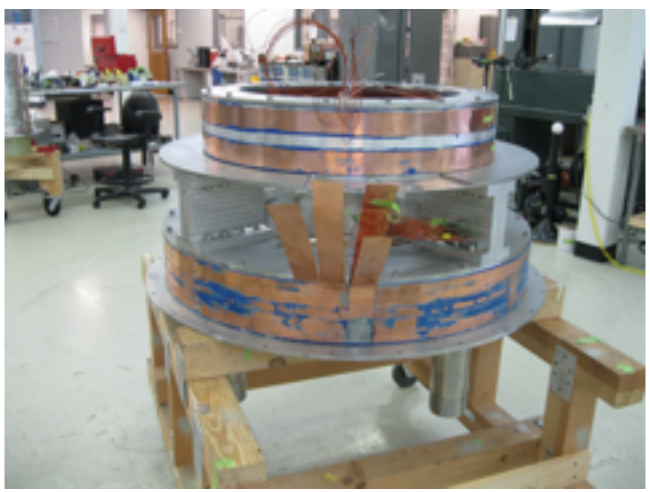
MDPX superconducting magnet system





- 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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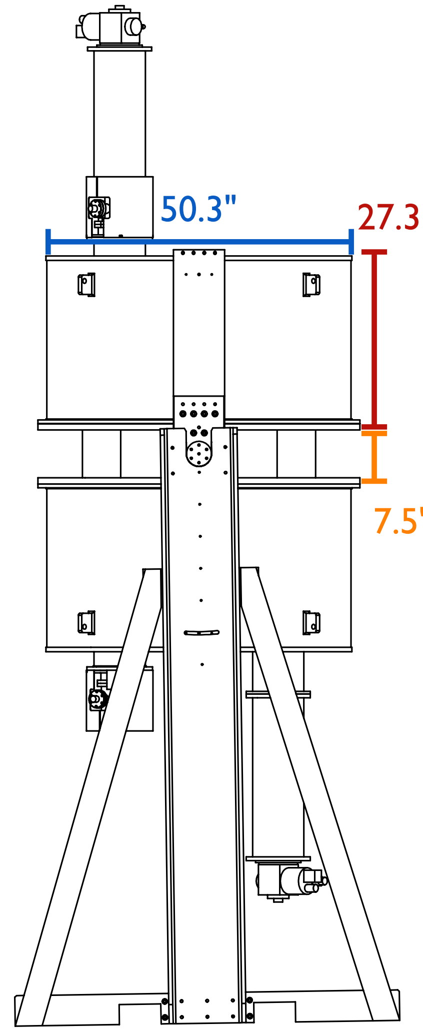
MDPX parameters: final "as-built" system

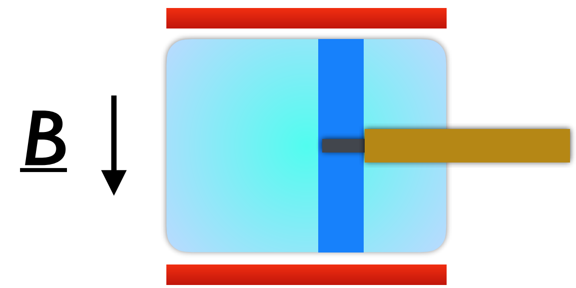


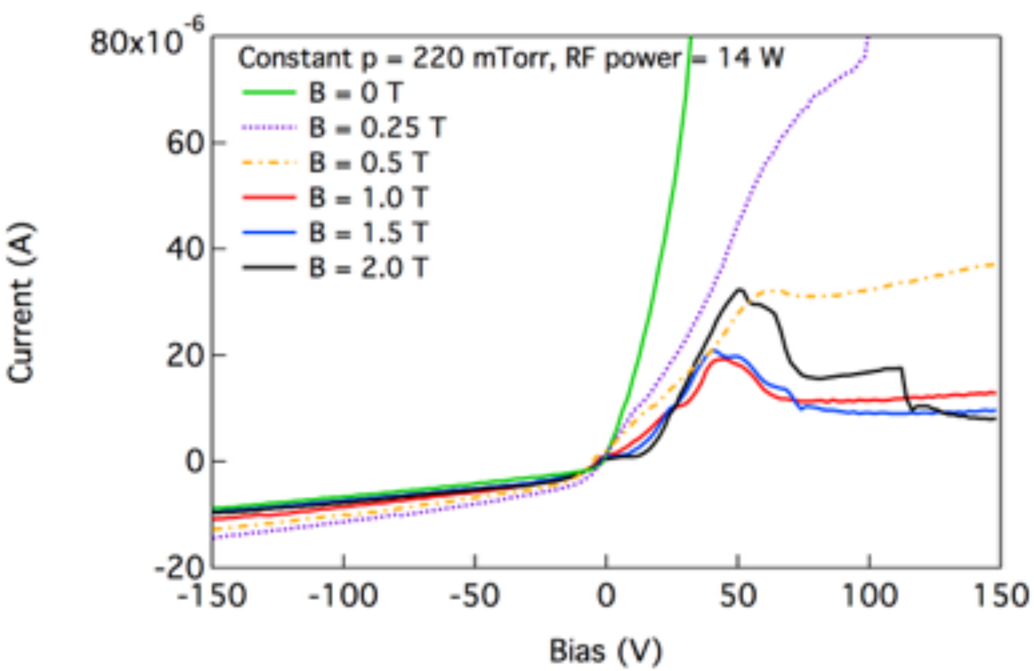
Magnetic field:	3.0 T (to date); 4 T (max)
Magnetic field gradient:	1 - 2 T /m
Magnet cryostat:	50 cm ID / 127 cm OD
Magnet material:	NbTi superconductor; cryogen-free system

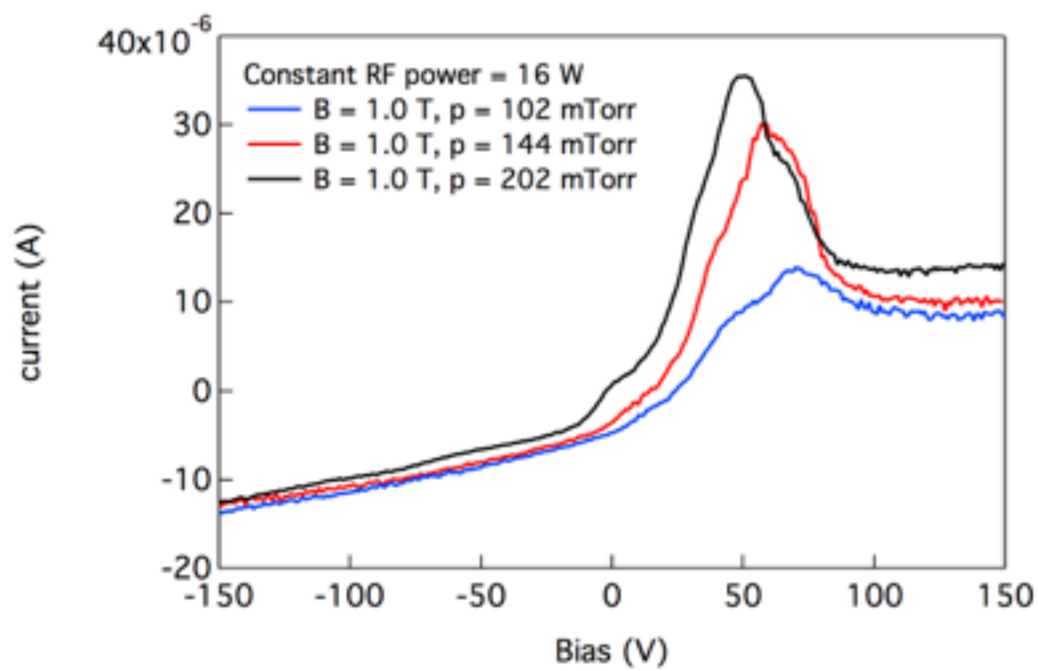
Magnet performance:	$T_{critical}$ = 6.4 K; $T_{minimum}$ = 4.2 - 4.8 K
Experiment volume:*	45 cm dia. x 175 cm axial
Uniform region:*	20 cm dia. x 20. cm axial
Total cold mass:	~2.5 tons

The magnetic field strongly modifies *in-situ* diagnostics - driving the need to develop new diagnostic tools

- The magnetic field adversely affects the performance of *in-situ* probes.
- Measurements show the effect of magnetic field and neutral pressure on single-tip Langmuir probe traces.







