The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

1856-39

2007 Summer College on Plasma Physics

30 July - 24 August, 2007

DUSTY PLASMA PHYSICS

Basic Theory and Experiments

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Basic Theory and Experiments

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CONTENTS

General references

- Shukla & Mamun, *Introduction to Dusty Plasma Physics,* IOP, Bristol, 2002. (SM)
- Goertz, Rev. Geophys. 27, 271, 1989. (G)
- Fortov et. al., Physics Reports 421, Dec. 2005. (F)
- Mendis and Rosenberg, *Cosmic Dusty Plasma*, Annu. Rev. Astron. Astrophys. 32, 419, 1994. (MR)
- Bouchoule, ed., *Dusty Plasmas: Physics, Chemistry and Technical Impacts in Plasma Processing*, John Wiley, New York, 1999. (B)
- Plasma Sources Science & Technology, Vol. 3 Number 3, August 1994. (PSST)
- *references to above sources*

Part I.—Introduction

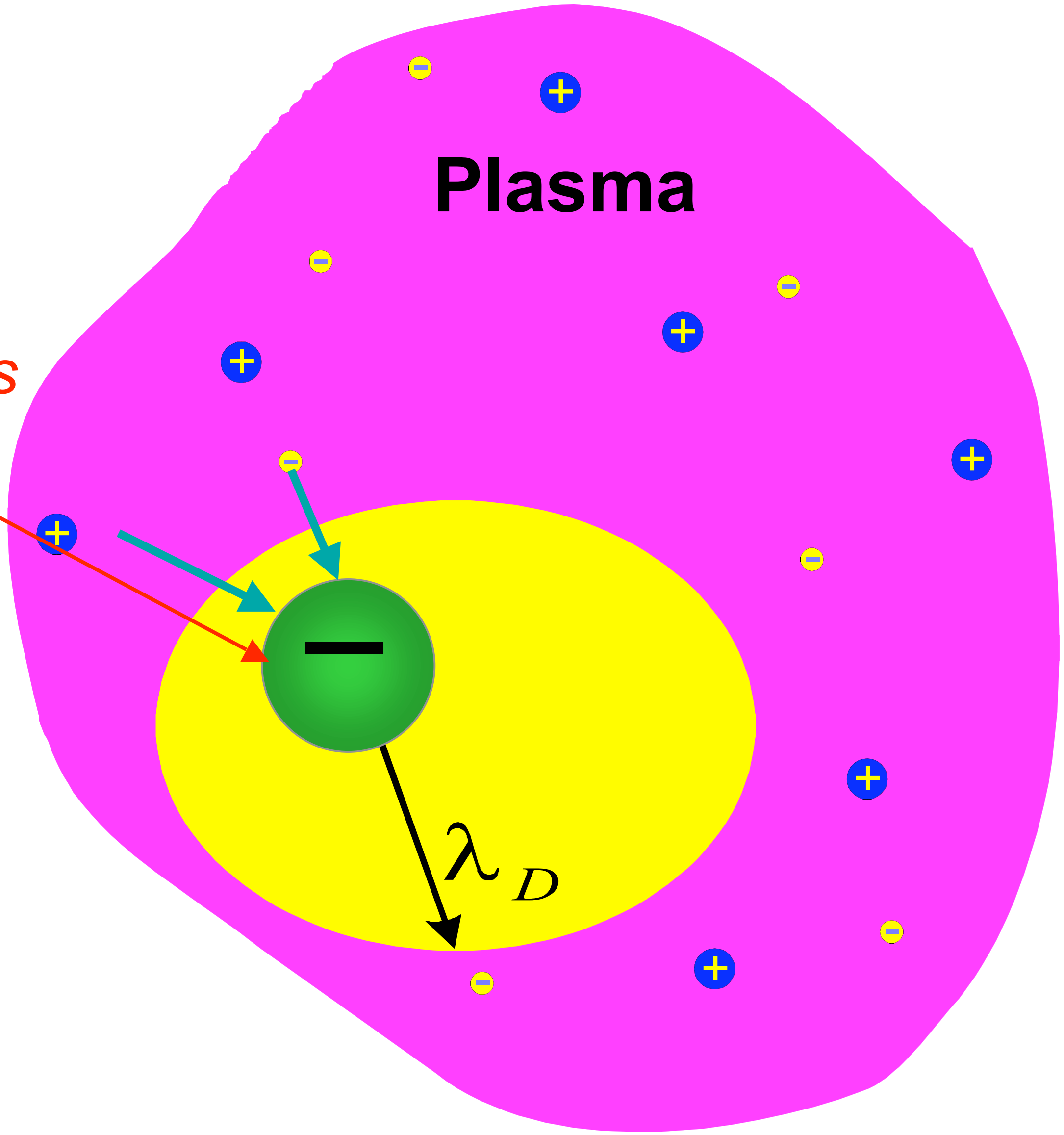
- what is a dusty plasma
- were are dusty plasmas
  - in space, astrophysics, and the lab
  - comets
  - noctilucent clouds, PMSEs
  - Saturn’s rings
  - plasma processing reactors
  - fusion devices

What is a dusty plasma?

plasma = electrons + ions

dusty plasma
= plasma + small particles of solid matter

- absorbs electrons and ions
- becomes negatively charged
- Debye shielding



Cosmic dusty plasmas (MR)

- Solar nebulae
- Planetary nebulae
- Supernova shells
- Interplanetary medium
- Molecular clouds
- Circumsolar rings
- Asteroids

Dusty plasmas in the solar system (G)

- Cometary tails and comae
- Planetary ring systems – Saturn’s rings
- Dust streams ejected from Jupiter
- Zodiacal light

Dusty plasmas on the earth

- Ordinary flames
- Atmospheric aerosols
- charged snow
- lightning on volcanoes

Man-made dusty plasmas

- Rocket exhaust
- Dust on surfaces in space (space station)
- Dust in fusion devices
- Thermonuclear fireballs
- Dust precipitators used to remove pollution from smoke stacks
- Plasmas used for microelectronic fabrication, e.g. semiconductor chips, solar cells and flat panel displays
- Plasma Enhanced Chemical Vapor Deposition (PECVD) technologies
- Dusty plasma devices (DPDs) used to produce and study dusty plasmas in the laboratory

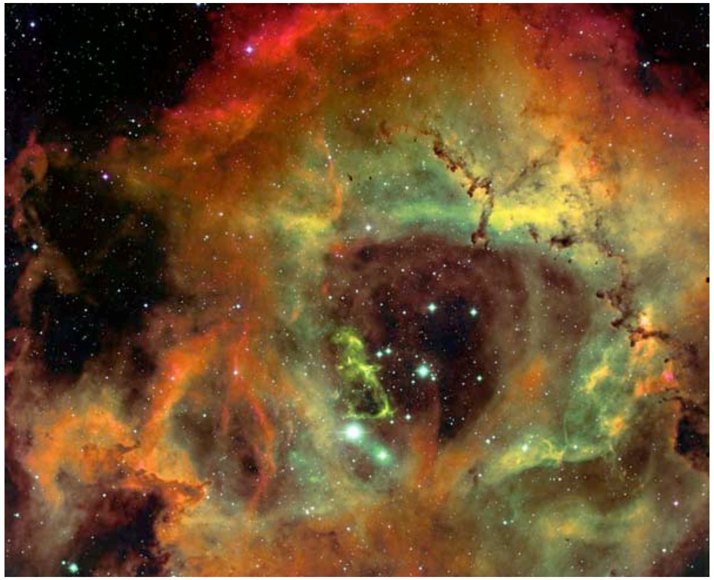
A flame is a very weakly ionized plasma that contains soot particles

An early temperature measurement in a dusty plasma.

the high degree of ionization in ordinary hydrocarbon flames (five orders of magnitude higher than that predicted by the Saha equation) is due to thermionic electron emission from 10 nm particles of unburnt carbon (soot)

D. A. Mendis, New Vistas in Dusty Plasmas, AIP Conf. Proc. 799, American Inst. Physics, Melville, N. Y. 2005, *p 583.*

Rosette Nebula



Our solar system accumulated out of a dense cloud of gas and dust forming everything that is now part of our world.

ASTRONOMY

- Gravity was the focus of 20th Century Astronomy
- For the 21st Century, it will be electromagnetism and plasmas in addition
- astrophysicists now realize that the dust may be charged and that must be taken into account

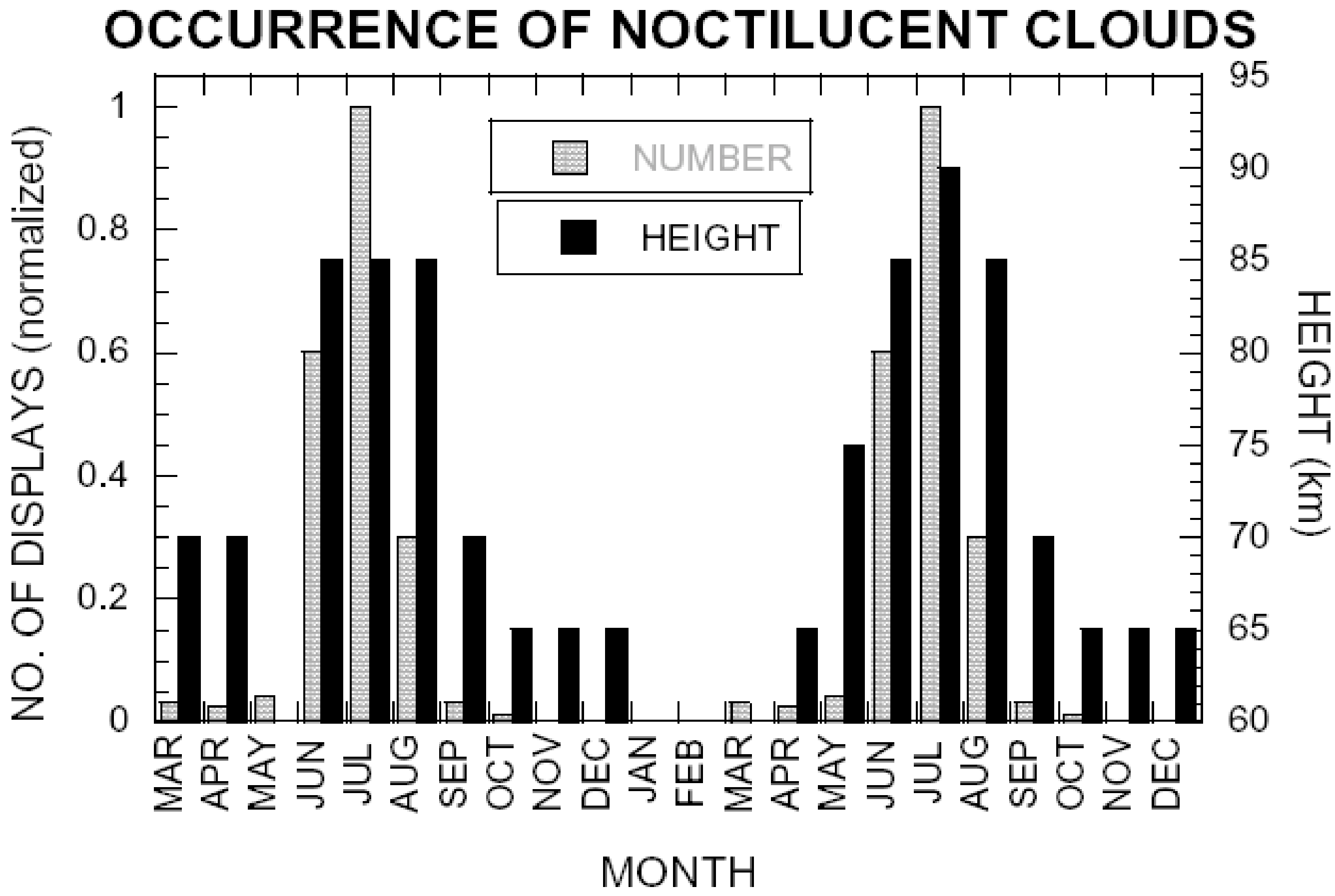
Comet Hale-Bopp (MR)

Noctilucent Clouds

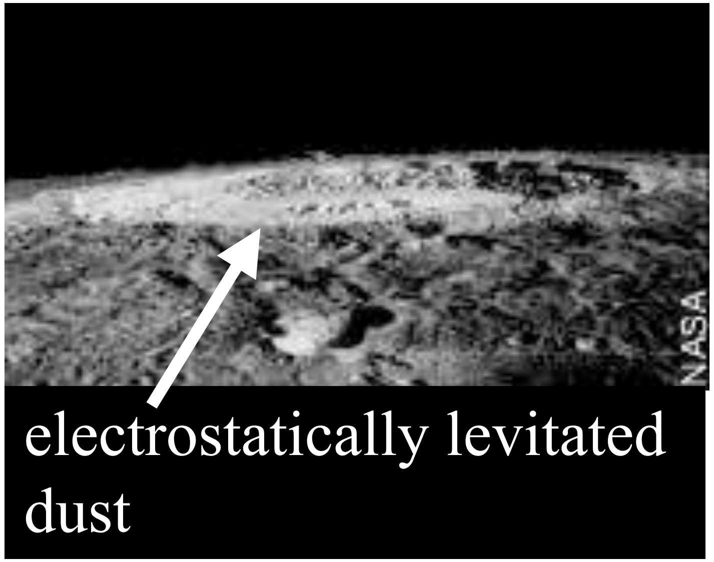
- an unusual atmospheric phenomenon occurring in the high latitude region of the earth's summer –(–140 C) mesosphere (50 – 85 km);
- glowing, silvery white clouds of ice crystals (50 nm) at about 80 km
- usually seen just after sunset
- associated with PMSE -polar mesospheric summer echoes – unusually strong radar echoes and electron "bite-outs'

average height of PMSEs and number of displays of NLCs

M. Rapp & F. –J. Lübken, Atmos. Chem. Phys. 4, 2601, 2004.



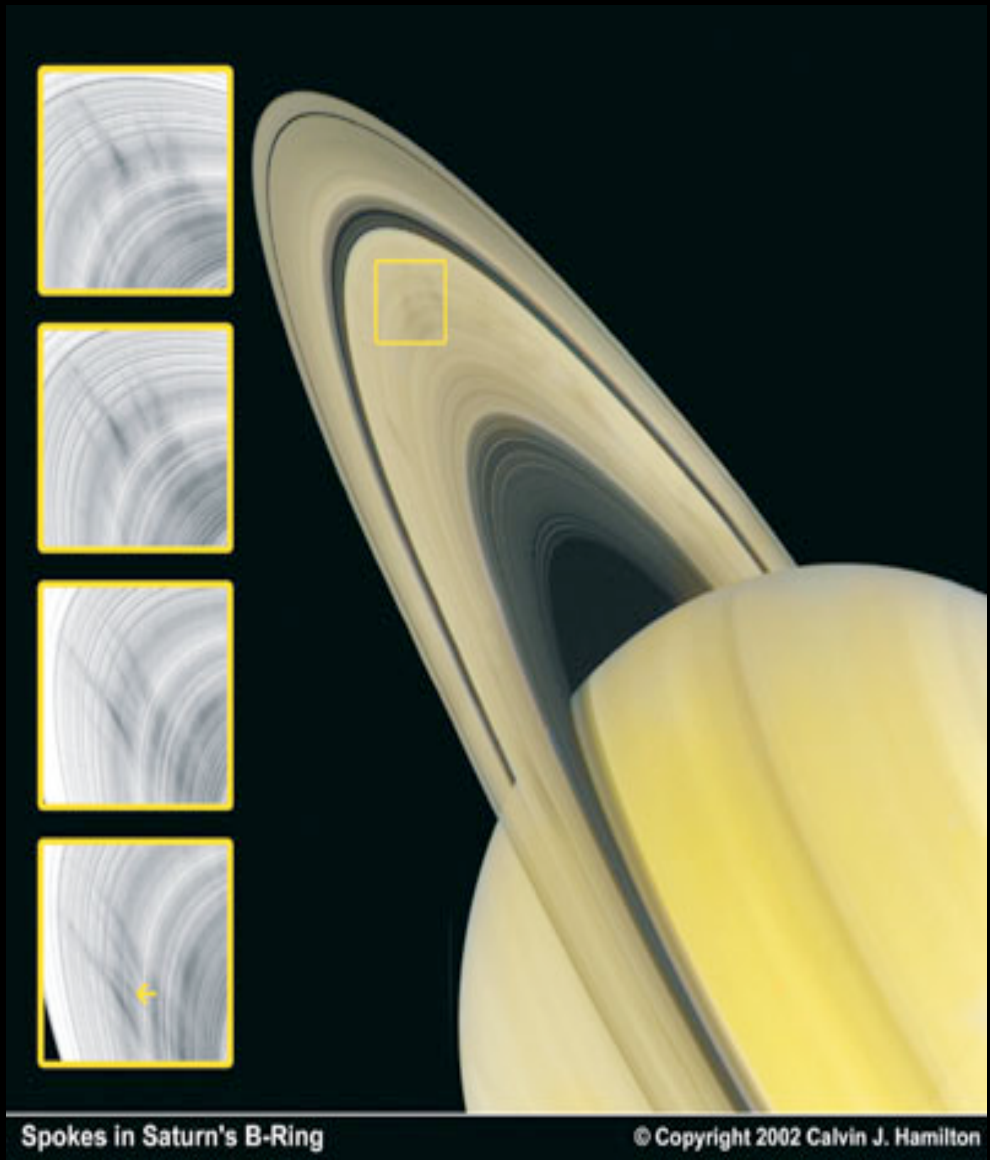
Apollo astronauts see "moon clouds"



- dust acquires a positive charge due to solar UV
- some grains are lifted off of the moon's surface by the electrostatic force

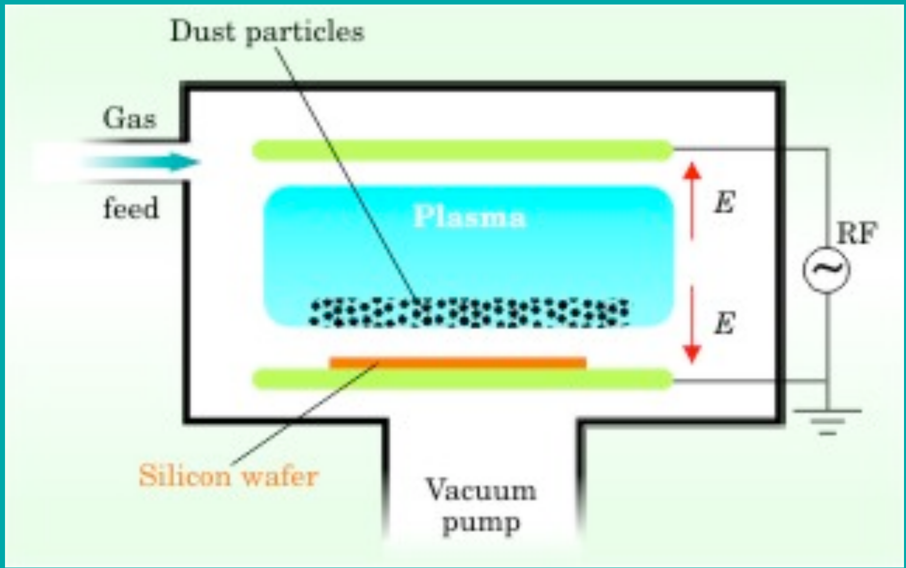
http://www.space.com/scienceastronomy/061007_moon_dust.html

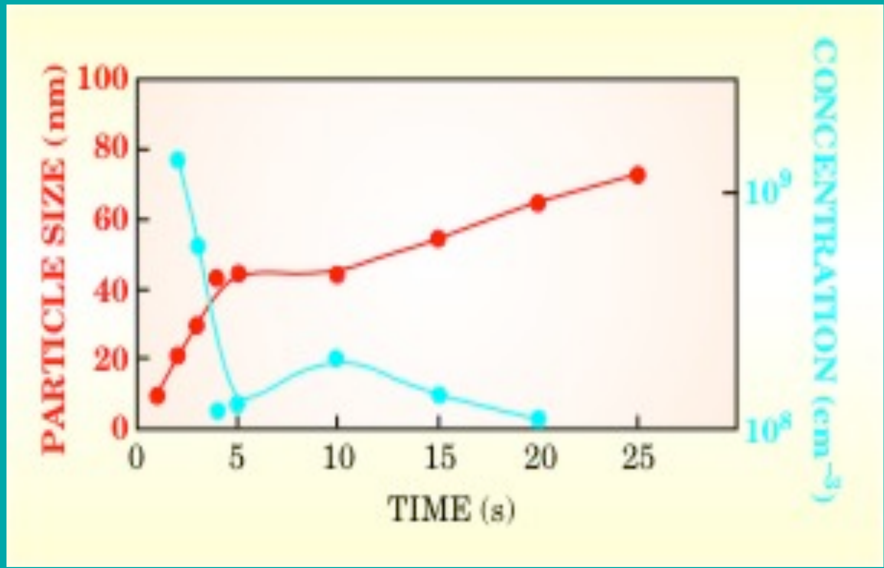
Spokes in Saturn's B ring (G, MR)



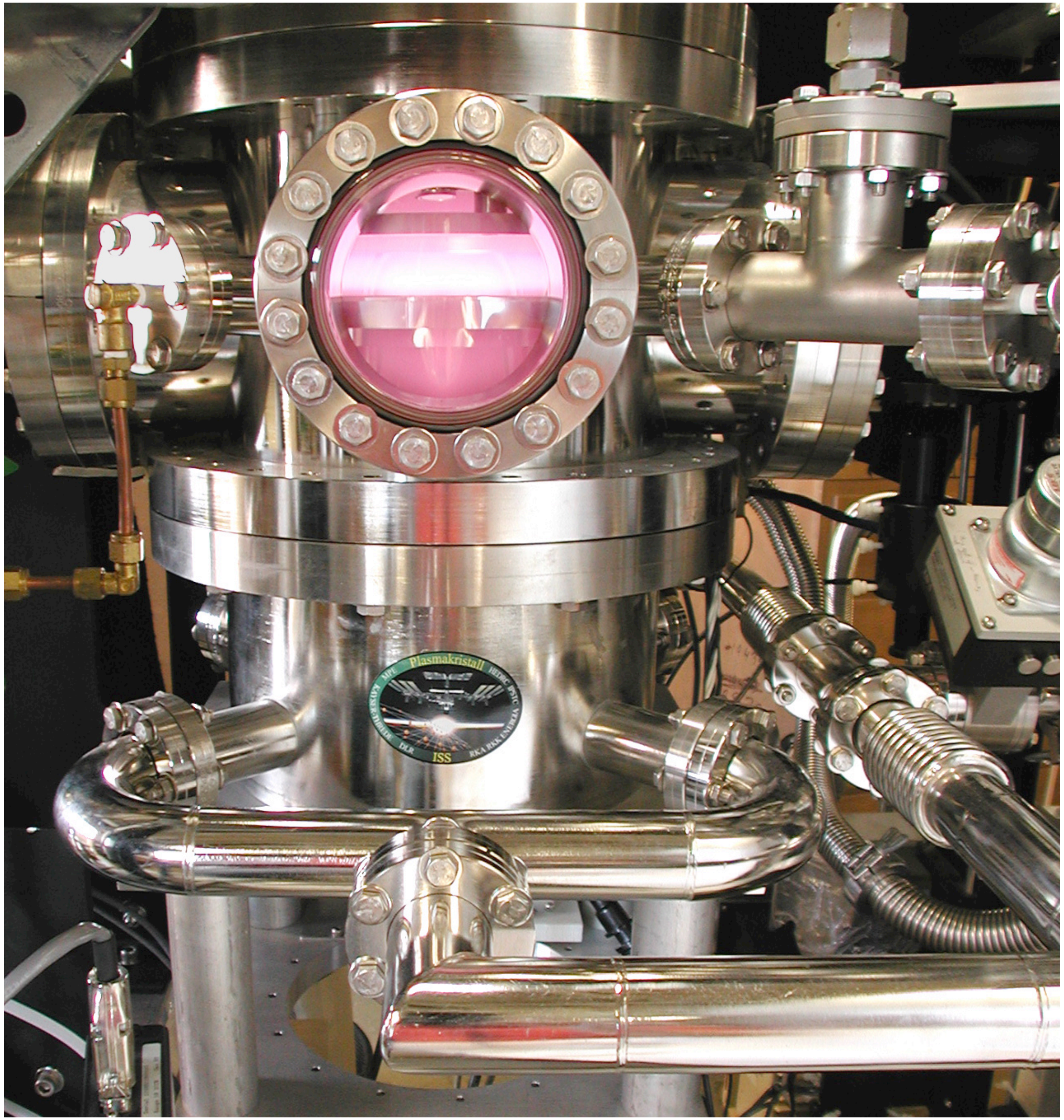
- discovered by Voyager 2 in 1980
- nearly radial spokes rotating around the outer portion of the dense B ring
- spokes seen in forward scattered light – fine dust
- spokes exhibit dynamical behavior on timescales of minutes.

Semiconductor Processing (B, PSST)



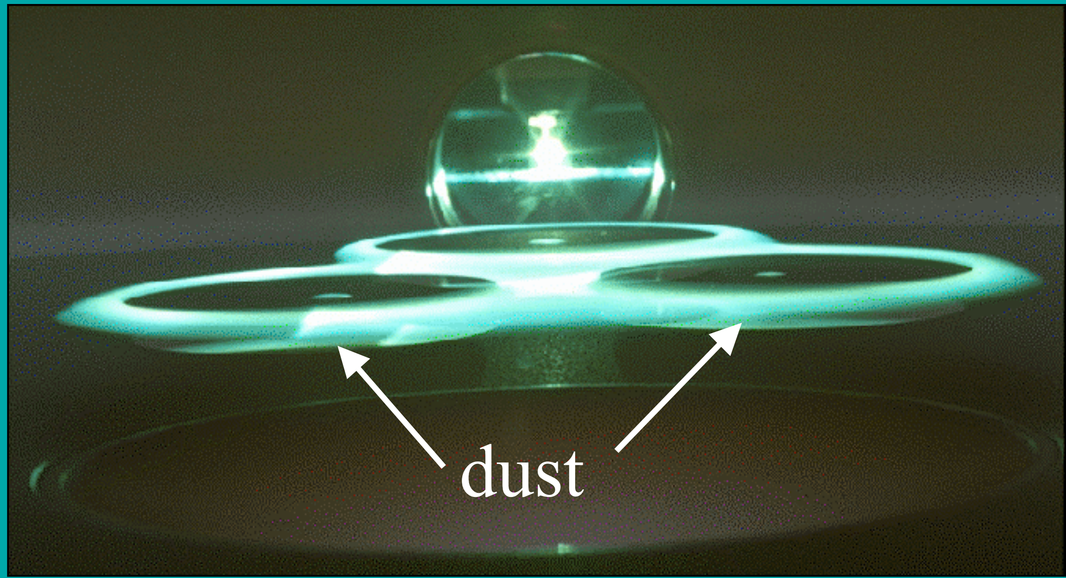


silane (SiH_4) + Ar + O_2 → SiO_2 particles



John Goree’s Lab at the Univ. of Iowa

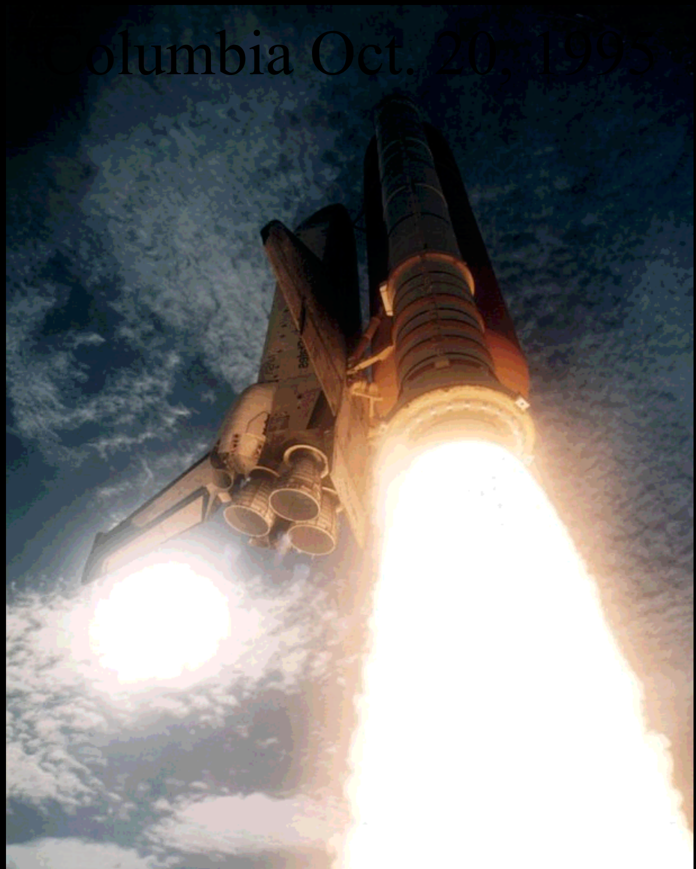
Semiconductor Manufacturing (B, PSST)



The formation of dust during the processing of semiconductor electronics is a serious problem for the industry. It has been estimated that up to one-half of all semiconductor chips were contaminated during processing.


THIS IS WONDERFUL— A COMPLETELY DUST-FREE LAB. WHAT DO YOU STUDY HERE?
Dust.
S.Harris

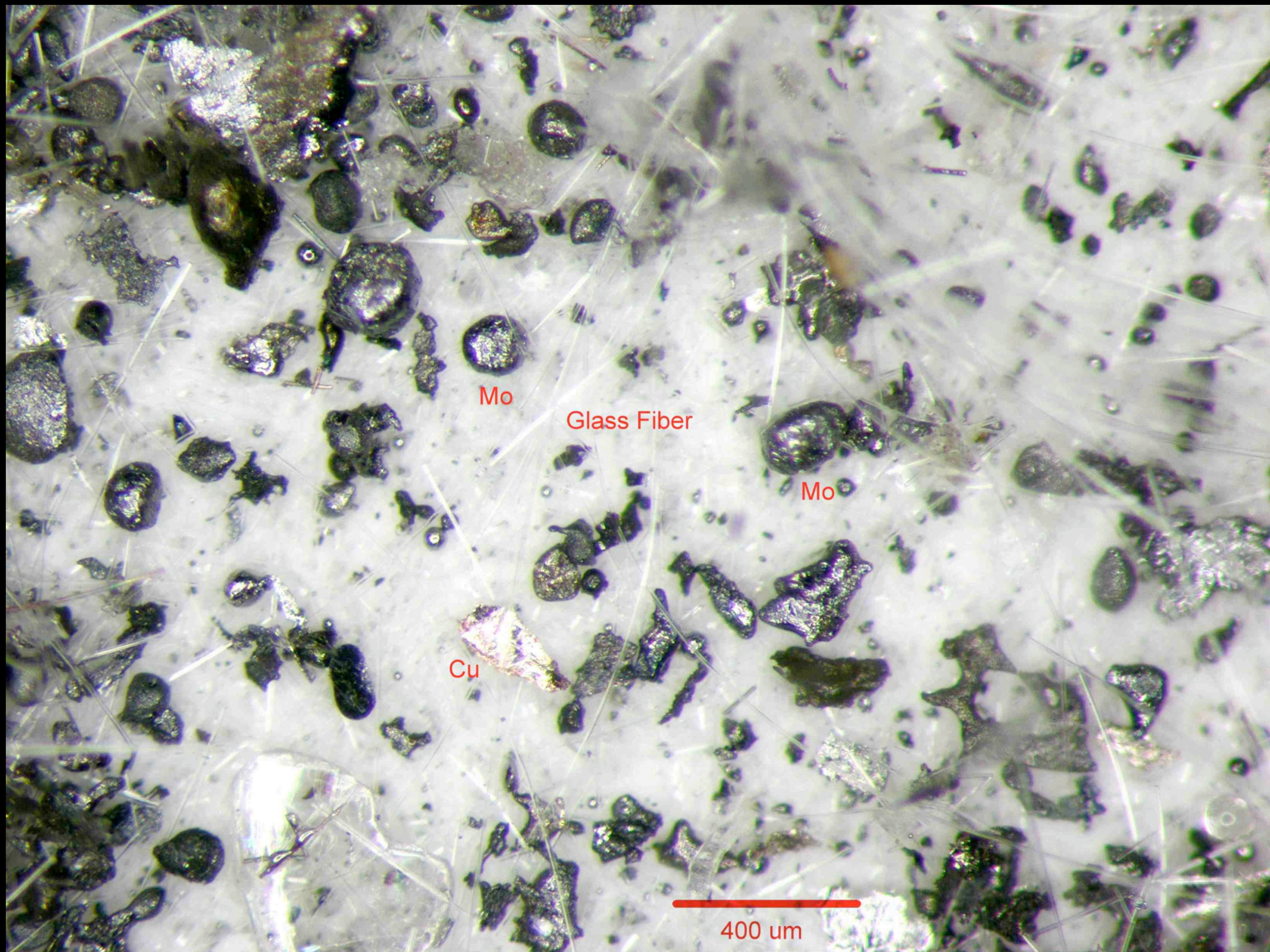
Rocket Exhaust is a Dusty Plasma



- 0.01-10 μm Al_2O_3 particles
- Charged dust may be trapped
  in earth's B field
- Particles may reach high altitudes and contribute to seed population for NLC
- Occurrence of NLC has increased over past 30 years!

dust in fusion devices ◊ D III

dust particles in tokamak C Mod



dust in fusion devices

- the “dust” is a result of the strong interaction between the material walls and energetic plasma which causes flaking, blistering, arching and erosion of the carbon limiters or beryllium surfaces.
- one problem is that the dust may retain a large inventory of tritium
- studies indicate that dust can be transported deep into the plasma causing a serious contamination problem.
- dust poses a serious concern for ITER

snowy plasma

- blowing snow can get charged by triboelectric charging (friction)
- both positive and negative snow has been found: –200 μC/kg and +72 μC/kg.
- The transport of snow along a surface is a process called *saltation*. The particles hop along the surface rebounding to heights of about 10 cm. The bouncing particles are usually negative, while the particles on the surface are positive.
- the electrostatic forces on the snow may be an important consideration in avalanches.