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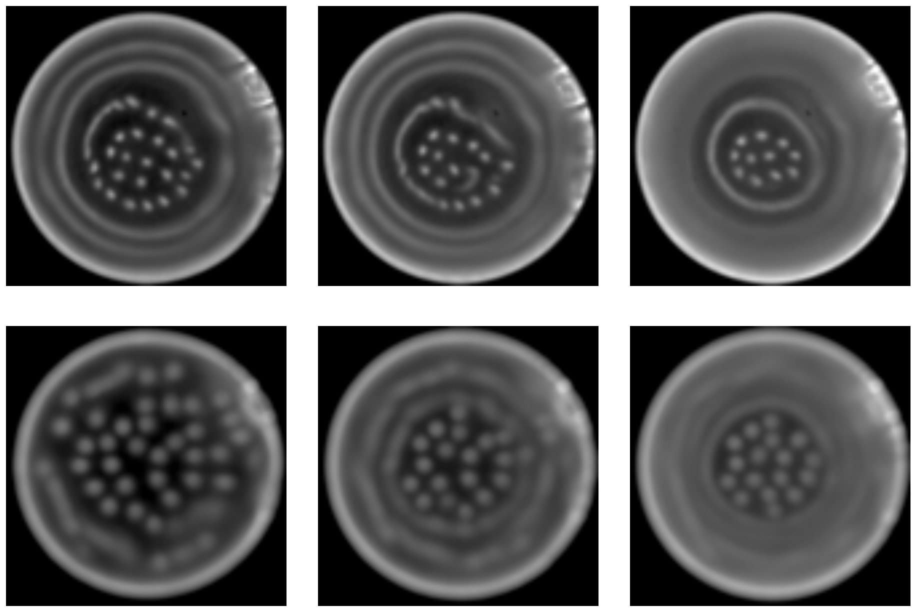
Filaments are columns of stable or mobile plasma structures that form parallel to the magnetic field

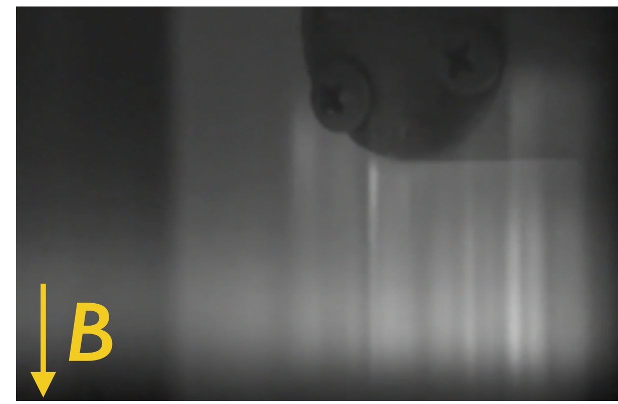
Plasma rings/filaments viewed from top camera (constant p = 4.7 Pa)

Upper electrode: Grid
Lower electrode: Aluminum

Upper electrode: Grid
Lower electrode: 2 mm Glass on Aluminum



0.40 W 0.85 W 1.20 W



View of filaments and dust shaker from side camera

- Appearance of filaments scales with decreasing rf power and pressure.
- May represent a local increase in plasma density.
- Can be stationary or mobile depending on the plasma parameters and boundary conditions.

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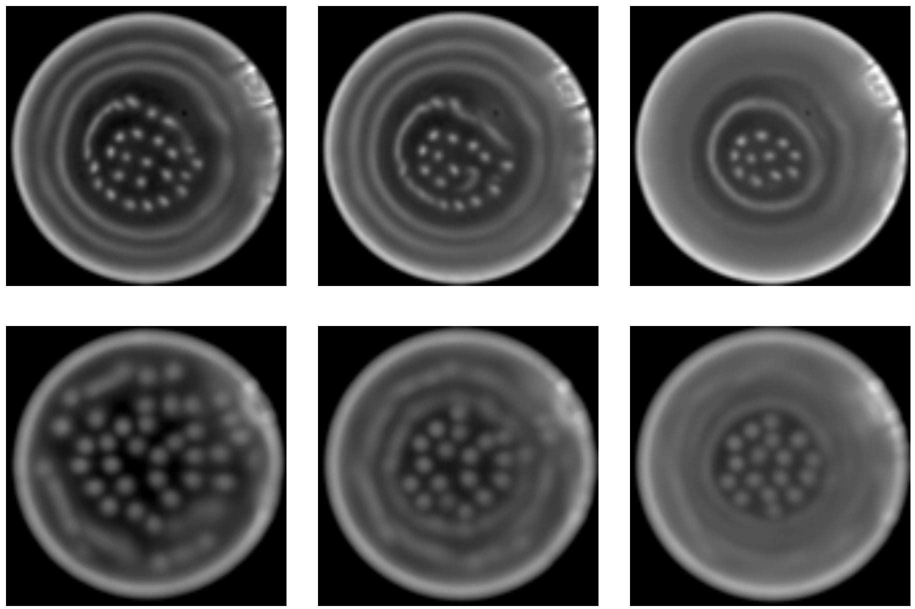
Filaments are columns of stable or mobile plasma structures that form parallel to the magnetic field

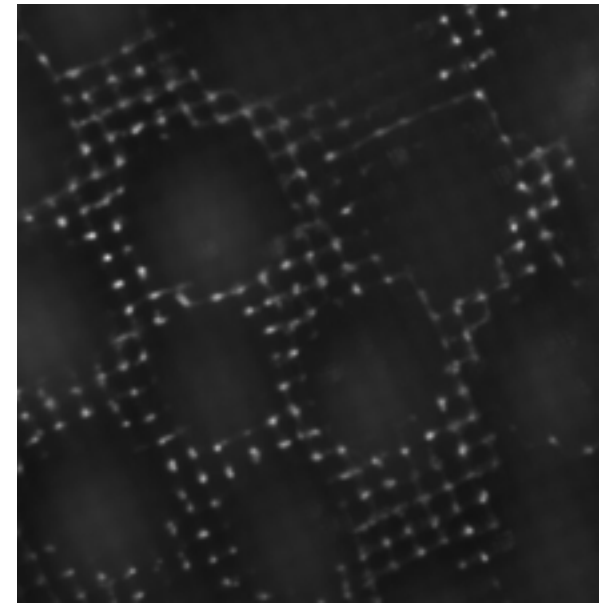
Plasma rings/filaments viewed from top camera (constant p = 4.7 Pa)

Upper electrode: Grid
Lower electrode: Aluminum

Upper electrode: Grid
Lower electrode: 2 mm Glass on Aluminum



0.40 W 0.85 W 1.20 W



Filaments compete with the formation of the grid

- Appearance of filaments scales with decreasing rf power and pressure.
- May represent a local increase in plasma density.
- Can be stationary or mobile depending on the plasma parameters and boundary conditions.