Milestones in dusty plasma research

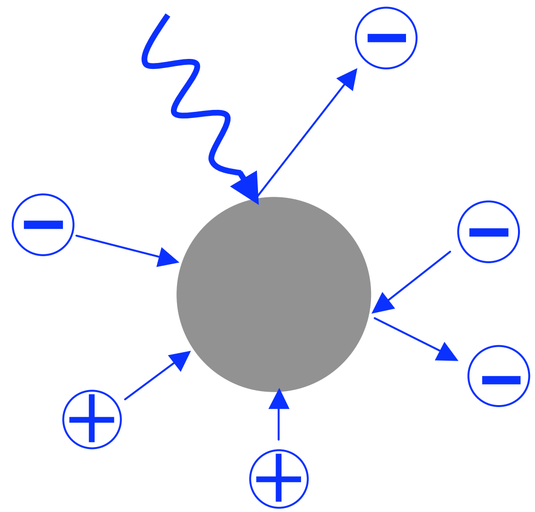
- the discovery of the spokes in Saturn’s B ring in 1980 and
- the realization of the dust contamination problem in the semiconductor processing industry at about the same time
- *provided the impetus that allowed the field of dusty plasma physics to flourish.*
- the discovery of the dust problem in fusion devices in1998 is another factor that continues to drive dusty plasma research

Part II.—Basic processes in dusty plasmas (SM, MR, F)

A. dust charging theory
B. the electrostatic potential around a dust particle
C. forces on dust particles in a plasma
D. strongly and weakly coupled dusty
E. Dusty plasmas under microgravity
F. particle growth in plasmas

A. Dust Charging Processes

- electron, positive and negative ion collection
- secondary emission
- UV induced photoelectron emission



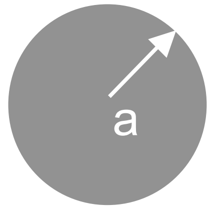
Total current to an electrically *floating* grain = 0

$$\Rightarrow \quad \Sigma I = I_e + I_+ + I_- + I_{sec} + I_{pe} = 0$$

The dust particle floats to a potential at which $\Sigma I = 0$

The Charge on a Dust Grain

- In typical lab plasmas $I_{sec} = I_{pe} = 0$, also take $I_- = 0$
- Electron thermal speed >> ion thermal speed so the grains charge to a negative potential φ_S ($= V_s - V_p$) *relative to the plasma*, until the condition $I_e = I_i$ is achieved.



- Take spherical grains of radius a
- electron current $$I_e = -en_e\sqrt{\frac{kT_e}{2\pi m_e}}\exp\left(\frac{e\varphi_S}{kT_e}\right)4\pi a^2$$
- orbital motion limited (OML) ion current $$I_i = en_i\sqrt{\frac{kT_i}{2\pi m_i}}\left(1-\frac{e\varphi_S}{kT_i}\right)4\pi a^2$$

Isolated *vs.* closely-packed dust (G, MR)

- when computing the charge $Q_d = eZ_d$ on dust particles we must first consider whether or not the particles can be considered as *"isolated"* or not.
- a single dust particle in a plasma is *isolated*
- when many dust particles are present with a number density n_d, the dust charge will be a function of the ratio of the interparticle spacing, $\Delta \sim (3/4\pi n_d)^{1/3}$ to the plasma Debye length, λ_{D}.

A. Isolated dust particles (F)

- $en_i = en_i + Q_d n_d$, $n_d \approx 0$, so $n_i \approx n_i$
- charging equation

$$-\left(\frac{T_e}{T_i}\right)^{1/2}\left(\frac{m_i}{m_e}\right)^{1/2}\exp\left(\frac{e\varphi_s}{kT_e}\right)+1-\frac{e\varphi_s}{kT_i}=0$$

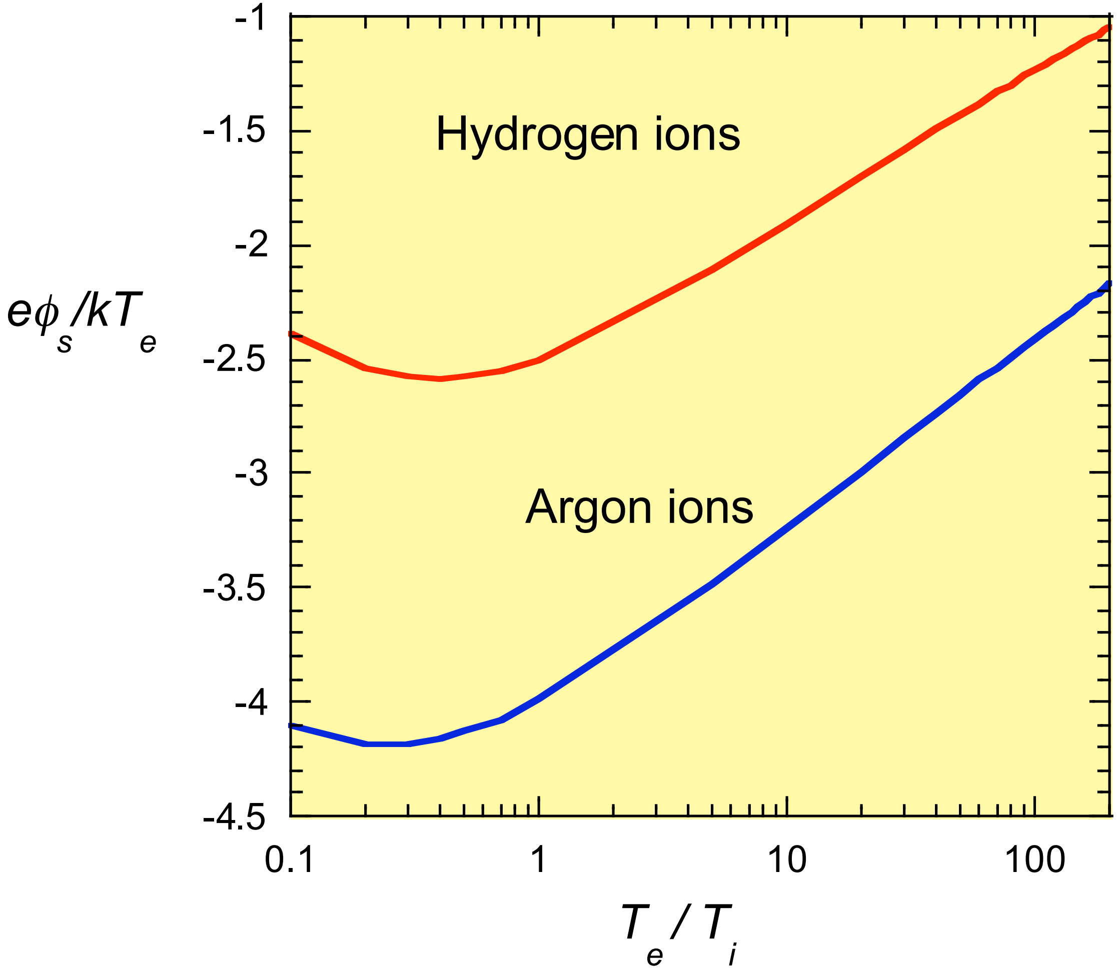
- define:

$$\psi_s = e\varphi_s / kT_e, \quad \mu = m_i / m_e, \quad \tau = T_e / T_i$$

-

$$\Rightarrow \quad -\tau^{1/2}\mu^{1/2}e^{\psi_s}+1-\tau\psi_s=0$$

dust potential and charge (F)



charge $Q_d = eZ_d$

$Q_d = C_d \varphi_s$

$C_d = 4\pi\varepsilon_o a$

Typical Laboratory Plasma

For $T_e = T_i = T$ in a hydrogen plasma,

$$\varphi_S = -\,2.5\,(kT/e)$$

If $T \approx 1$ eV and $a = 1$ μm,

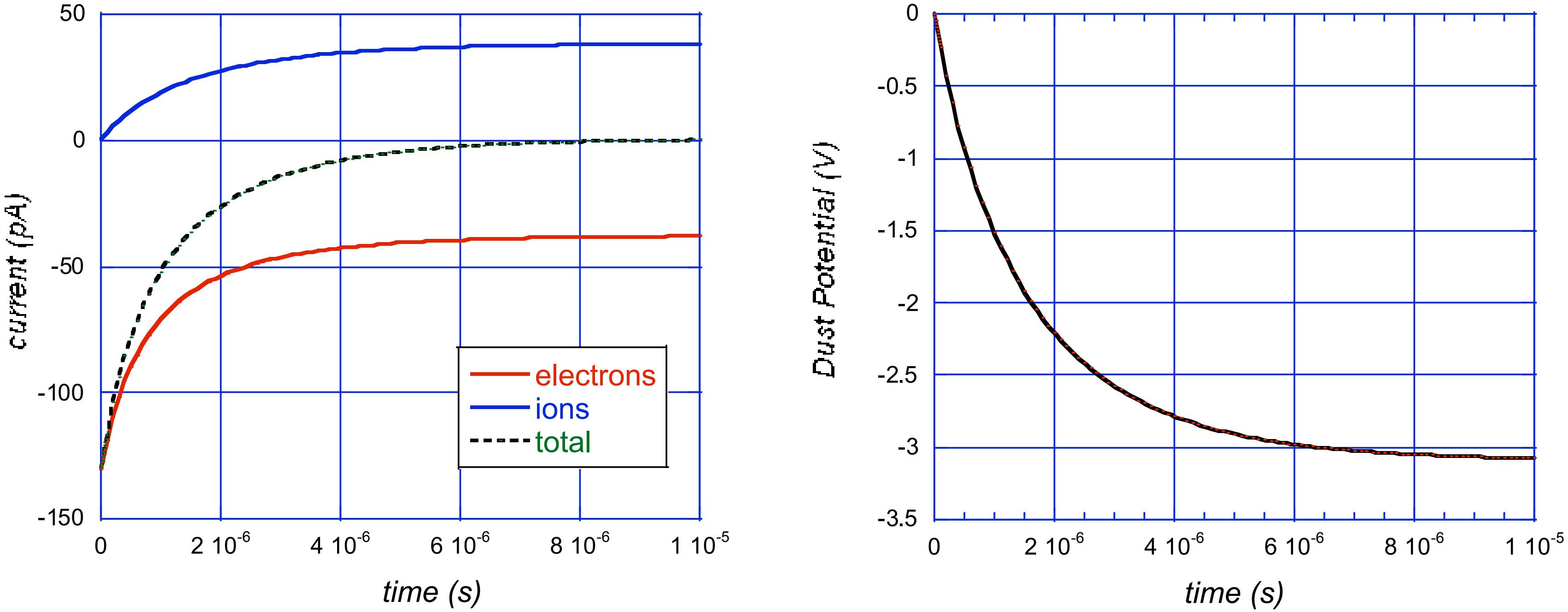
$$Q_d \approx -\,2000\ e$$

Mass, $m_d \approx 5 \times 10^{12}\ m_p$

Evolution of grain charge

$$\frac{d\varphi_d}{dt} = \frac{en_o a}{4\varepsilon_o}\left[-V_{T_e} e^{\varphi_d/T_e} + V_{T_i}\left(1-\varphi_d/T_i\right)\right]$$

H^+ ions, $T_e = 2.5$ eV, $T_i = 0.025$ eV, $n_{e,i} = 10^{15}\ m^{-3}$



$$q_d = \int_0^\infty \left(I_e + I_i\right) dt = 1.62\times10^{-16}C \approx 4\pi\varepsilon_o a\varphi_d$$

Characteristic charging time t_{ch}

- $t_{ch} \sim \dfrac{Q_d}{I_o}$, where $I_o = I_{eo} = I_{io}$ are the steady state

  electron and ion currents to the particle, $Q_d = 4\pi\varepsilon_o a V_s$

- using $I_{eo} = en_e\sqrt{\dfrac{kT_e}{2\pi m_e}}e^{eV_s/kT_e}4\pi a^2$, then, for a Ar^+ plasma

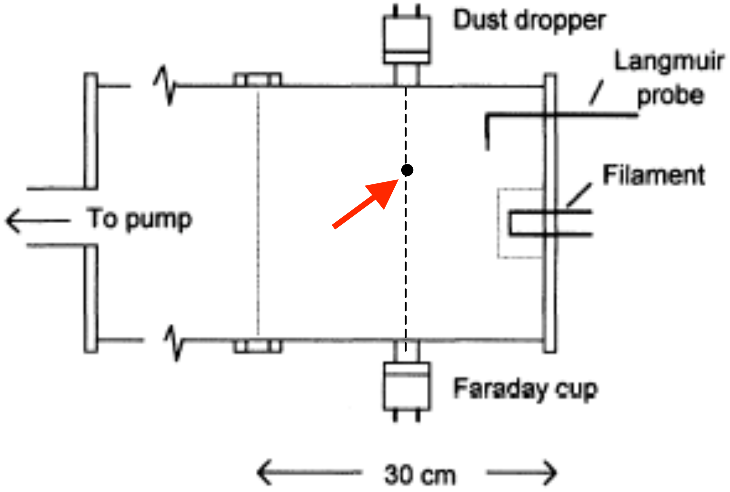
  with $T_e = 2eV, V_s$; $-4kT_e/e$, $n_e \sim 10^{15}m^{-3}$, $a = 1\mu m$

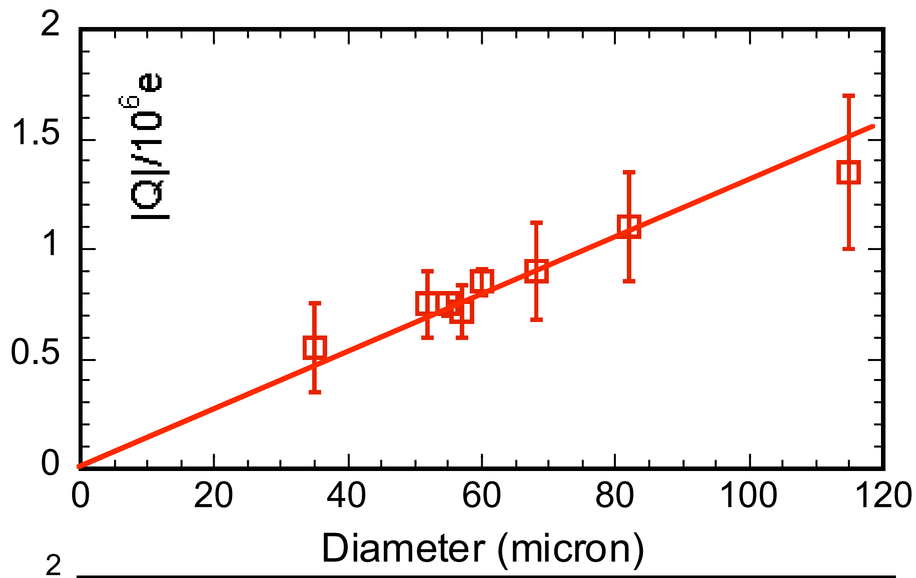
- $\Rightarrow \quad t_{ch} \approx 0.16\, m\sec$

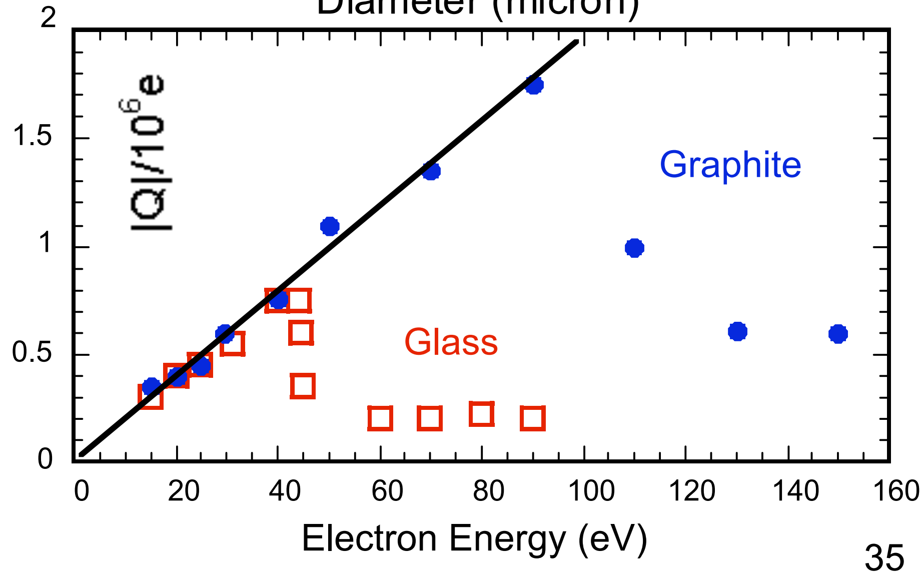
- note that $t_{ch} \sim \dfrac{1}{n_e a}$ (see Fortov, p. 13)

Dust Charge Measurements

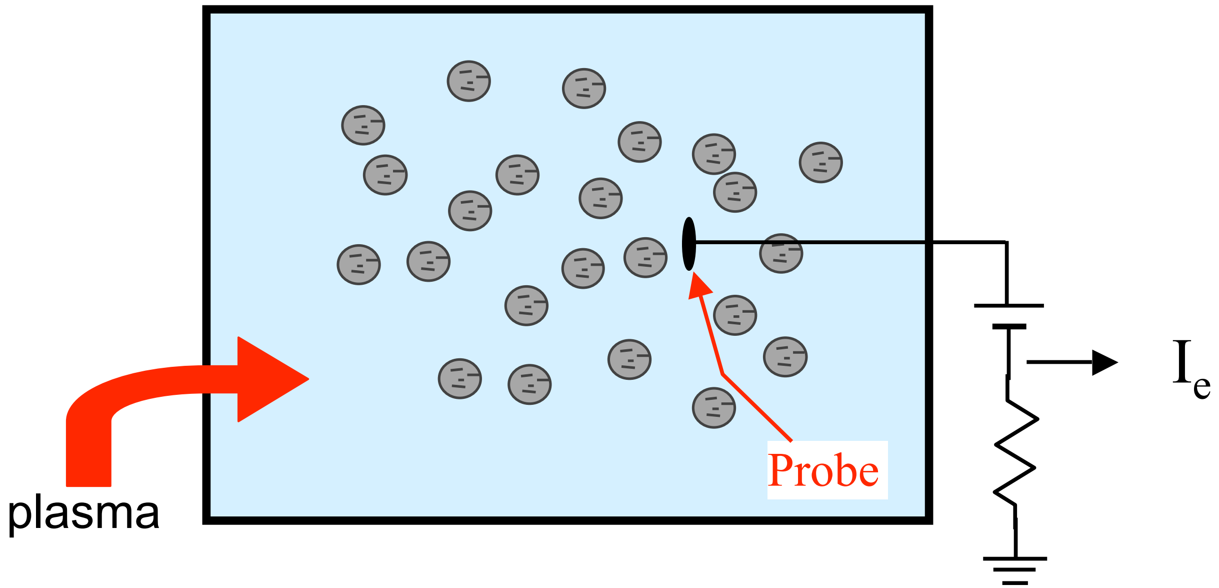
Walch, Horanyi, & Robertson,
Phys. Rev. Lett. 75, 838 (1995)

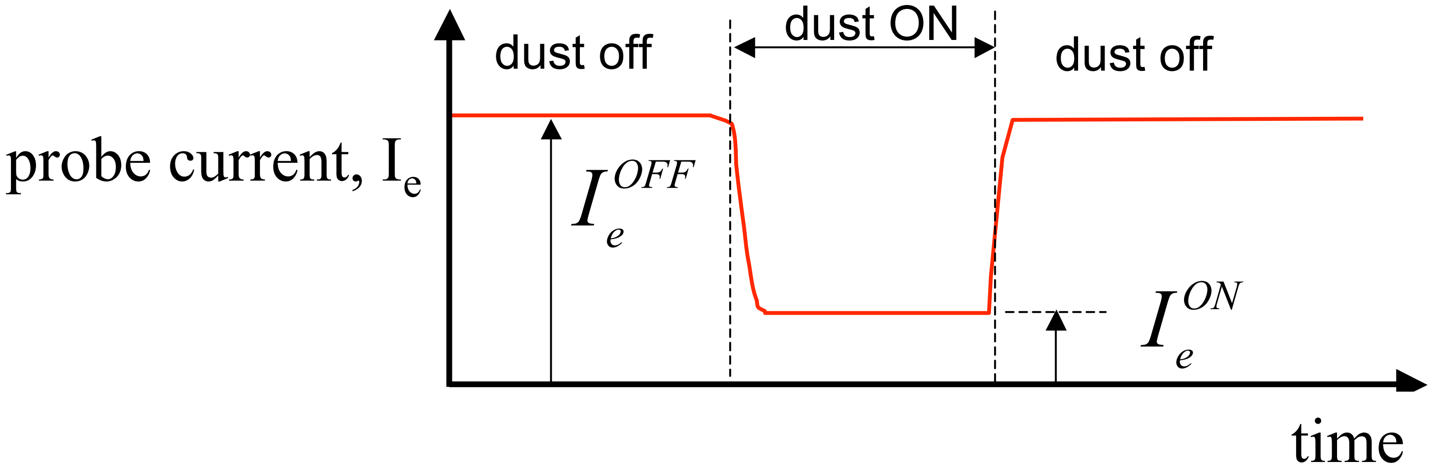




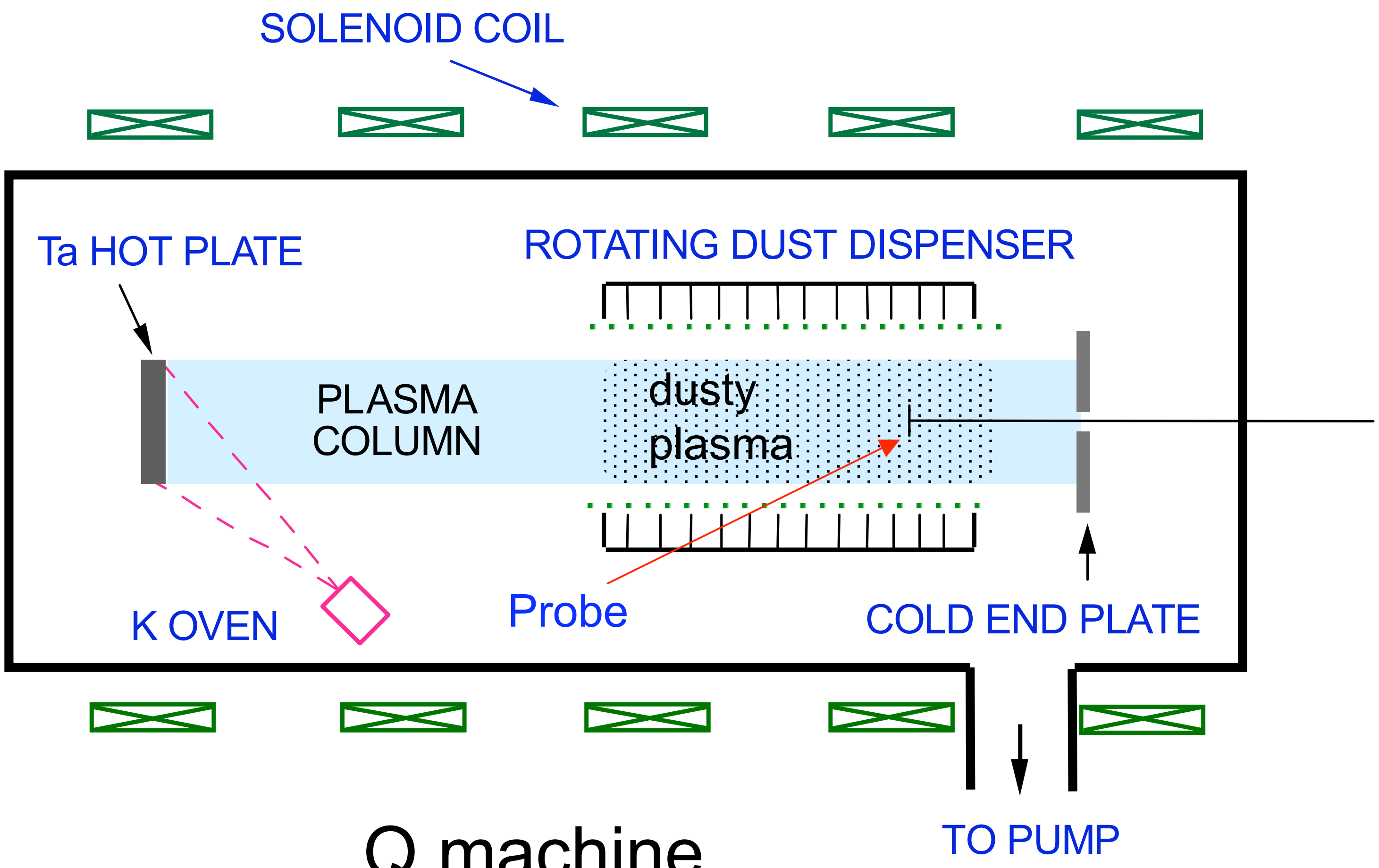


Langmuir probe measurements



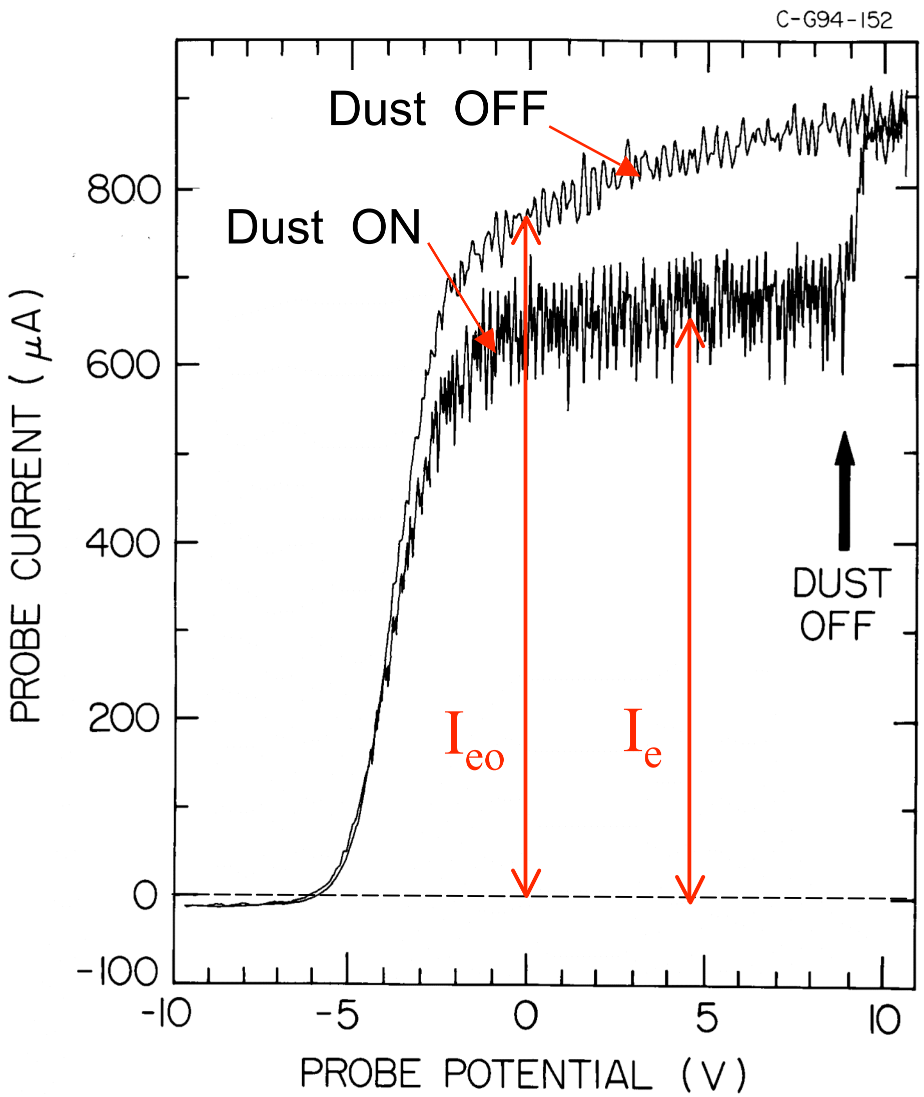


Dusty Plasma Device (F61)



Q machine

Langmuir probe measurements



- When the dust is turned ON, the electrons become attached to the dust grains and as a result the
the electron current to the probe decreases.

- The quantity $Z_d n_d$ and estimated by measuring the reduction in the electron probe current and using the neutrality condition $n_i = n_e + Z_d n_d$, using

$$Z_d n_d = n_o(1 - I_{e,dust}/I_{eo})$$

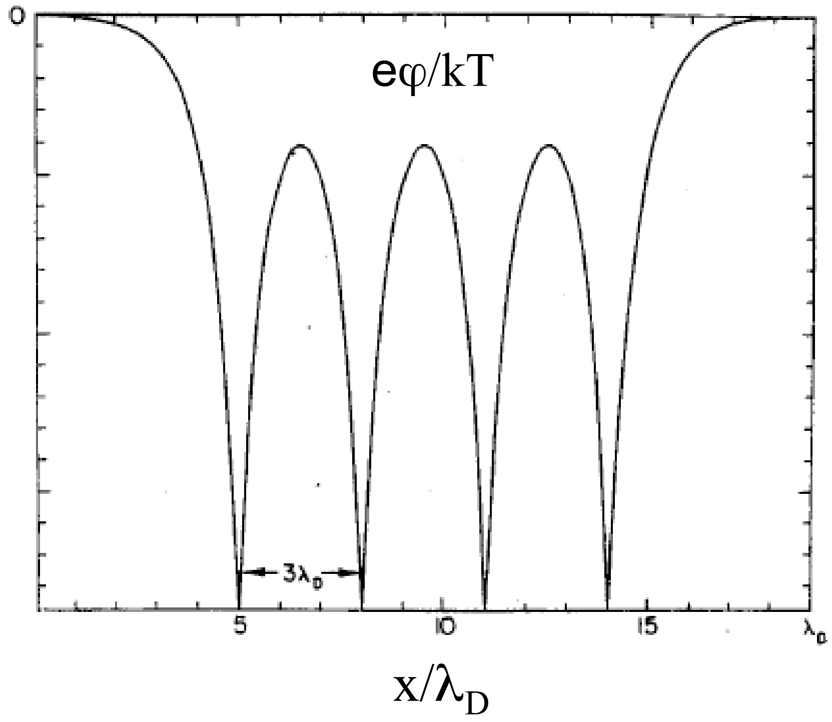
where n_o is the initial plasma density.

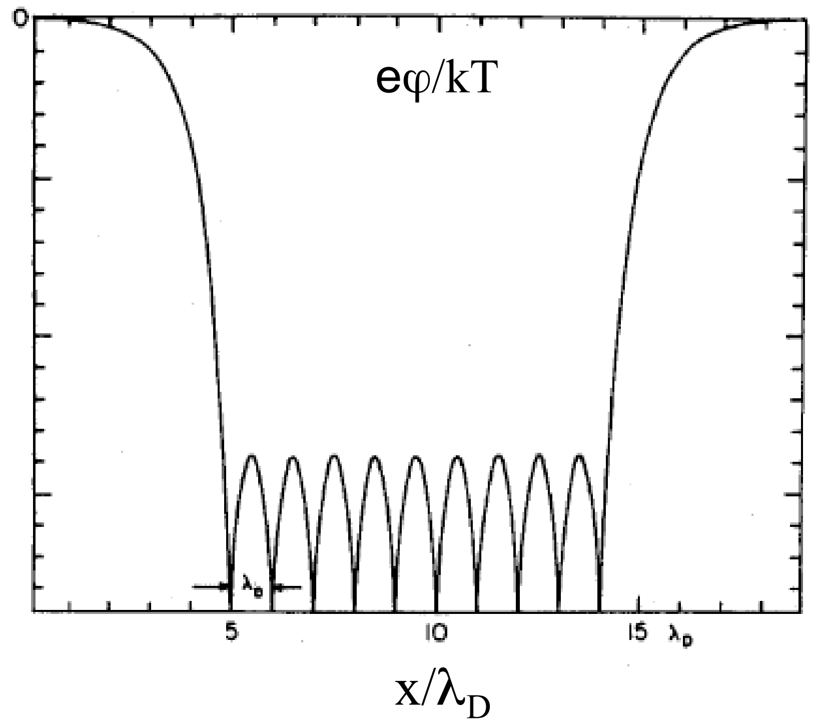
close-packing effect (G)

- if many dust grains are present the charge on a single grain is reduced, usually by a large value
- this reduction is due to the fact that the grain surface potential is not only due to the charge on this grain but to all other dust grains in its vicinity
- this effect is important when the intergrain spacing $\Delta \sim \lambda_D$

close-packing effect (G)

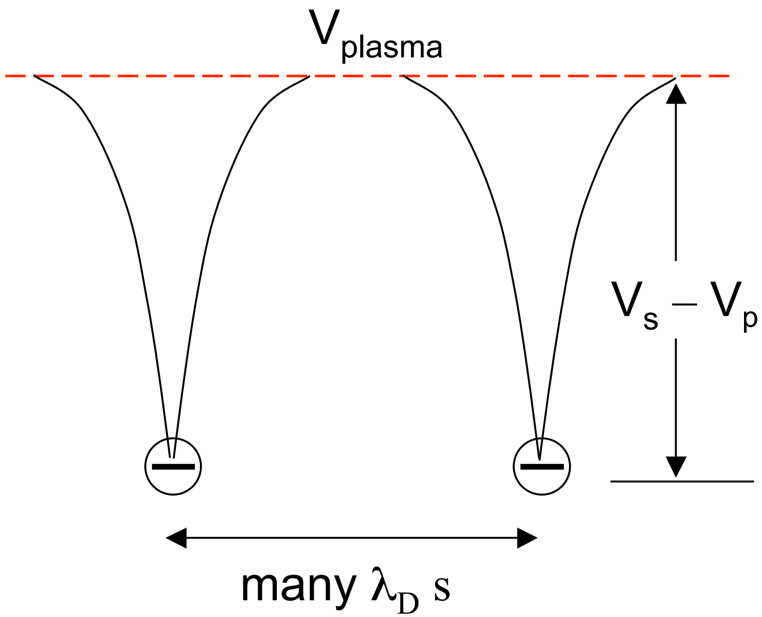
Equally spaced infinite plane sheets of dust grains



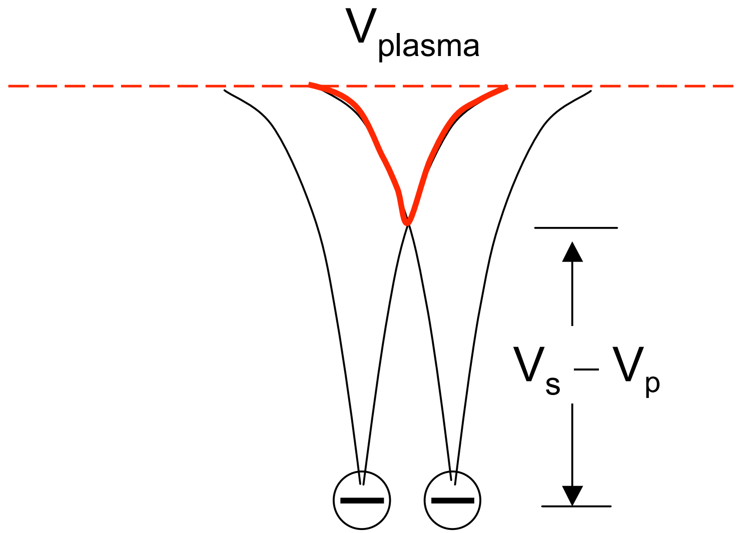


when the electrons are shared by many particles,
each particle gets a smaller portion.