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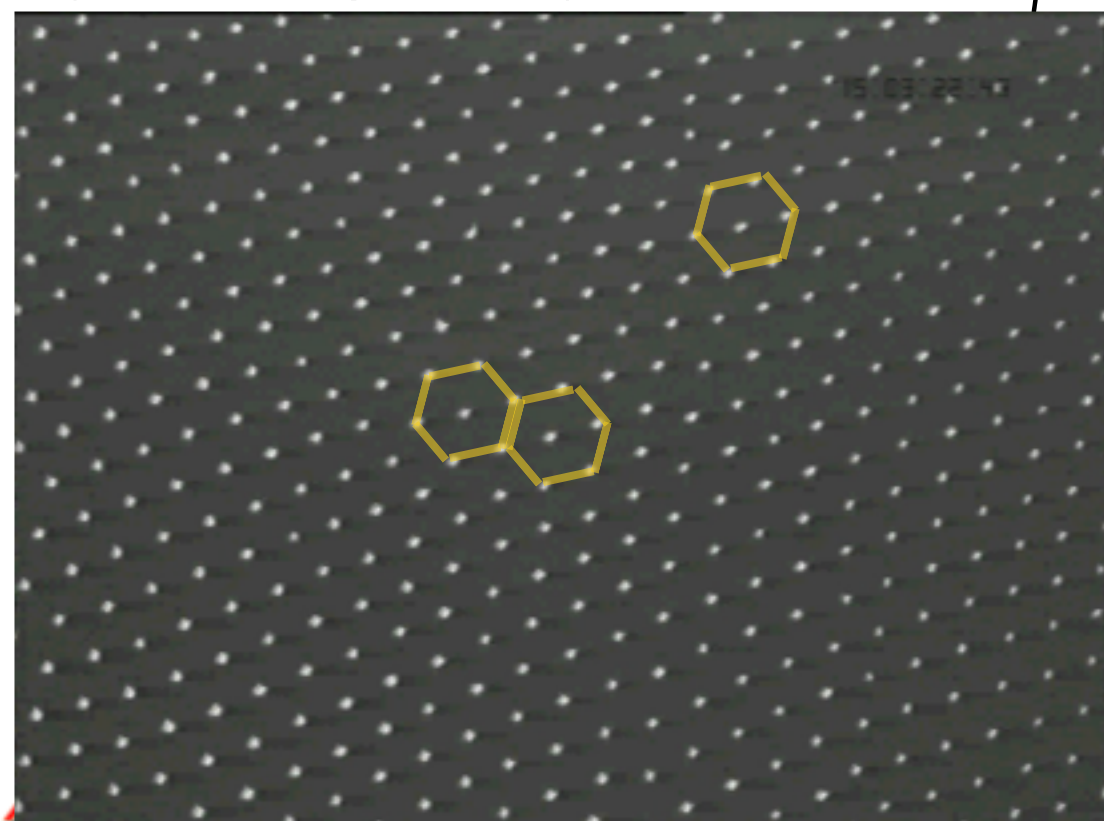
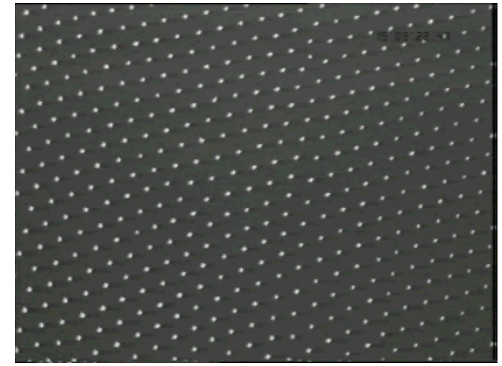
Self-organization in dusty plasmas

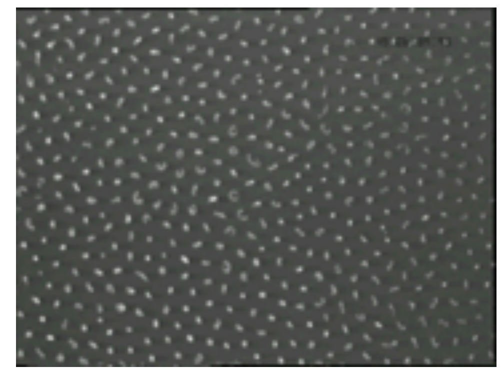
- Γ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction (Yukawa, Debye-Hückel):

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





$\Gamma >> 1$



$\Gamma \sim 1$

$\Gamma < 1$

At high magnetic field, the dusty plasma becomes spatially aligned to a wire mesh