Isolated grains



close-packed grains



In simpler terms, when a fixed number of electrons are shared by many particles, each particle gets a smaller portion.

close-packing effect: theory

$$-en_e\left(\frac{kT_e}{m_e}\right)^{\frac{1}{2}} e^{e\varphi_s/kT_e}\pi a^2 + en_i\left(\frac{kT_i}{m_i}\right)^{\frac{1}{2}}\left(1-\frac{e\varphi_s}{kT_i}\right)\pi a^2 = 0$$

$$n_i = n_e - Zn_d \Rightarrow n_e = \left(1 + Zn_d / n_i\right)$$

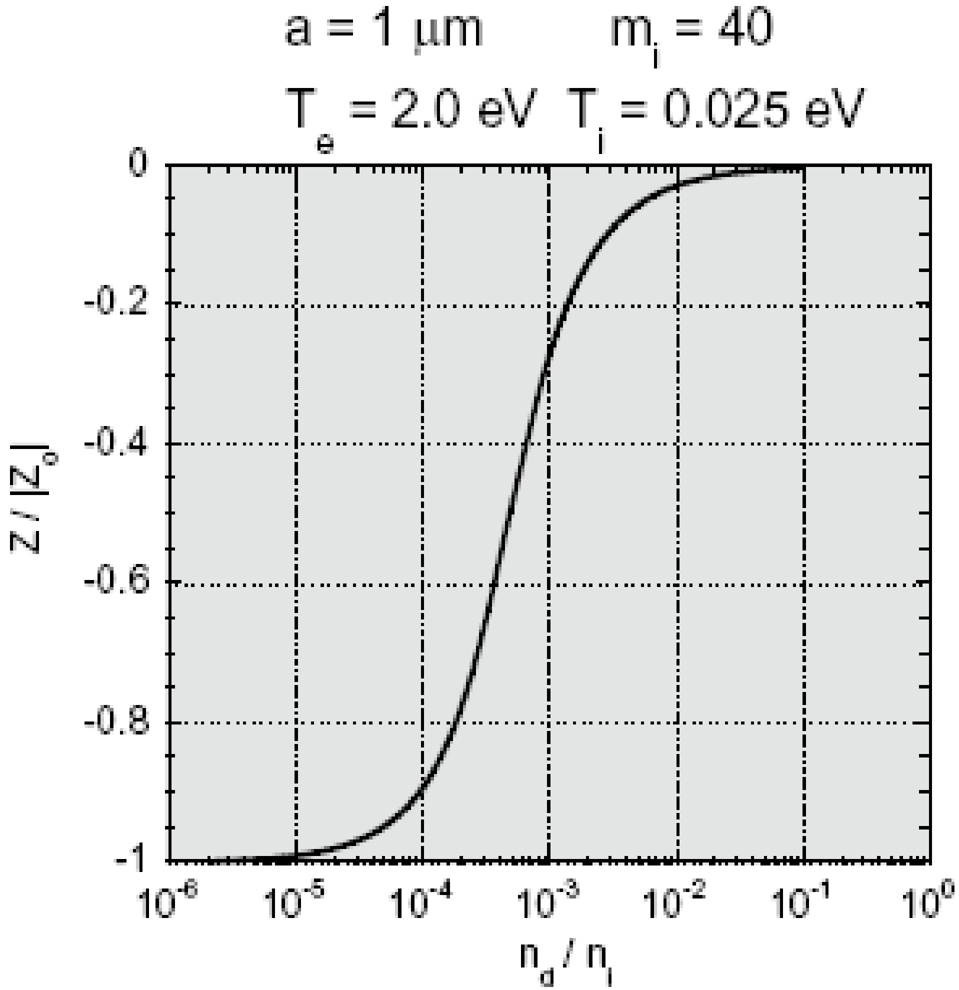
$$eZ = 4\pi\varepsilon_o a\varphi_s$$

$$\tau \equiv T_e / T_i, \ \mu \equiv m_i / m_e, \ \psi_s \equiv e\varphi_s / kT_e$$

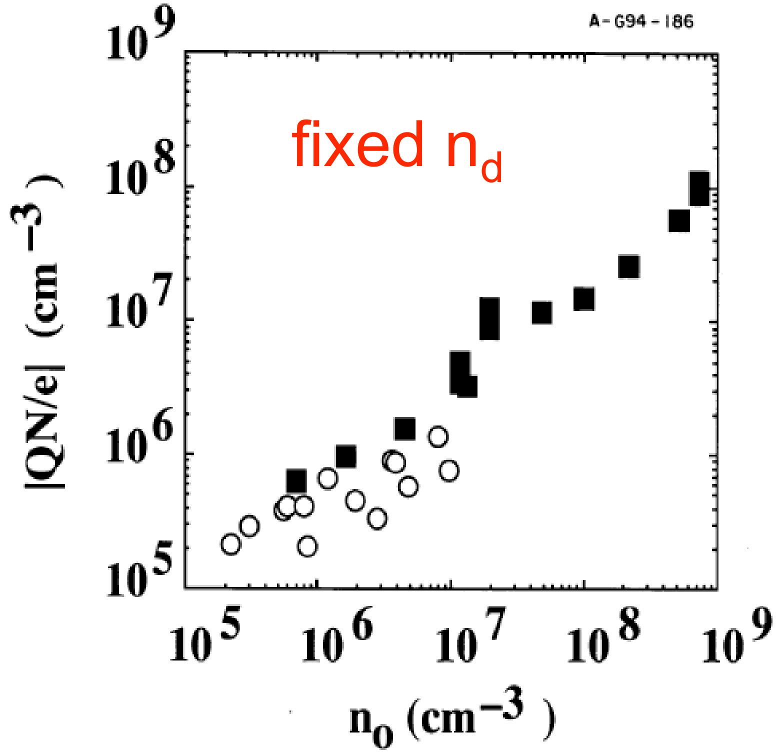
$$\Rightarrow -\mu^{\frac{1}{2}}\tau^{\frac{1}{2}}\left[1+\left(\frac{4\pi\varepsilon_o}{e}\right)P\psi_s\right]e^{\psi_s} + 1 - \tau\psi_s = 0$$

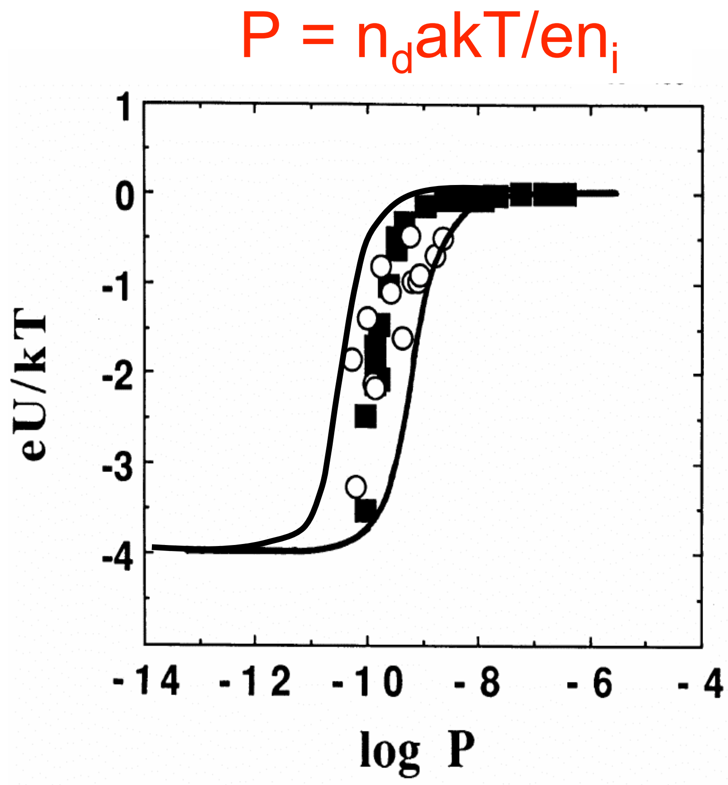
$$P \equiv \frac{n_d akT_e}{en_i} \ (Havnes\ parameter)$$

close-packing effect: results



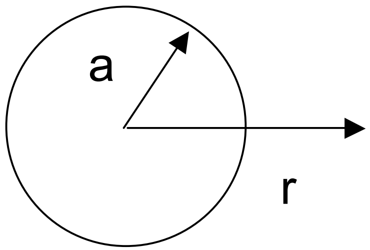
close-packing effect: experiment





(see, F61)

B. the electrostatic potential around a dust particle-isotropic plasma



$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} = -\frac{e}{\varepsilon_o}(n_i - n_e)$$

$$\varphi(a) = \varphi_s, \;\; n_i(a) = 0$$

$$\varphi(\infty) = 0, \;\; n_i(\infty) = n_o$$

assume Boltzmann electrons and ions with $e\varphi / kT_{e(i)} < 1$

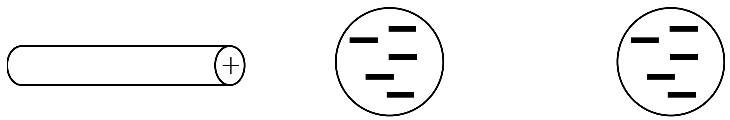
$$\varphi(r) = \frac{eZ}{r} e^{-(r-a)/\lambda_D} \approx \underbrace{\frac{eZ}{r} e^{-r/\lambda_D}}_{\text{Yukawa Potential}}, \;\; for \;\; a << \lambda_D$$

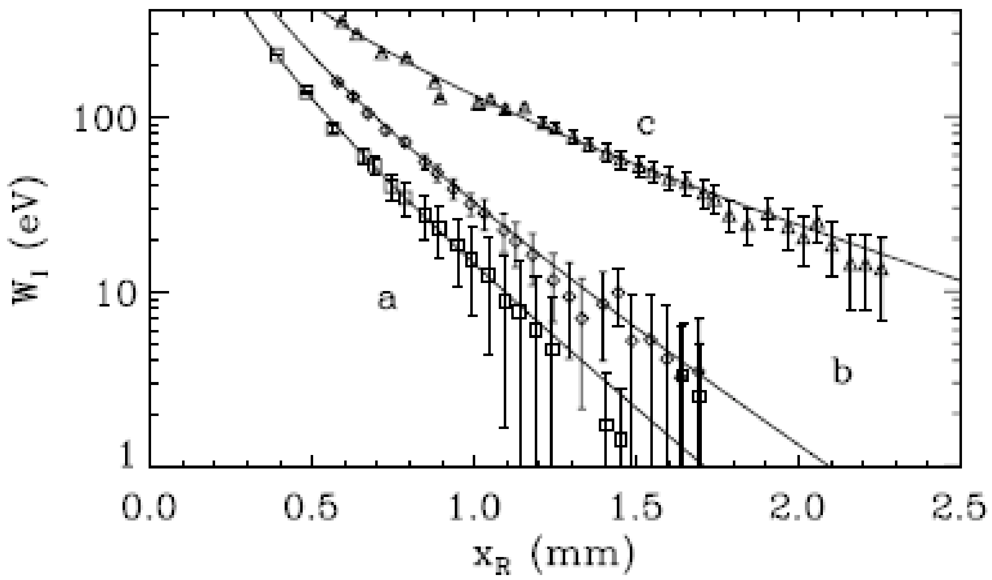
Yukawa Potential

electrostatic PE between particles (F18)

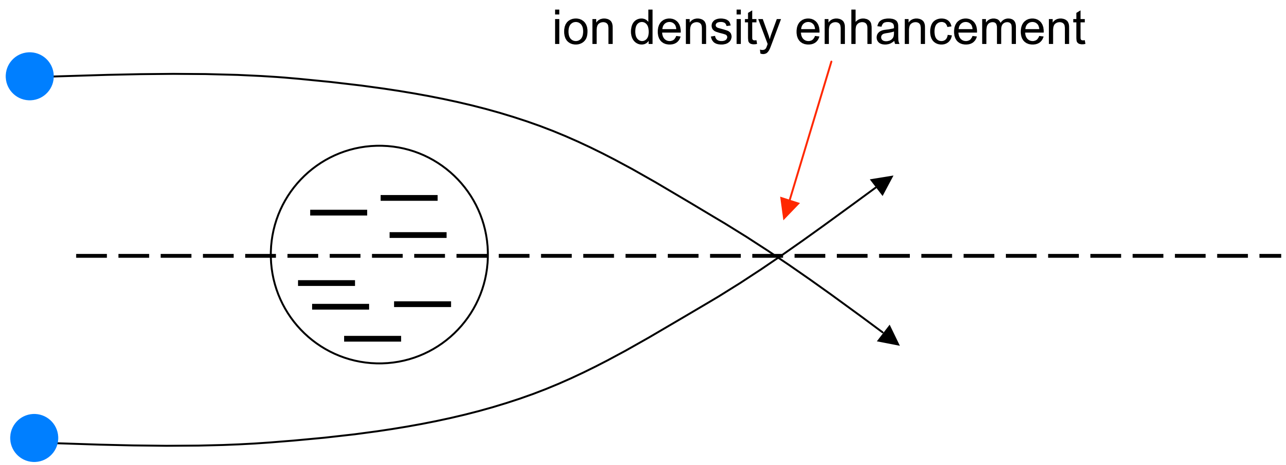
$$U_{el}(r) ; \frac{e^2 Z^2}{r} e^{-r/\lambda_D}$$

experiments

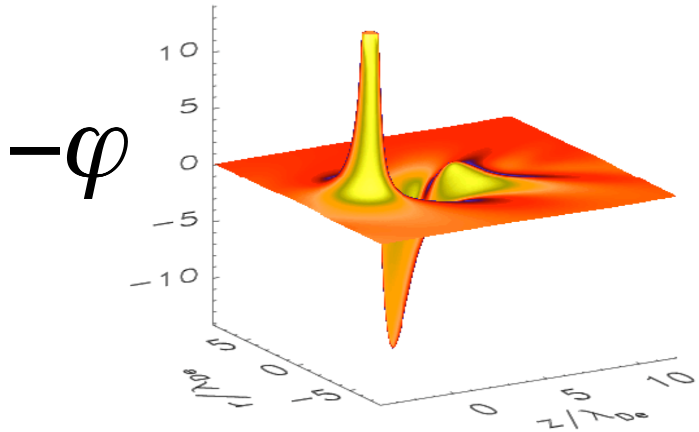




the electrostatic potential around a dust particle-with ion flow



F157-159



C. Forces on dust particles (F, p 40)

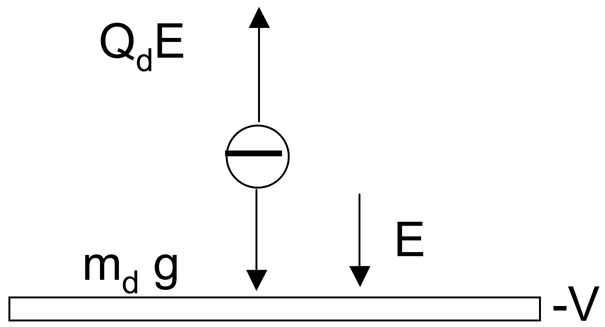
1) gravity: $F_g = m_d g = (4\pi/3)a^3 \rho_d g$

where ρ_d is the density of the dust material, typically ~ 1000 – 2000 kg/m^3

for thin-walled hollow microspheres of wall thickness t, $m_d \cong 4\pi a^2 t$

2) electric force: $F_e = Q_d E$

can be used to levitate negative particles:



for a 1 micron particle

$m_d \sim 8x10^{-15}$ kg

$Q \sim -2000e$

$m_d g = Q_d E$

$E = m_d g/Q_d \sim 2.5$ V/cm

3) neutral drag force: F_{nd} (F, p. 46)

u_d = dust velocity, $v_{T,n}$ = gas thermal speed, N = gas density

(a) $u_d \gg v_{T,n}$ $$F_{nd} = \pi a^2 N m_n u_d^2$$

(b) $u_d \ll v_{T,n}$ $$F_{nd} = m_d u_d \underbrace{\left(\delta \frac{8\sqrt{\pi}}{3} a^2 N \frac{m_n}{m_d} v_{T,n} \right)}$$

dust-neutral collision frequency, ν_{dn}

where $1<\delta<2$ is a factor that depends on how the atoms are scattered on the dust surface.