Key scale lengths:
B = 1 T
P = 120 mTorr

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

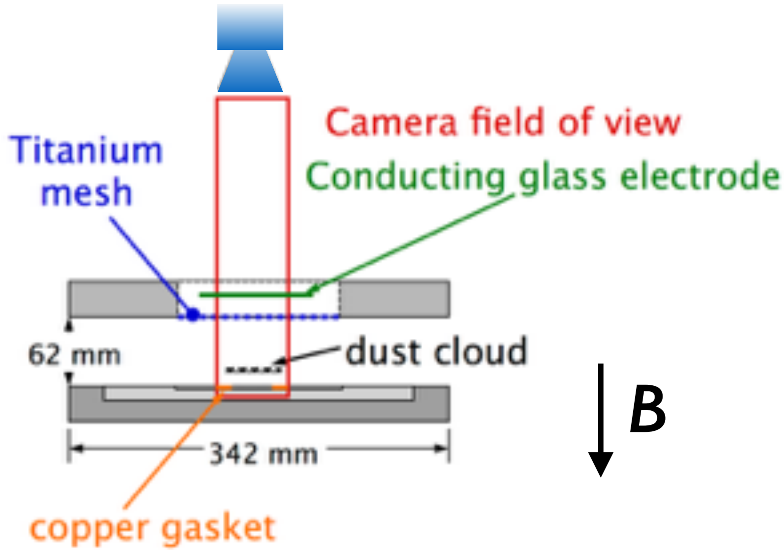
$\lambda_{mfp-electron} \sim 8$ mm

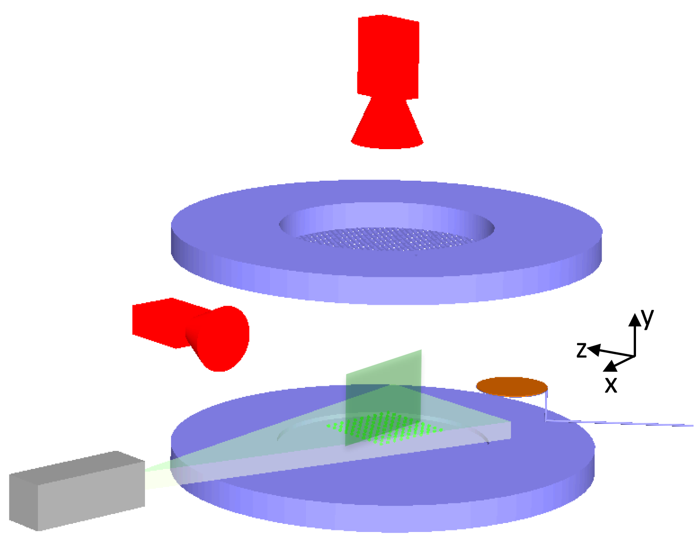
$\lambda_{De} \sim 0.2$ mm

$r_{Le} \sim 0.006$ mm

$r_{Li} \sim 0.15$ mm

Dust cloud pattern:
30 - 40 mm <u>*below*</u> top electrode





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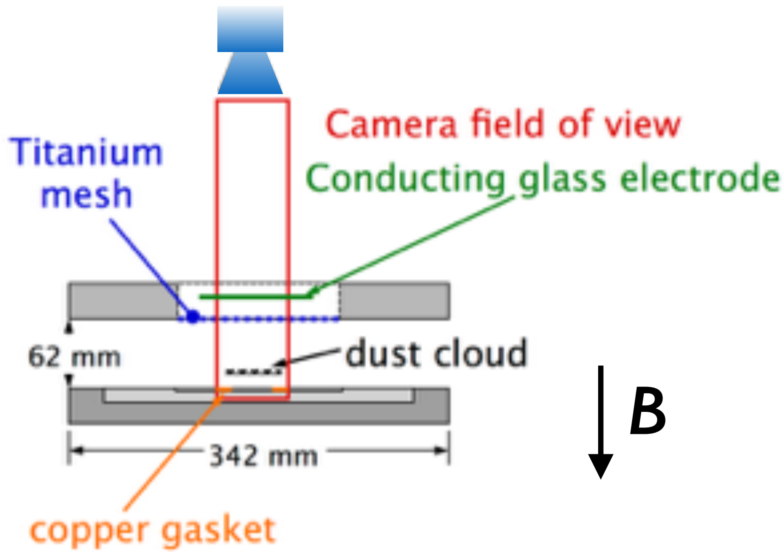
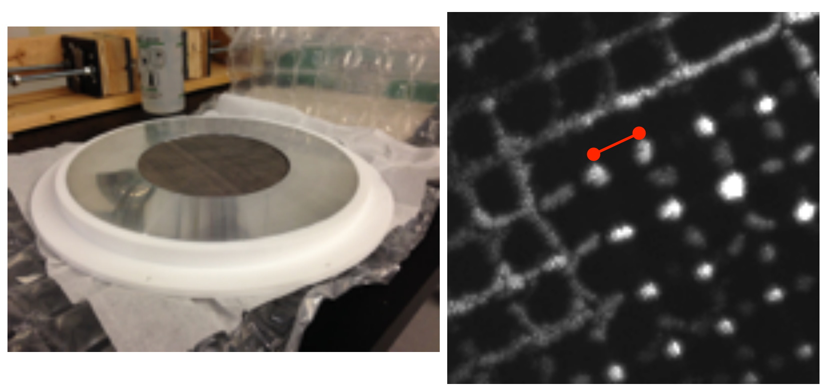
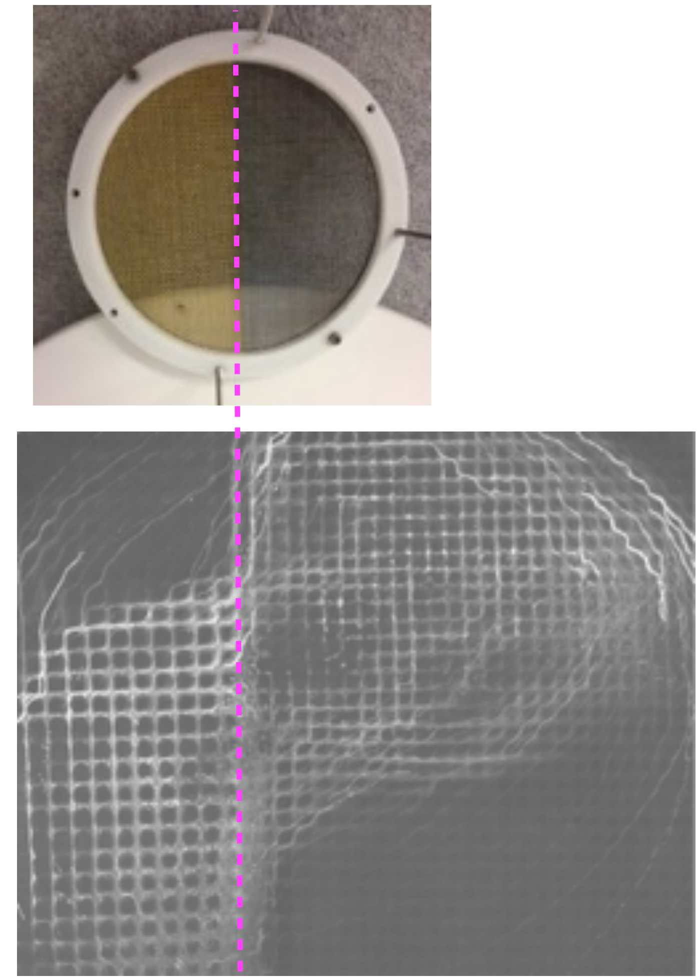




Grid pattern in dust: ~0.65 ± 0.02 mm
Mesh wire used: **#40 titanium mesh**
Center-to-center spacing: 0.635 mm



Experiment repeated with a “double” mesh using #24 brass and #30 aluminum mesh

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At high magnetic fields, the dusty plasma becomes spatially aligned to a wire mesh

Key scale lengths:
B = 1 T
P = 120 mTorr

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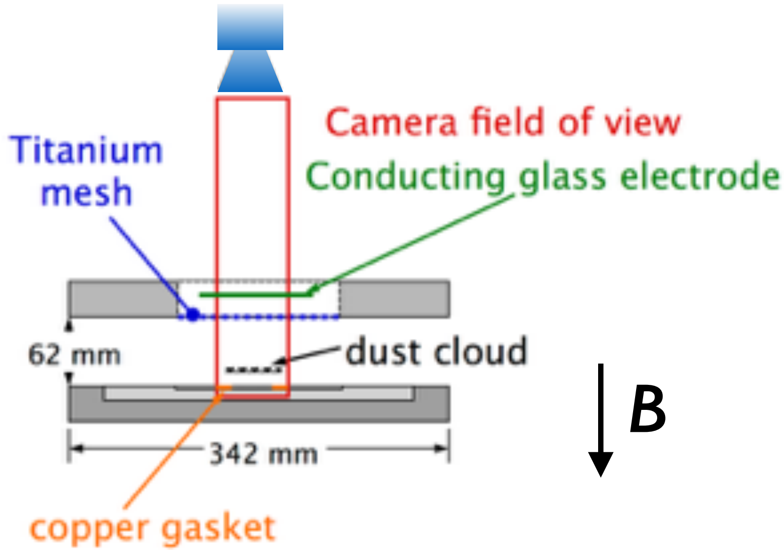
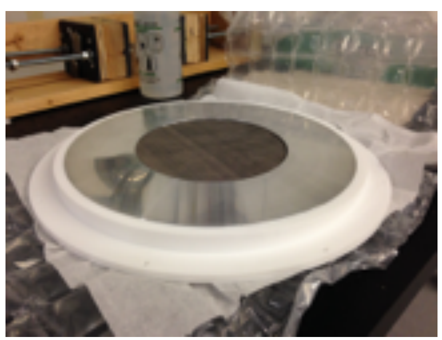
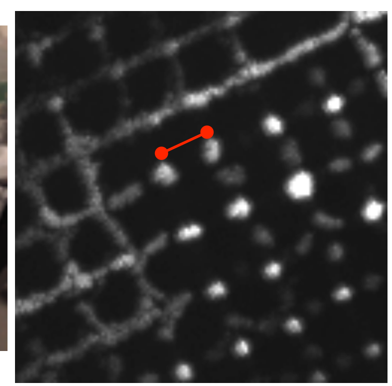
Dust cloud pattern:
30 - 40 mm ***<u>below</u>*** **top electrode**







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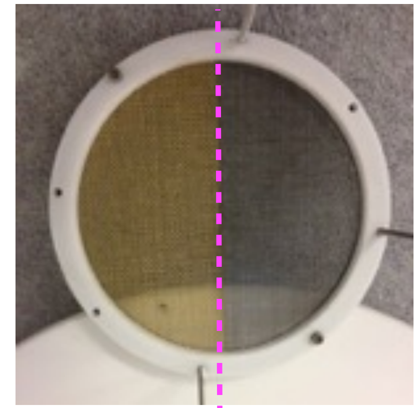

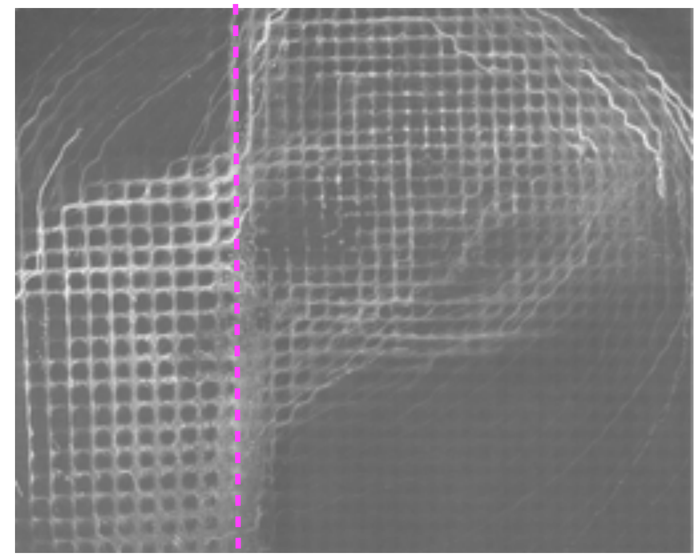

Experiment repeated with a “double” mesh using #24 brass and #30 aluminum mesh

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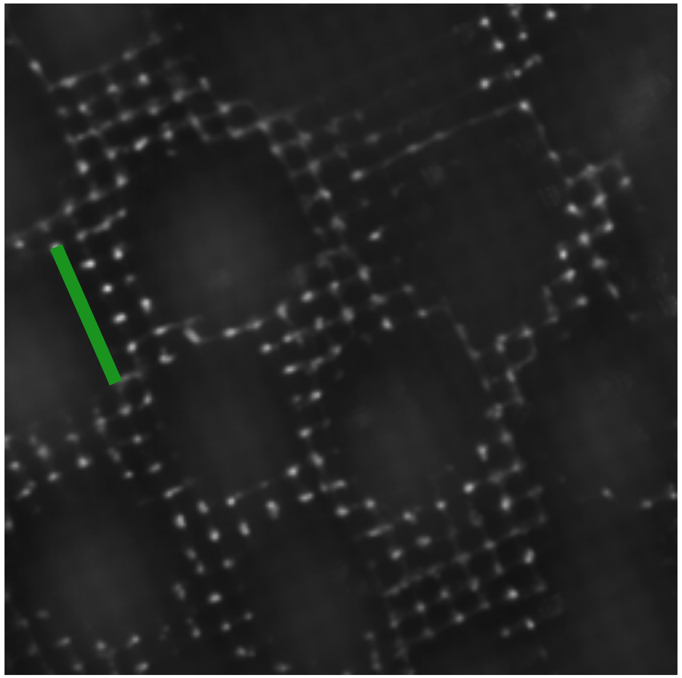
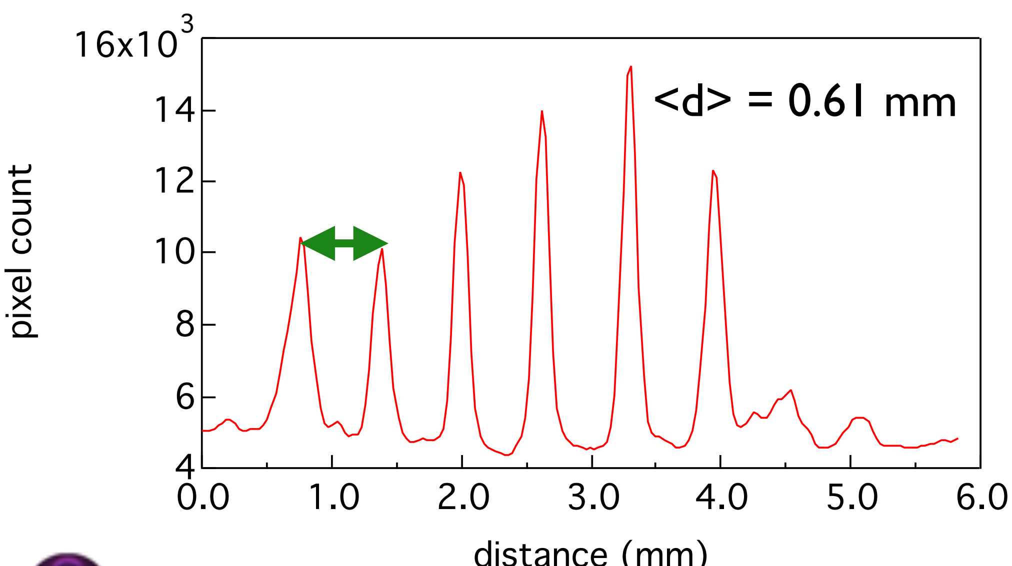
Structure persists over a range of magnetic field, pressure, and particles sizes

Close-up of a 450 x 450 pixel region

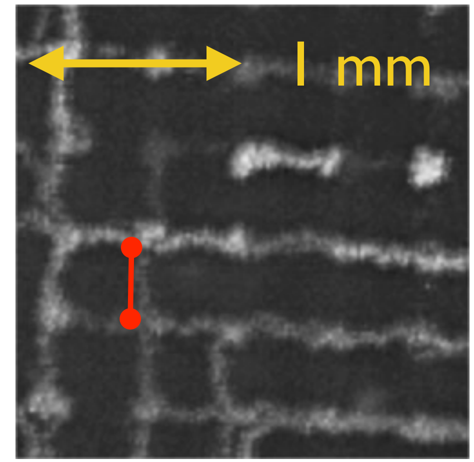


2 T
90 mTorr
0.5 μm

d = 0.61 mm

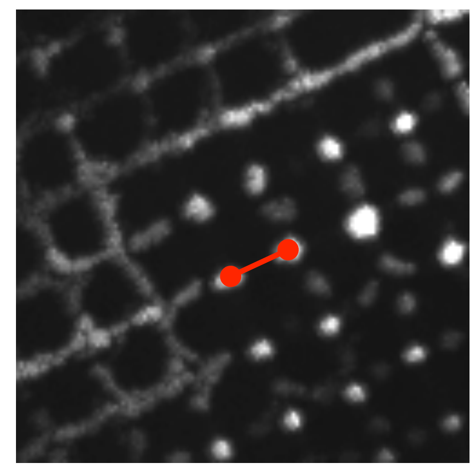


Close-up of a 125 x 125 pixel region



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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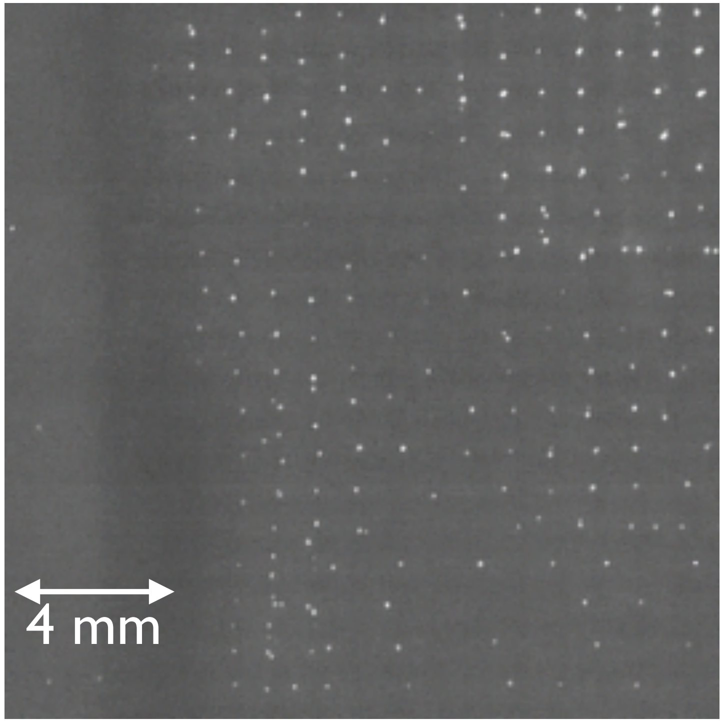
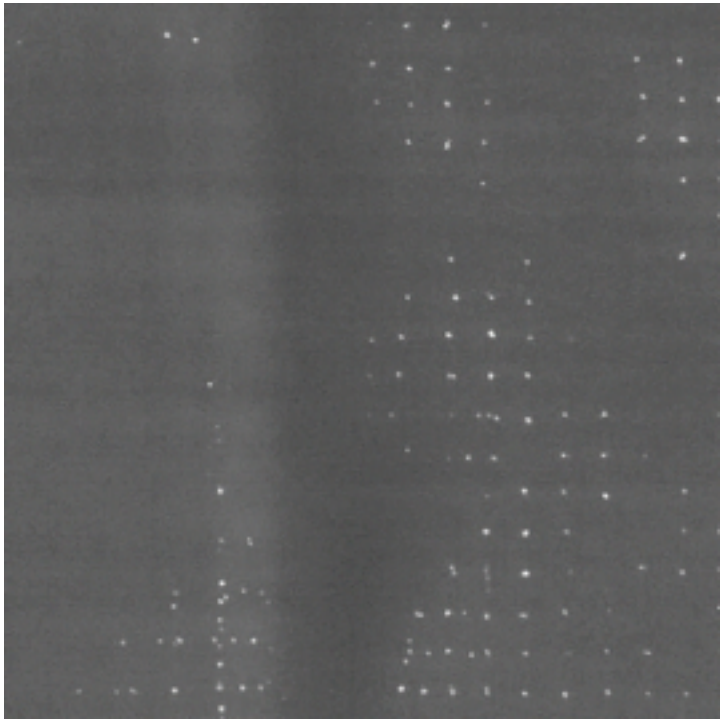
Developing control over the ordered structures

B = 2.02 T
P = 137 mTorr
RF power = 1.6 W



B = 2.52 T
P = 137 mTorr
RF power = 1.6 W



Movies showing motion of dust particle motion in the imposed grid.