4) thermophoresis force: FTh (F, p 46)

This force arises if there is a temperature gradient in the neutral gas. It is due to the asymmetry in the momentum transfer to dust from neutrals and is directed toward lower gas temperatures. This force can be used to levitate particles against gravity.

$$F_{th} = \frac{4\sqrt{2\pi}}{15} \frac{a^2}{v_{T,n}} \kappa_n \nabla T_n$$

where κ_n is the thermal conductivity coefficient of the gas, which for atomic gases $\kappa_{\mathrm{n}} \approx 1.33\left(v_{T,n} / \sigma_{nn}\right)$, where σ_{nn} is the cross-section for neutral-neutral collisions

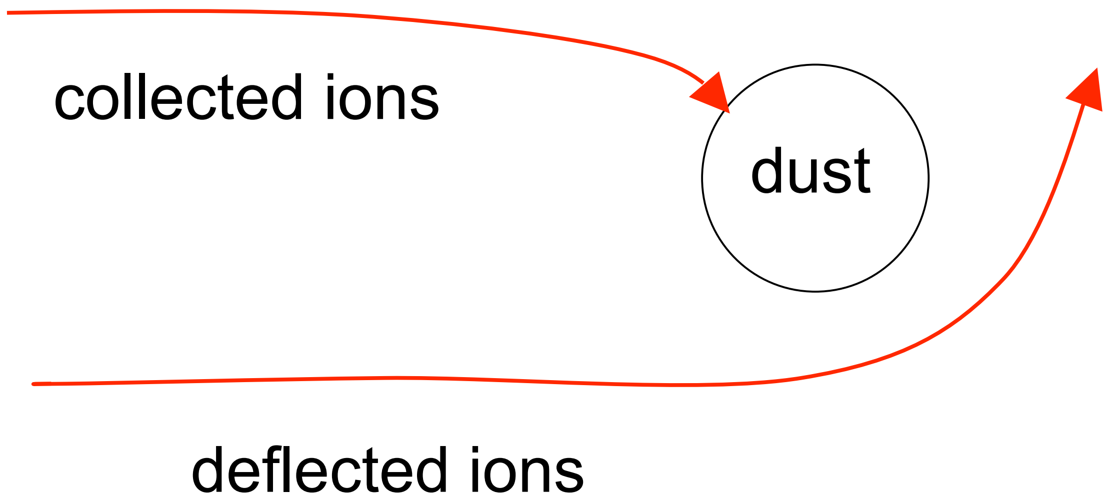
5) Ion drag force, Fid (F, p41)

- *This force arises from the momentum transfer from flowing ions to charged microparticles in a plasma.*

- *This can be one of the most important forces that gives rise to particle transport in dusty plasmas.*

- *Ion flows are usually produced by large scale electric fields that typically exist in plasmas.*

5) Ion drag force, Fid, *continued*



$$F_{id} = F_{ic} + F_{io}$$

Collection force due to ions impinging on grain

Orbit force due to ions deflected by grain

5) Ion drag force, Fid, *continued*

(a) collection force, F_{ic}

simplified theory of Barnes et. al. (F198)

u_i = ion drift speed

$$F_{ic} = n_i m_i u_i u_s \pi b_c^2$$

where $u_s = \left(\dfrac{8kT_i}{\pi m_i} + u_i^2 \right)^{\frac{1}{2}}$, mean ion speed

and $b_c = a\left(1 - \dfrac{2e\varphi_s}{m_i u_s^2}\right)^{\frac{1}{2}}$, collision impact parameter

5) Ion drag force, Fid, *continued*

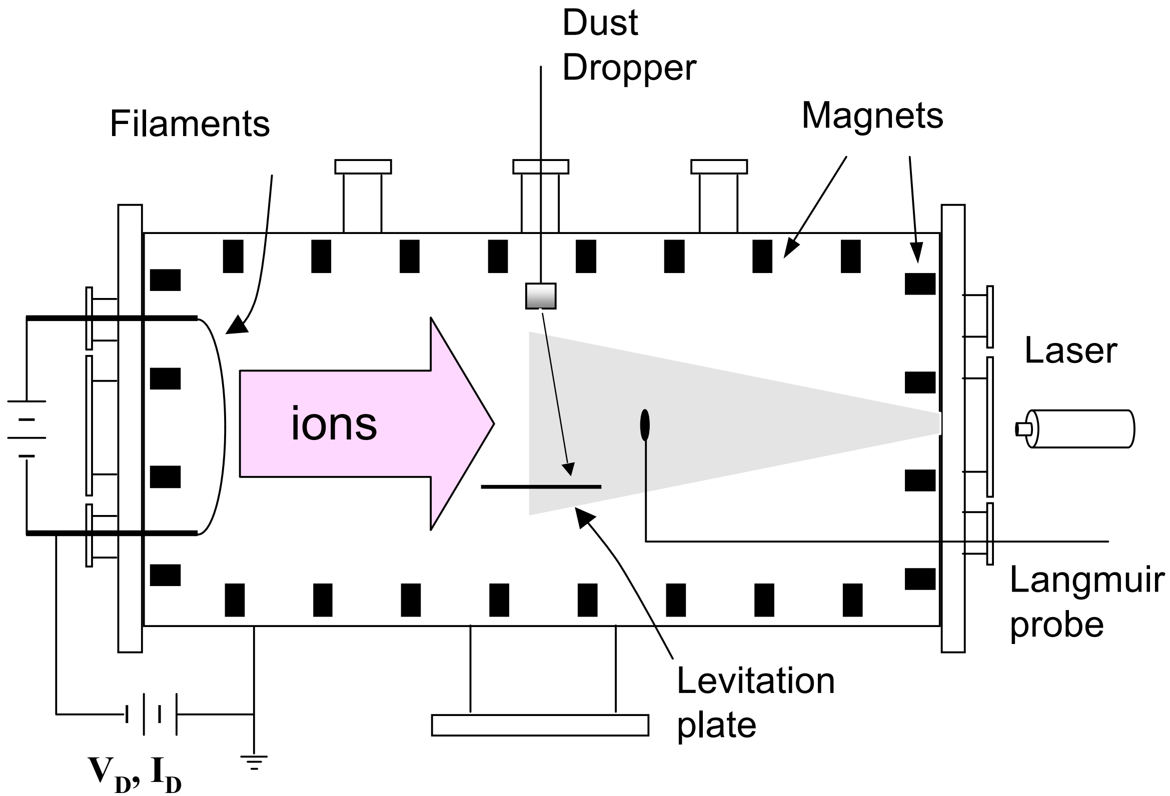
(b) orbit force F_{io}

$$F_{io} = 4\pi n_i m_i u_i u_s b_{\pi/2}^2 \Lambda$$

where $b_{\pi/2} = \dfrac{eQ_d}{4\pi\varepsilon_o m_i u_s^2}$, impact parameter for 90° collisions

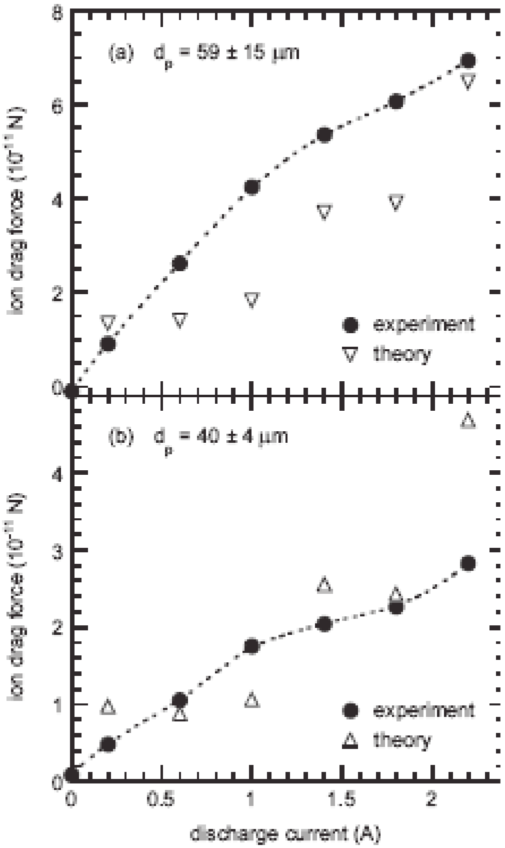
and $\Lambda = \dfrac{1}{2}\ln\left(\dfrac{\lambda_D^2 + b_{\pi/2}^2}{b_c^2 + b_{\pi/2}^2}\right)$, Coulomb logarithm (up to λ_D)

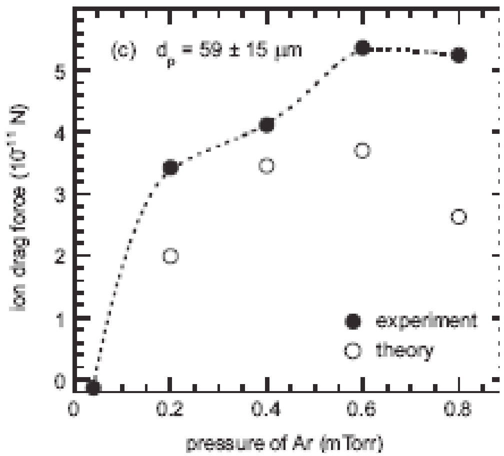
5) Ion drag force: experimental measurements



- glass microspheres falling through the plasma are deflected by ions which acquire drift due to a weak ambipolar electric field in the plasma
- the ion drag force is determined from the measured deflection angles

exp. results – ion drag





D. Weakly vs. strongly coupled dusty plasmas (F, p 69)

- The fundamental characteristics of a many-particle interacting system is the coupling constant

- $\Gamma = \dfrac{\text{potential energy of interation between particles}}{\text{average kinetic energy of the particles}}$

- $\Gamma = \dfrac{Q^2 / 4\pi\varepsilon_o \Delta}{kT} = \dfrac{Q^2}{4\pi\varepsilon_o kT\Delta}$

  where Δ is the average interparticle spacing, usually

  taken to be the Wigner-Seitz radius $\Delta = \left(\dfrac{4\pi n}{3}\right)^{-1/3}$

  where n is the particle density

(a) Weakly coupled plasma

- Consider a typical laboratory plasma with a density

  $n : 10^{15} m^{-3}$, and electron temperatrure $T_e = 2eV$
- For this plasma, $\Delta ; 6 \times 10^{-6} m$.
- The resulting potential and kinetic energies are:

  $PE ; 4 \times 10^{-23} J$ and $kT_e ; 3.2 \times 10^{-19} J$,
- coupling constant $\Rightarrow \quad \Gamma \sim 10^{-4} << 1$.
- This is an example of a weakly coupled plasma.
- Most "ordinary' plasmas are weakly coupled.

(a) Strongly coupled plasma

- Consider now a typical laboratory dusty plasma with a = 5 μm, $\Delta = 140\mu m$, $T_e = 2eV$, $T_d = 0.03eV$
- In this case $Q_d \sim 10^4 e$
- Now, $\Rightarrow \Gamma \sim 10^4 >> 1$
- This is a strongly coupled dusty plasma

Factors that contribute to making dusty plasmas strongly coupled

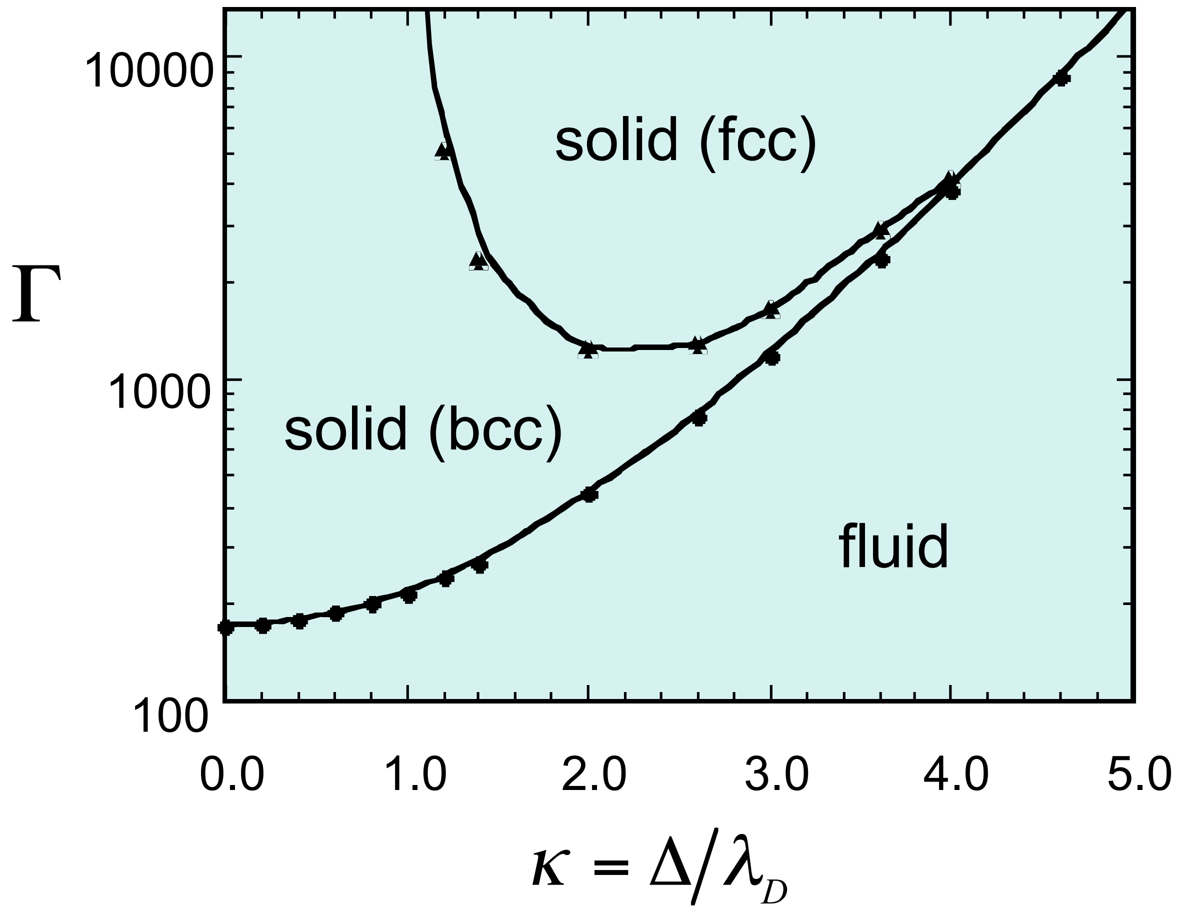
- $Q_d = eZ_d$, with high Z_d ($\sim 10^3 - 10^4$), $\Gamma \sim Z^2$
- Dust grains are easily cooled to near room temperature by neutral gas interactions
- Dynamic time scales for microparticle relaxation in a plasmas are relatively short compared to colloidal systems.

Classification of many-particle systems

Γ	**class**	**phase**
<< 1	weakly coupled	gas
~ 1	?	liquid
>> 1	strongly coupled	solid

By varying Γ it is possible to study the phase transitions in a strongly coupled dusty plasma crystal

Phase Diagram of a Yukawa System



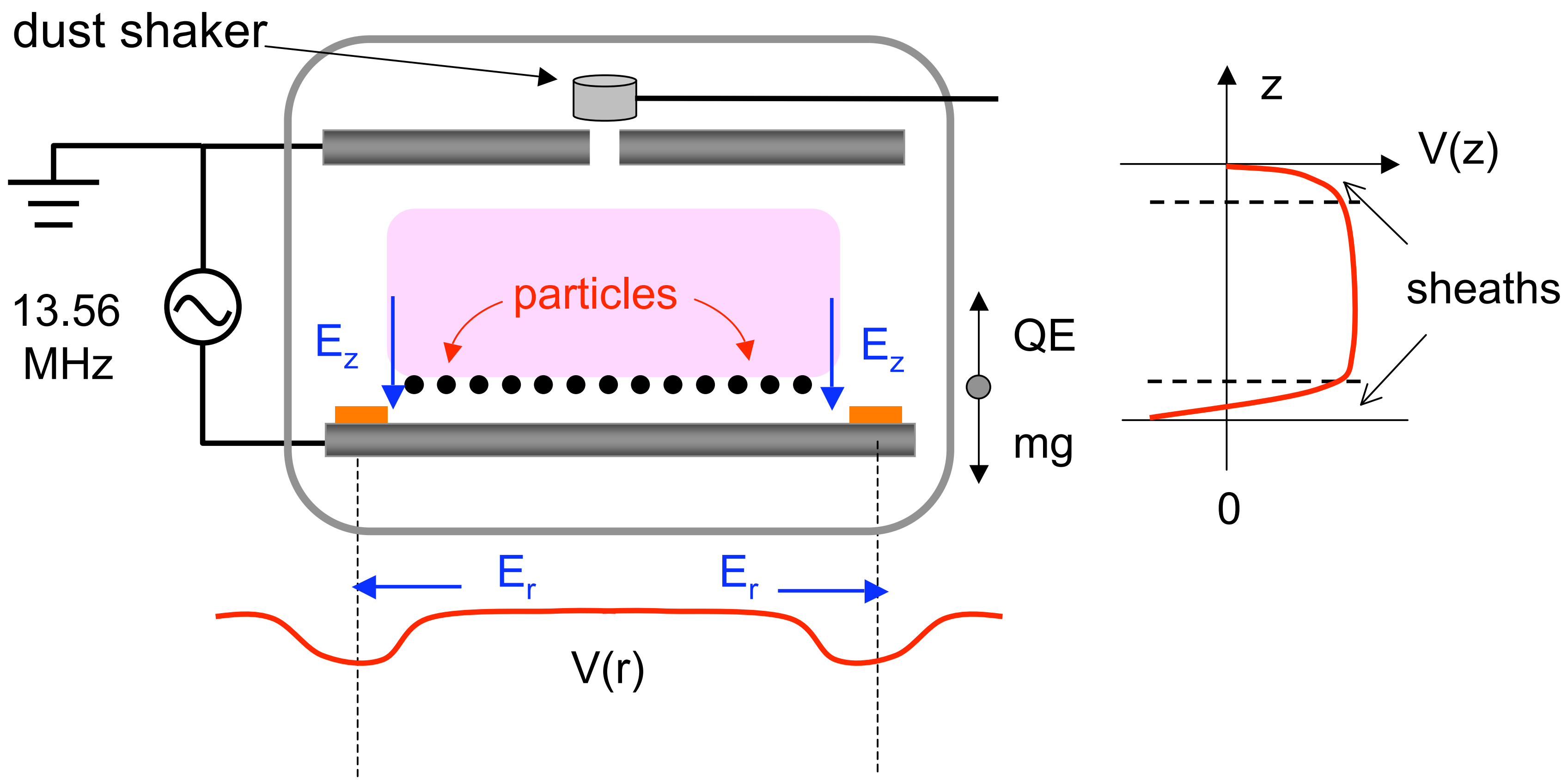
F370, 372, 373

Condition for forming a "dust crystal" $\Gamma > \Gamma_M \approx 171$

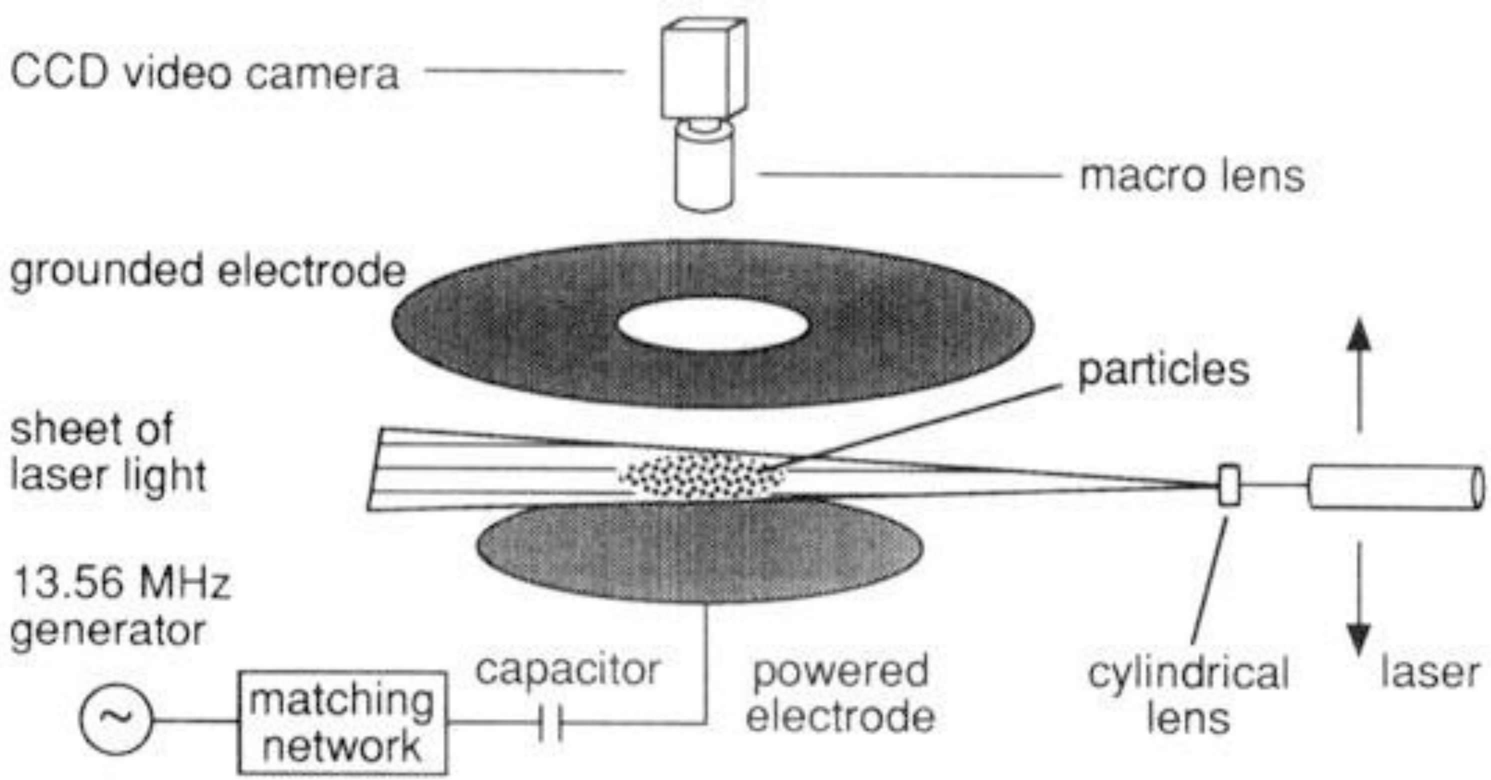
Experimental observation of strongly coupled dusty plasmas *Coulomb crystals (F11-14)*

- In 1986, Ikezi gave theoretical arguments indicating that a Coulomb lattice of small particles could be produced. He discussed the conditions for solidification.
- In 1994, 4 experimental groups (MPE, Taiwan, Japan, Kiel Univ.) announced the observation of Coulomb solids in RF parallel plate discharges (GEC cells).

RF plasma discharges (PSST)

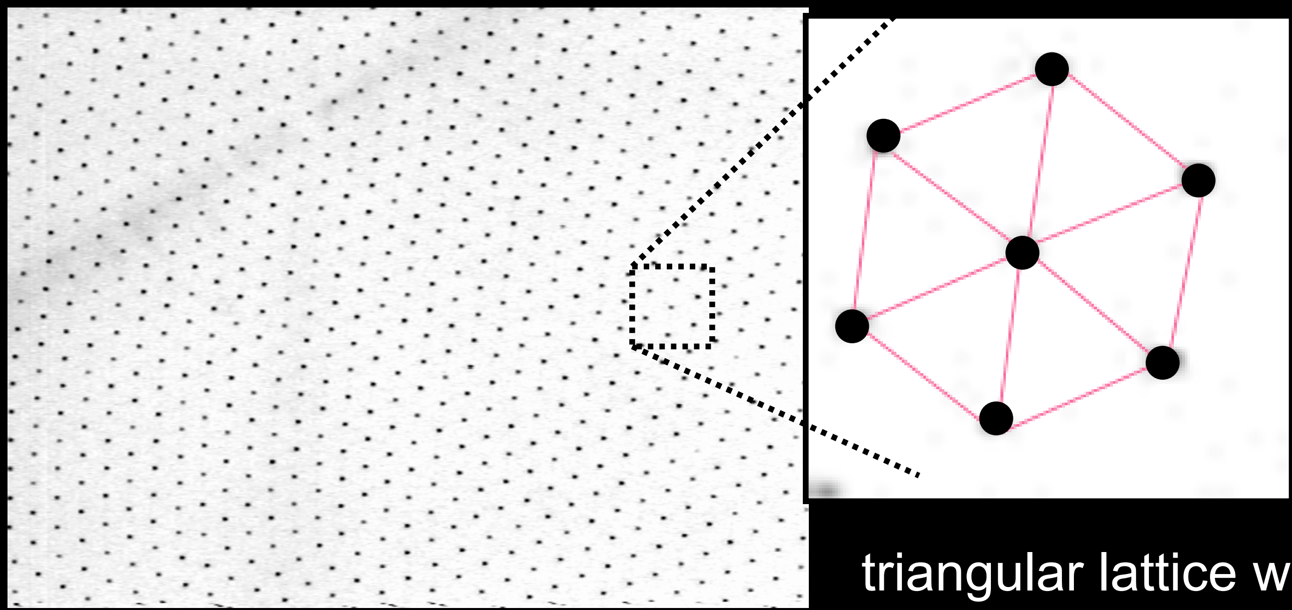


RF Dusty Plasma Device



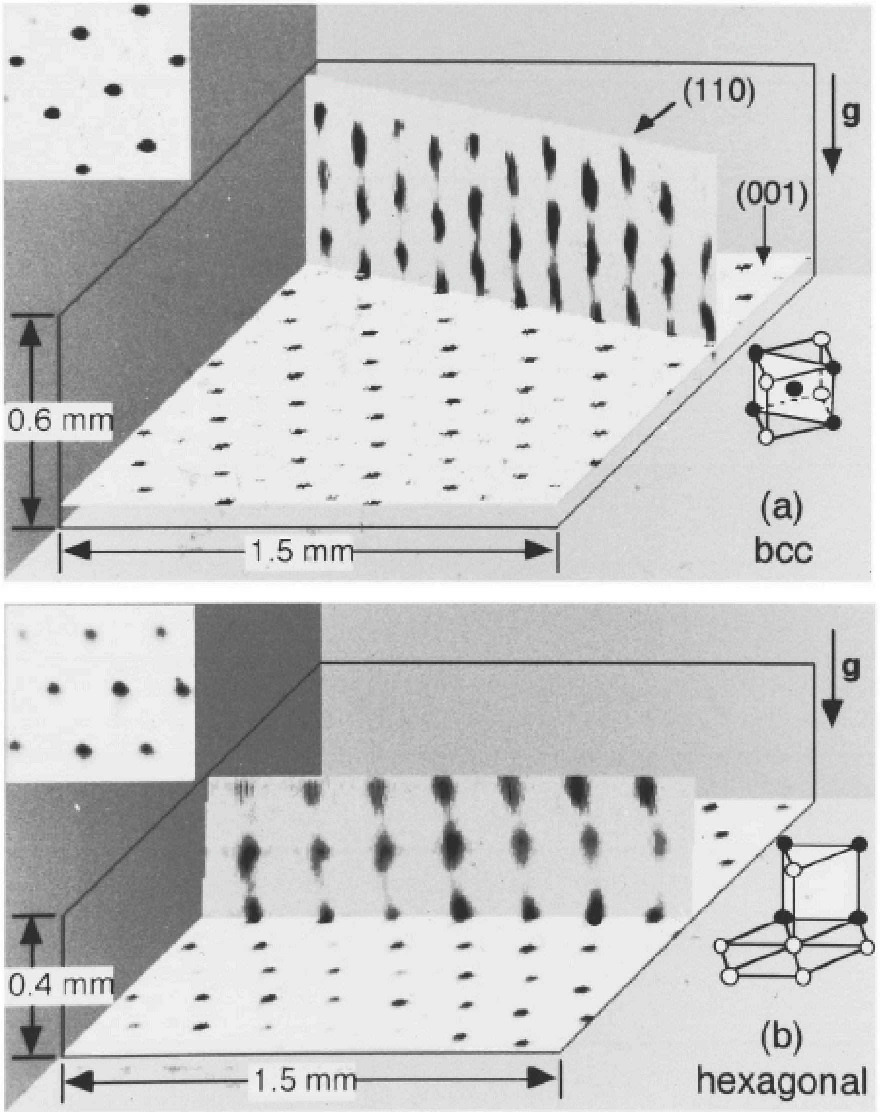
Coulomb Crystal

John Goree – Univ. Iowa

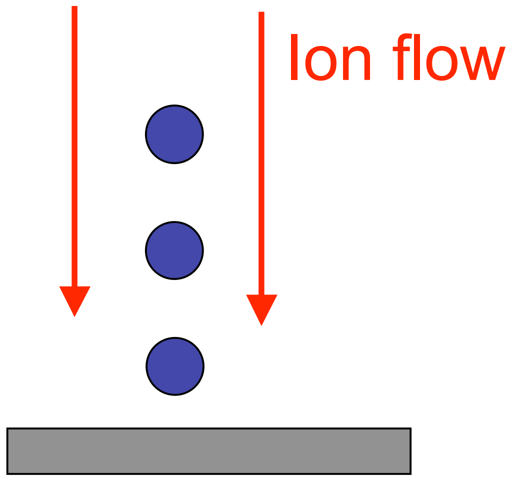


triangular lattice with
hexagonal symmetry

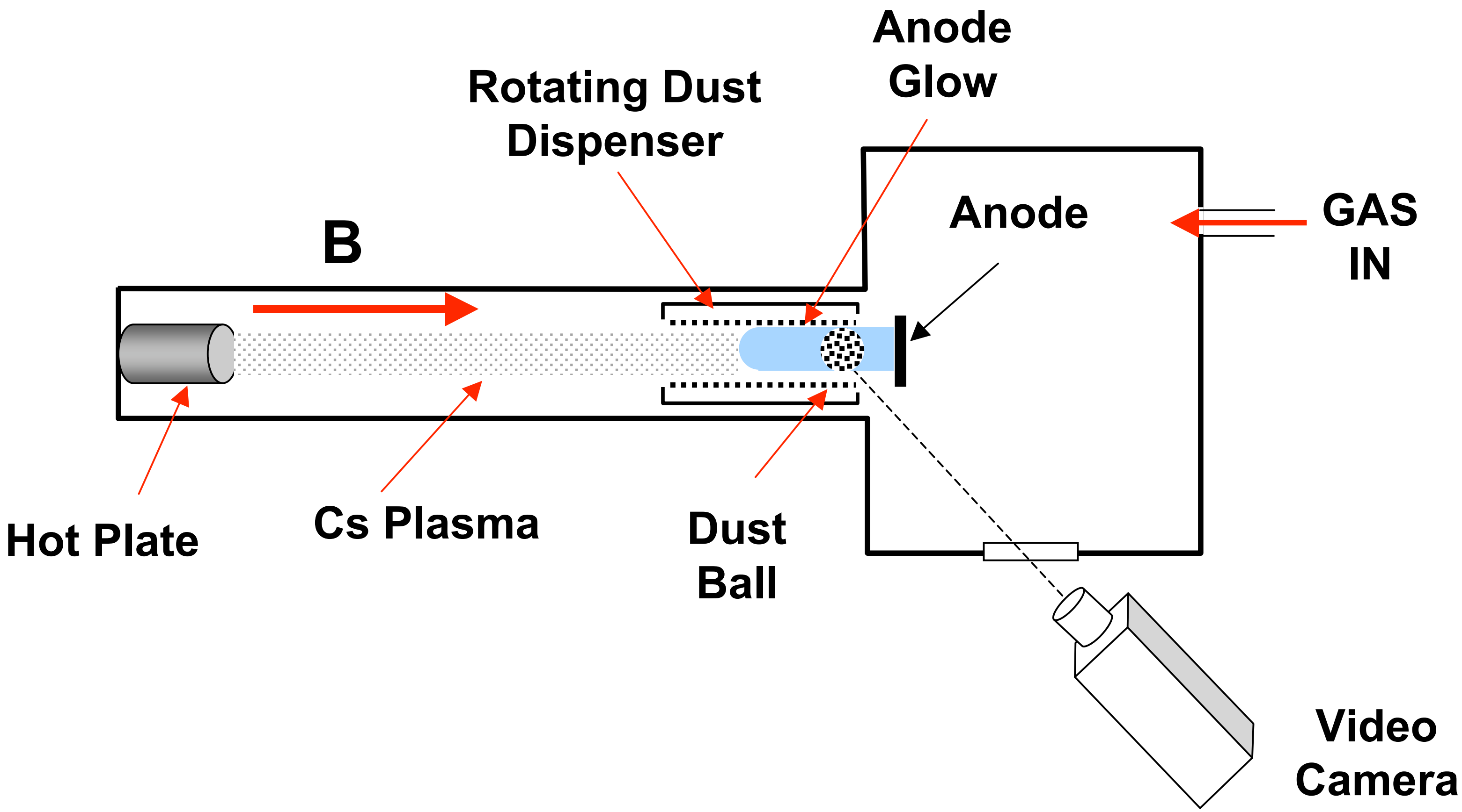
A plasma crystal having multiple layers



The particles are vertically aligned due to the downward ion flow

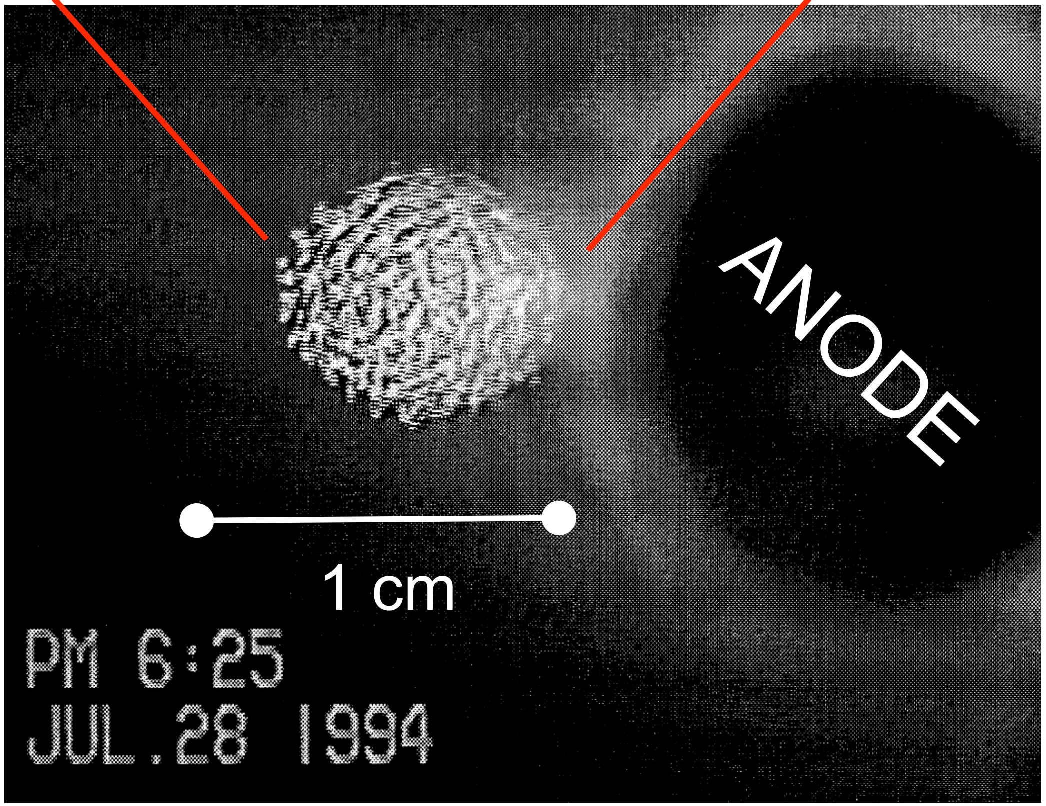


Observation of the Dust Balls



Barkan and Merlino, Phys. Plasmas 2, 3261, 1995.