- Double-mesh is used to impose two patterns on the suspended dust particles.
- Extended the range of magnetic field to B = 2.5 T.
- With increasing magnetic field, particles become strongly confined to the pattern established by the mesh.

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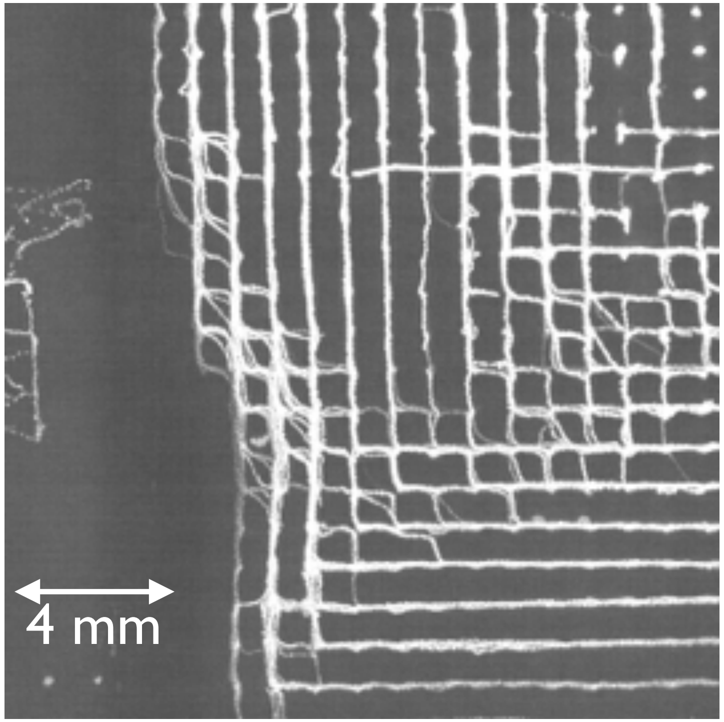
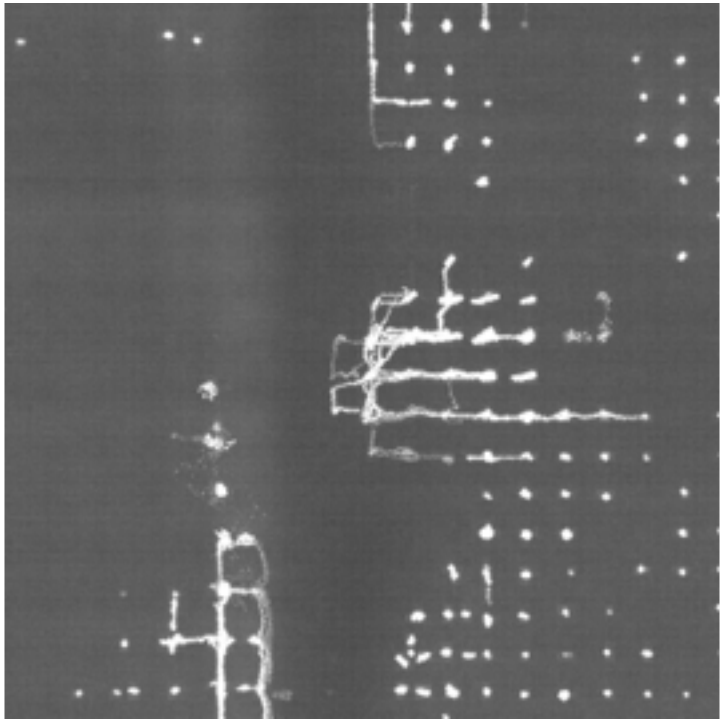
Developing control over the ordered structures

B = 2.02 T
P = 137 mTorr
RF power = 1.6 W



B = 2.52 T
P = 137 mTorr
RF power = 1.6 W



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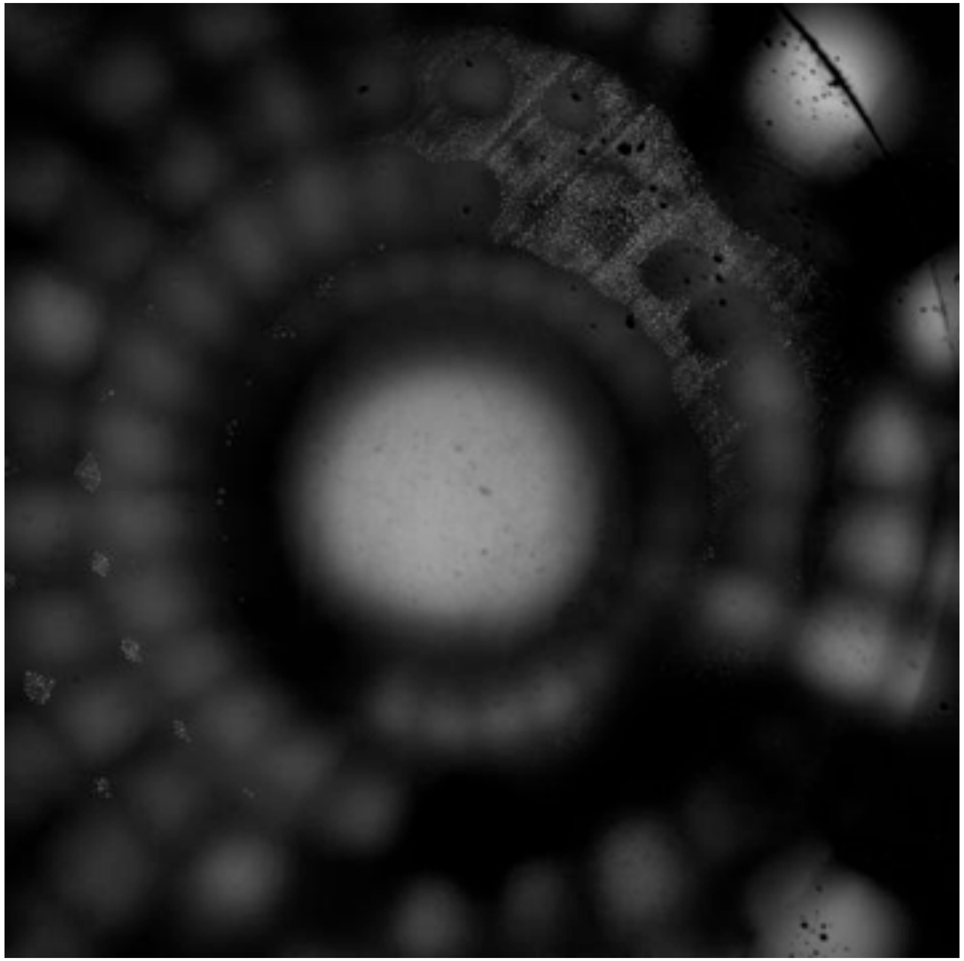
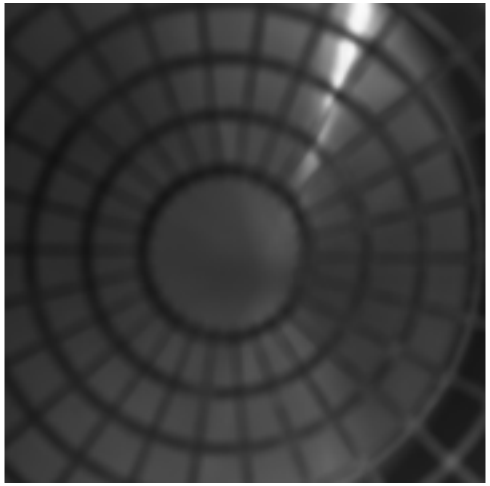
Developing control over the ordered structures

B = 1.0 T
P = 115 mTorr
RF power = 2.8 W



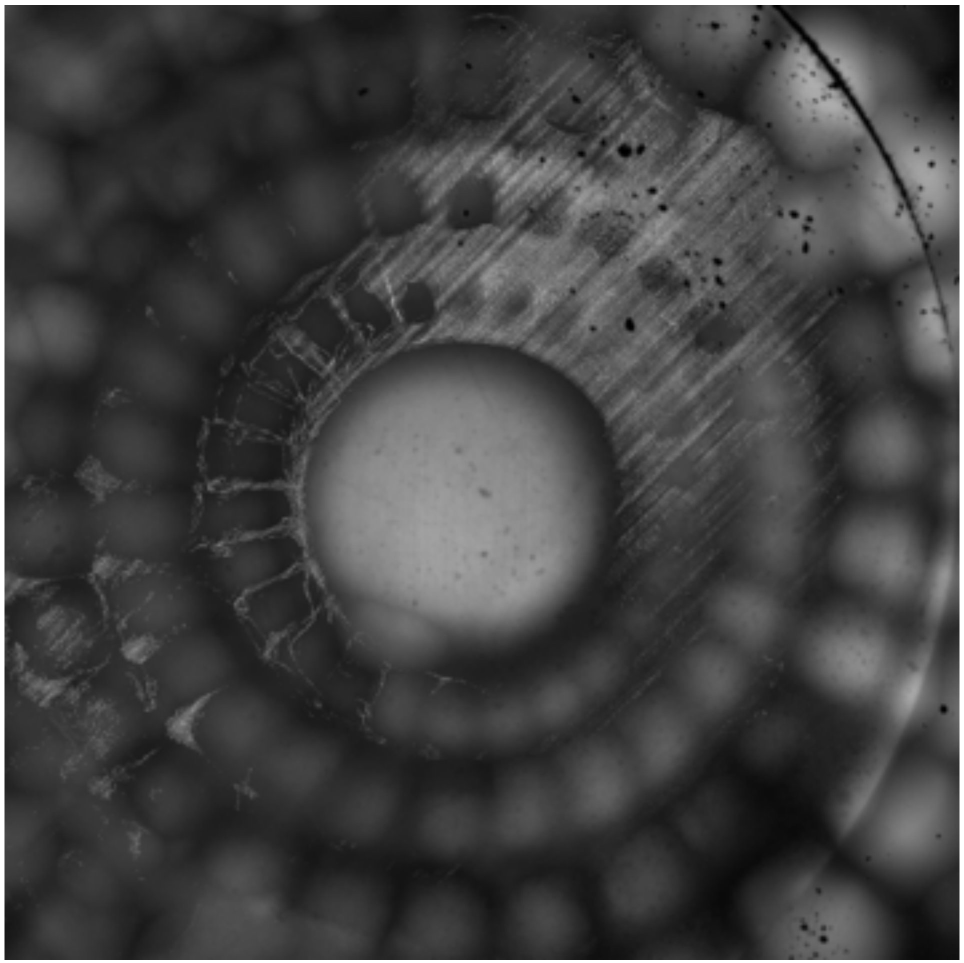


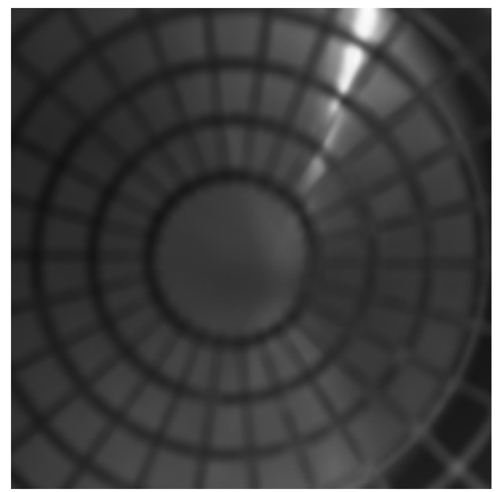
"spider web grid"

- Continuing to test the formation of ordered structure.
- Using a new shaped grid from UMBC with a wider electrode spacing.
- Initial measurements show that the dust particles appear to be constrained by the new grid.

Developing control over the ordered structures

B = 1.0 T
P = 115 mTorr
RF power = 2.8 W



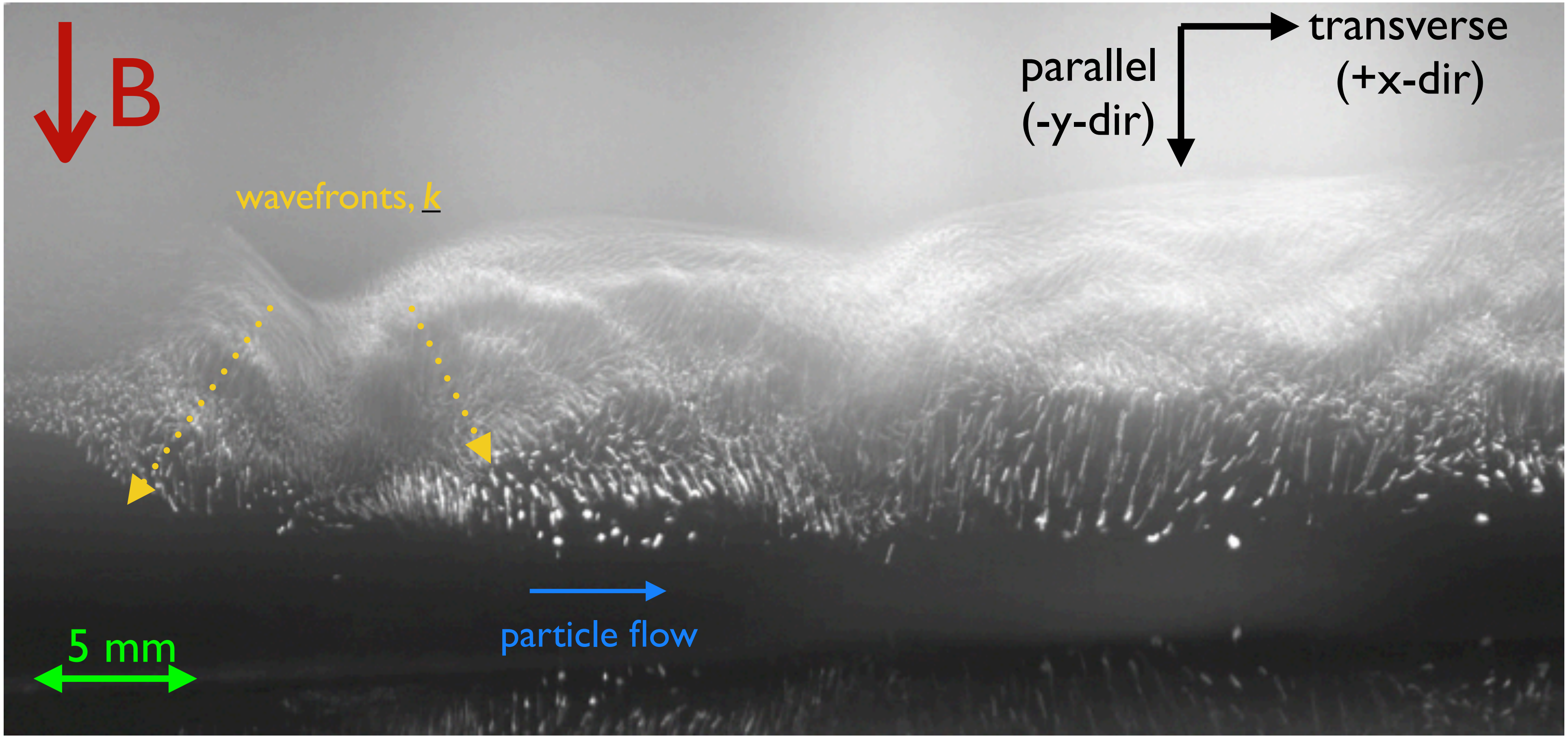


"spider web grid"

- Continuing to test the formation of ordered structure.
- Using a new shaped grid from UMBC with a wider electrode spacing.
- Initial measurements show that the dust particles appear to be constrained by the new grid.

Beginning studies of dust acoustic/dust density waves at high magnetic field

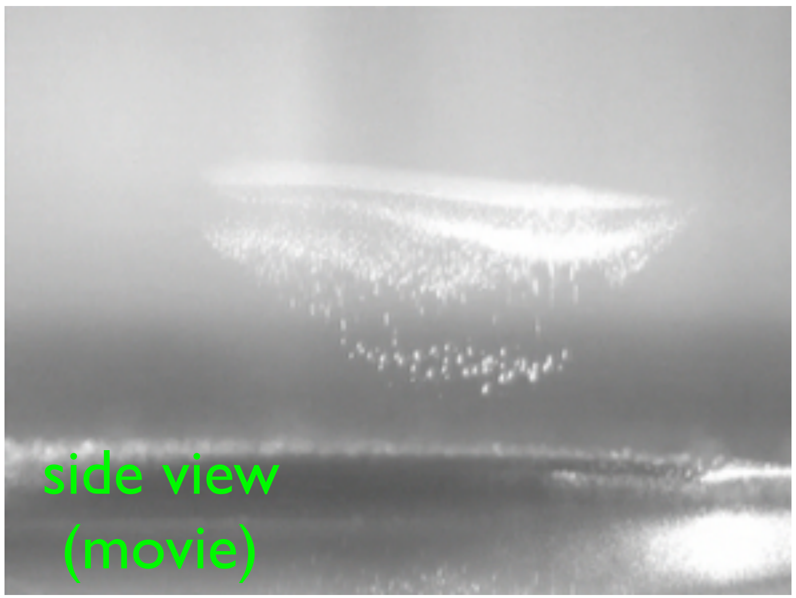
Most recent wave measurements:
B = 1.0 T
2 micron diameter particles
p = 140 mTorr

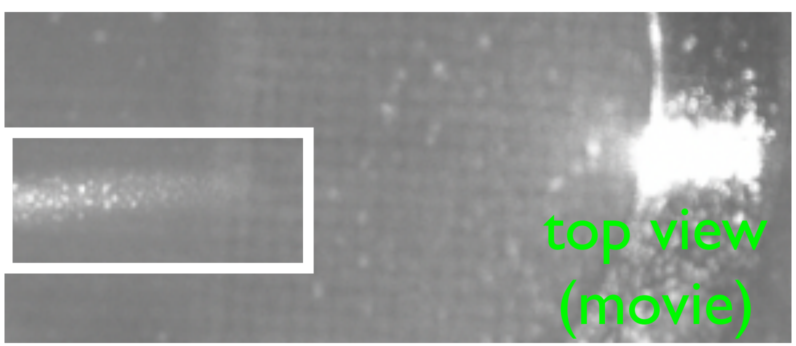


Original video: 100 fps, slowed by 1/10th

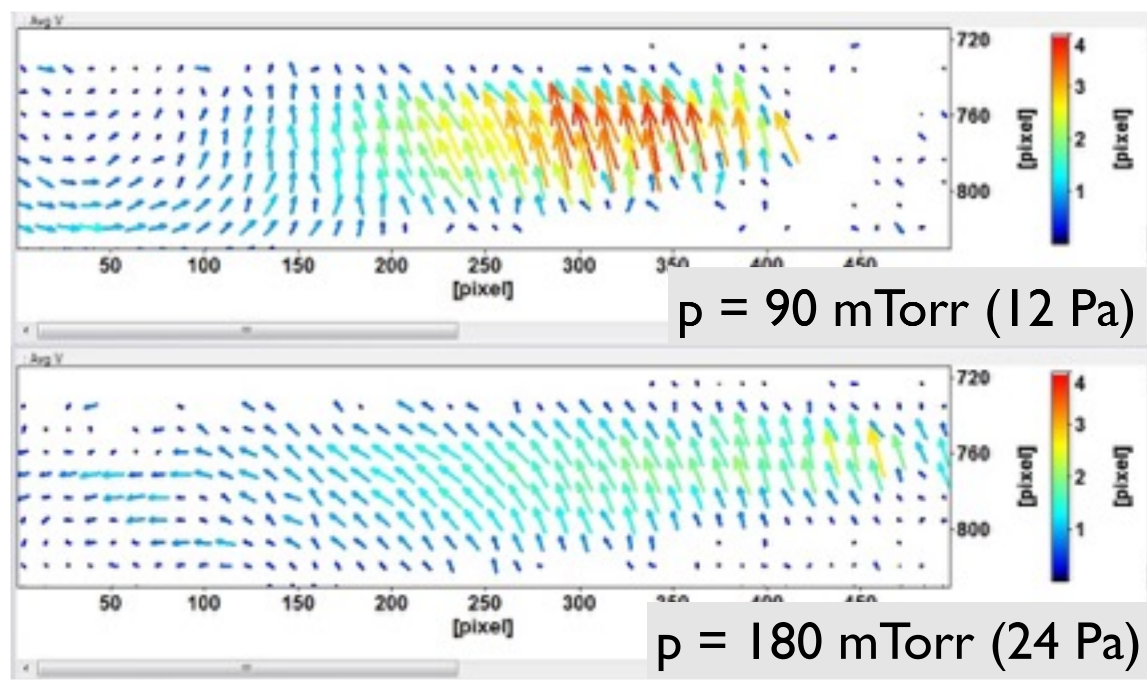
Most recent measurements confirm the simultaneous presence of dust density waves with a strong circulation of the dust particles in the plasma

2 micron, RF = 2 W, B = 1. 5 T,
p = 90 mTorr





- Latest measurements use a dual camera arrangement to visualize the particle cloud through side and top ports.
- Measurements are performed sequentially.
- Confirms the circulation of the particles, but also indicates a more complex three-dimensional flow - likely driven by ion E x B motion.



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Summary: current status of the MDPX device

- <u>Engineering status:</u>
  - 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.

- <u>Research status:</u>
  - 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.

OUTLOOK FOR DUSTY PLASMA RESEACH

References

- Journals
  - JPP - Journal of Plasma Physics
  - PoP – Physics of Plasmas
  - PRL – Physical Review Letters
  - PRE – Physical Review E
  - PPCF – Plasma Physics and Controlled Fusion
  - PSS – Planetary and Space Science
  - TPS – IEEE Transactions on Plasma Science

- Textbooks
  - *Introduction to Dusty Plasma Physics* – P. Shukla and A. Mamun
  - *Physics and Applications of Complex Plasmas* – S. Vladimirov, K. Ostrikov, and A. Samarian
  - *Plasma Physics* – A. Piel

Selected list of institutions involved in dusty plasma research

- US
  - Auburn University (Physics)
  - Baylor University (Physics)
  - Caltech (Physics)
  - University of Alabama at Huntsville (Mech. Eng.)
  - University of California - San Diego (Elec. Eng.)
  - University of Colorado (Physics)
  - University of Iowa (Physics)
  - University of Michigan (Elec. Eng.)
  - University of Minnesota (Mech. Eng.)
  - MIT (Nucl. Eng.)
  - Virginia Tech
  - Wittenberg University
  - Los Alamos National Lab
  - Princeton Plasma Physics Lab
  - Naval Research Lab
- International
  - Germany: *U. Kiel, U. Giessen, U. Greifswald, U. Bochum, Germany Aerospace Center (DLR)*
  - Russia: *Russian Academy of Sciences, Joint Institute for High Temperatures (JIHT)*
  - France: *CNRS - Marseilles, U. Orleans*
  - Sweden: *Royal Institute of Technology, Univ. of Stockholm*
  - Japan: *U. Kyoto, Japanese Space Agency*
  - India: *Inst. Plasma Research (IPR), U. Delhi*

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Outlook for dusty plasma research is very promising

- Dusty plasma as "model systems" for soft condensed matter, fluid systems and statistical mechanics - need new insights and people to help make these connections.
- A unified model of dust grain charging in plasmas still remains elusive - can a model be developed that works for lab, fusion, and space plasmas?
- Upcoming space missions to Jupiter, comets, Moon, Mars will involve study of charged dust or charged ice in solar system environment - need a new generation of lab studies to support these missions.
- Several groups around the world are studying magnetic field effects - need new models, theories, and diagnostic tools to understand experimental observations.
- Dust formation and control in fusion is a major issue for plasma-material interaction studies - dust is a contaminant, but can it be used to control and fuel the plasma or forn disruption mitigation?
- New "multi-user" dusty plasma lab facilities for ground- and space-based research are coming online.