Dust (Coulomb) Ball

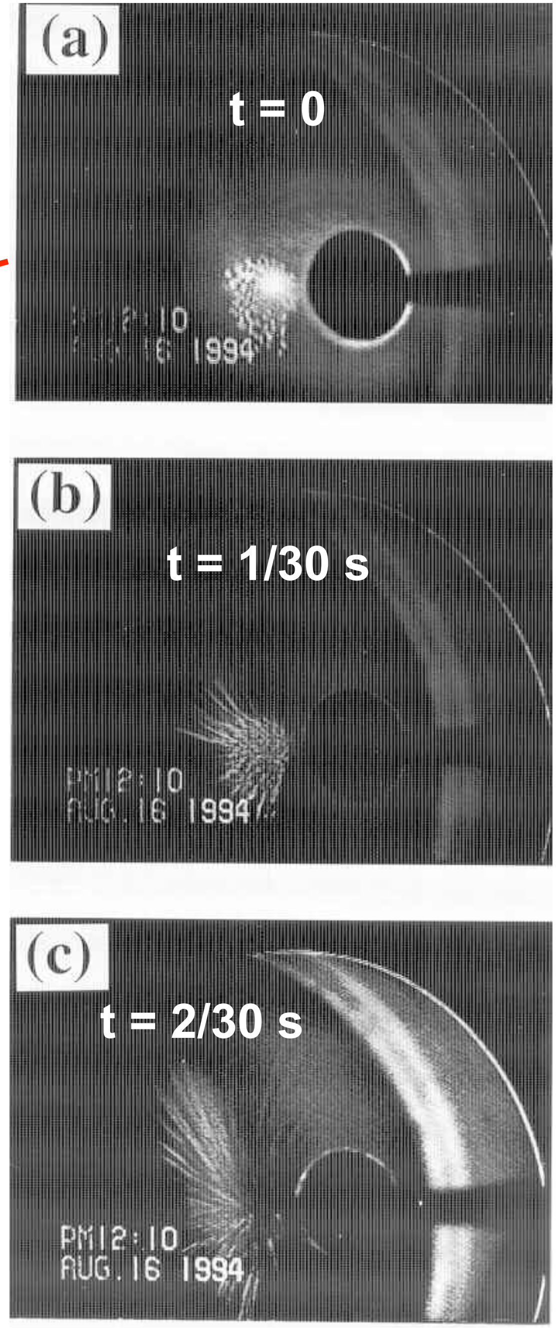


coulomb explosion

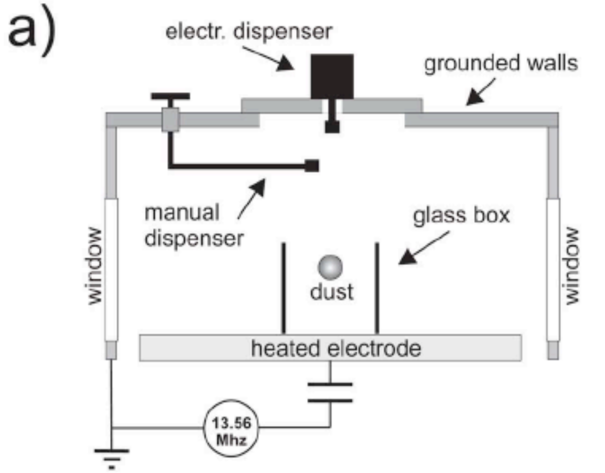
electrostatically confined
dust ball at t = 0

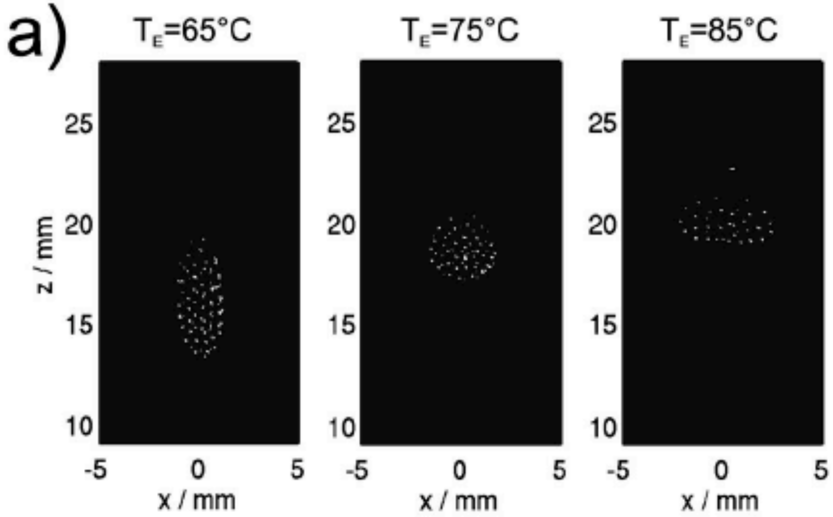
electrostatically confinement
suddenly turned off

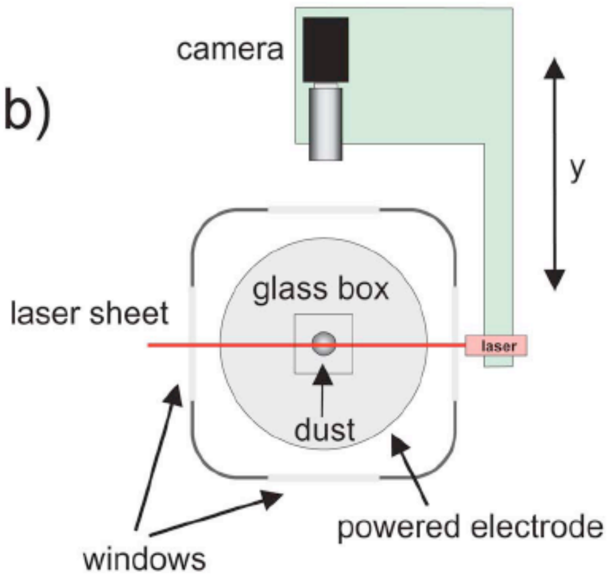
The electrostatic confinement is turned off by turning the plasma off. With the plasma off, there is no Debye shielding. This causes the dust to experience a large repulsive force leading to an acceleration of almost 3 g's

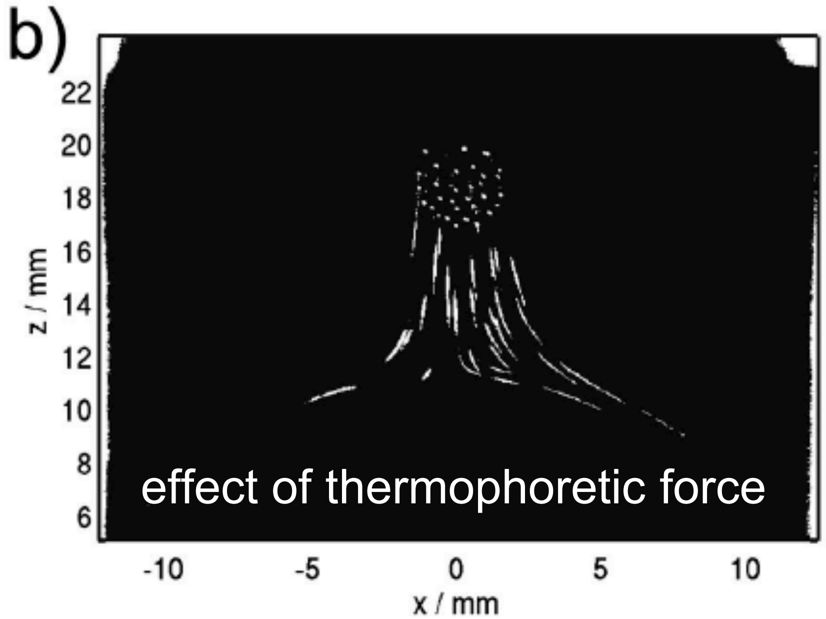


Coulomb Balls

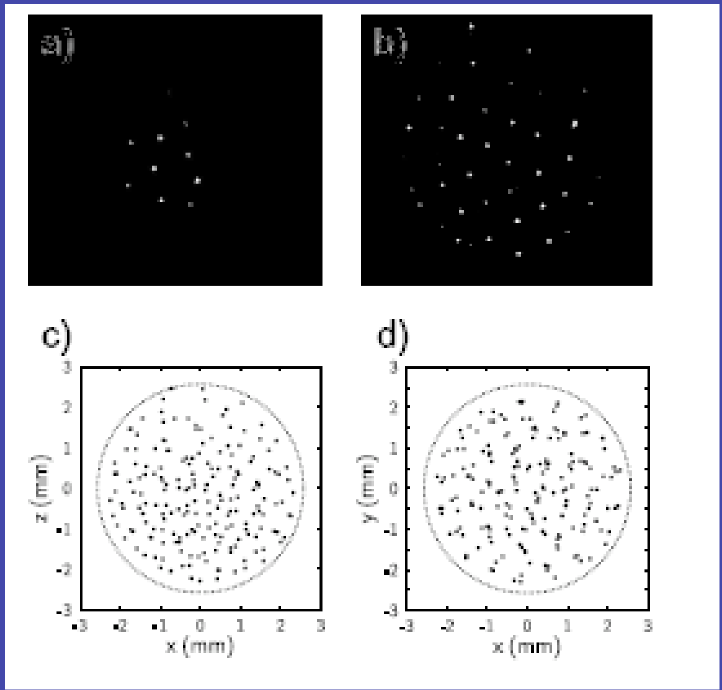


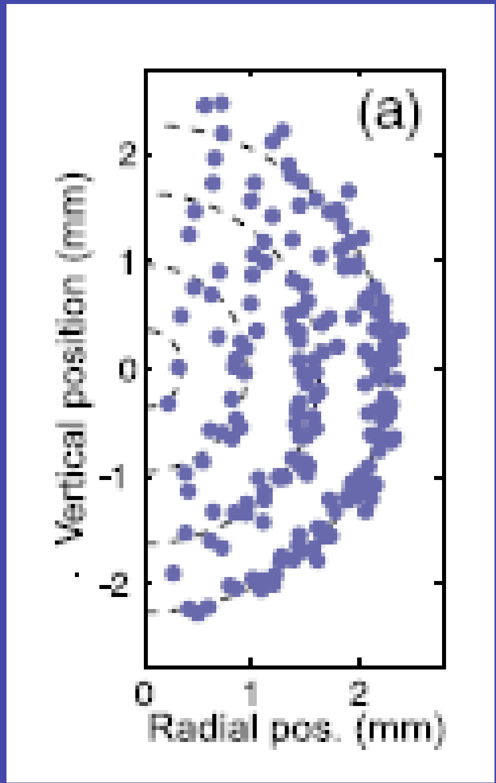






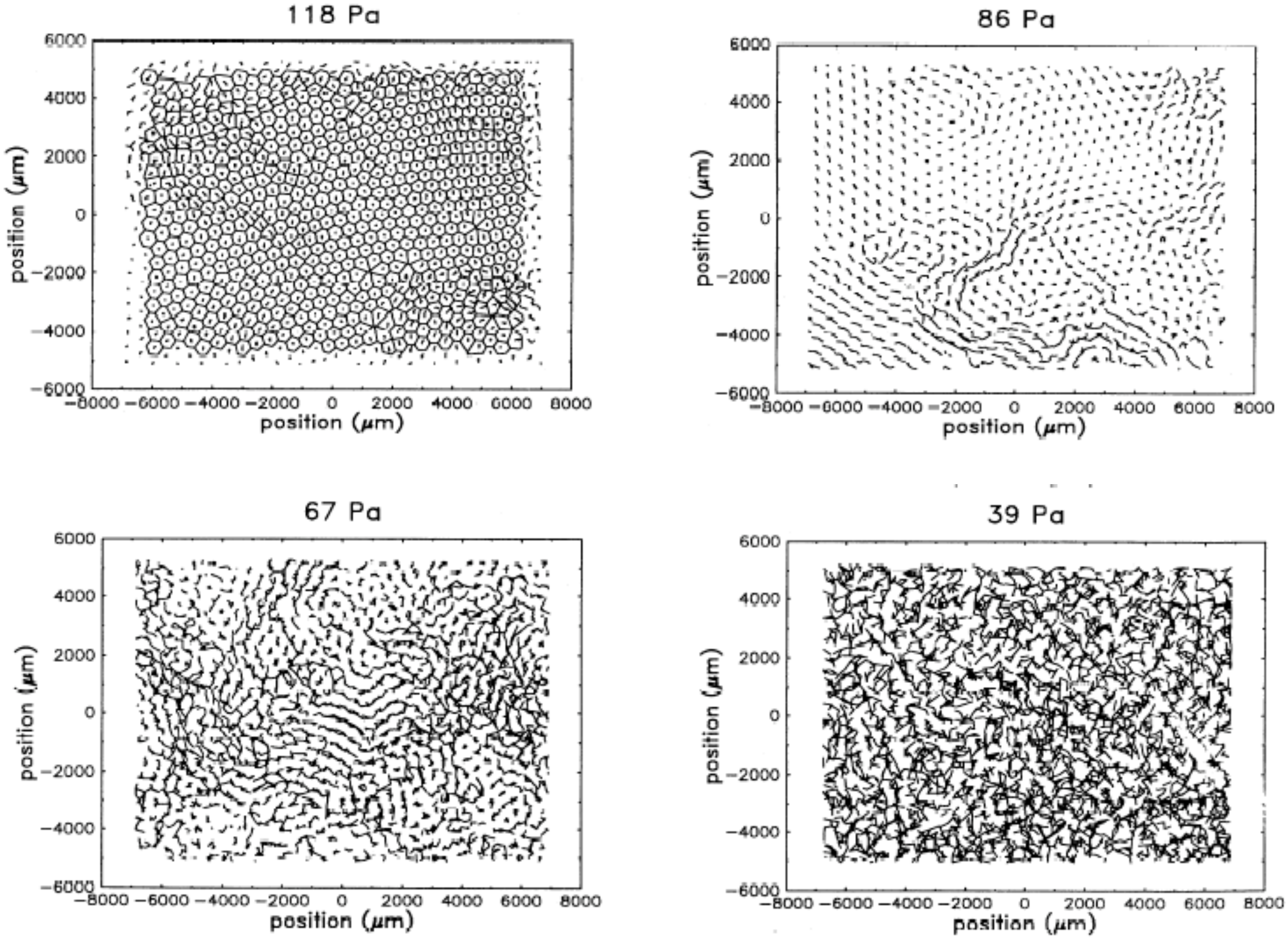
Dust Coulomb Balls





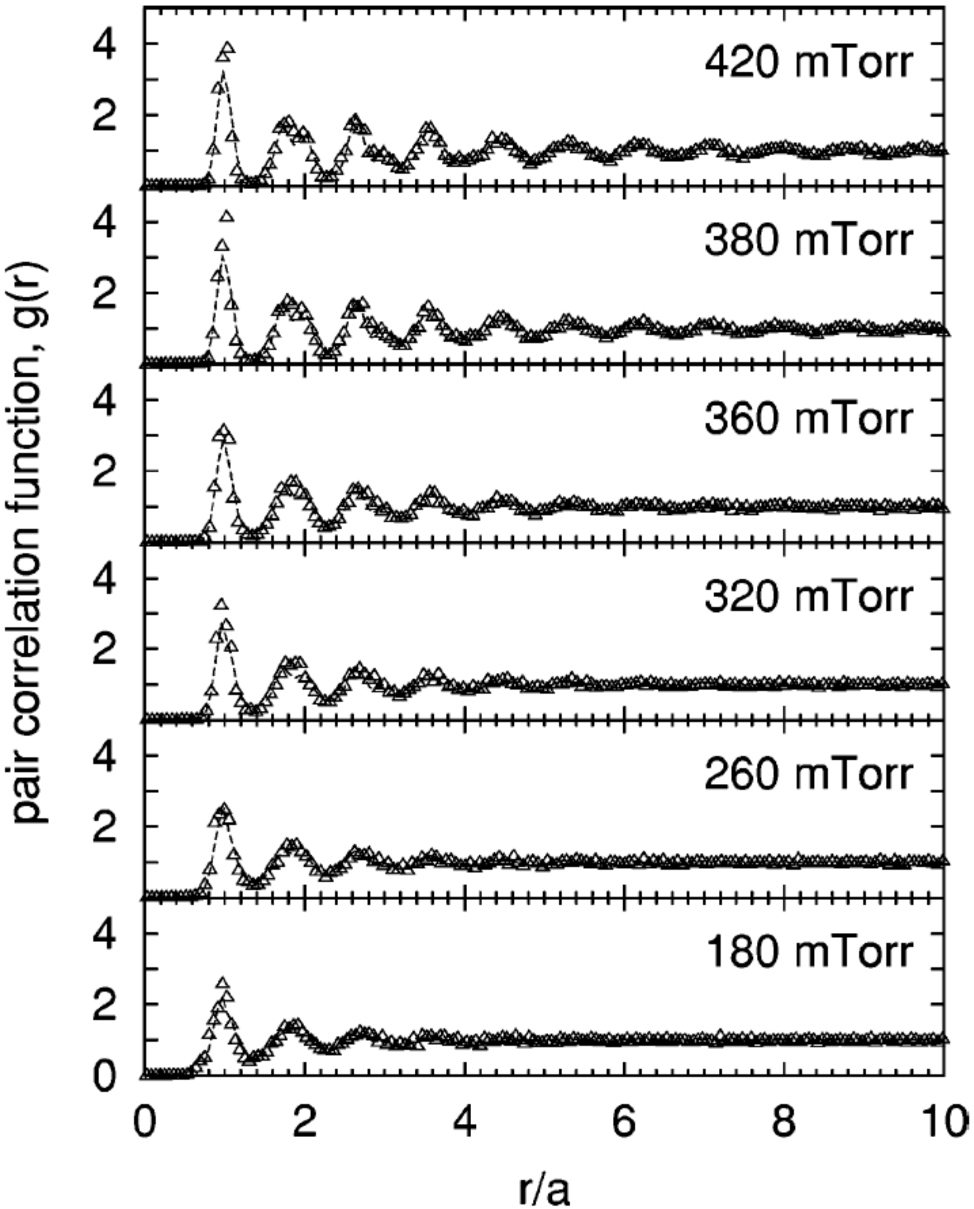
Arp, Block, Piel & Melzer, PRL, 15 Oct. 2004

Melting of a Plasma Crystal



Melzer, Homann, and Piel, PRE 53, 2747 (1996)

Melting



- The pair correlation function g(r)

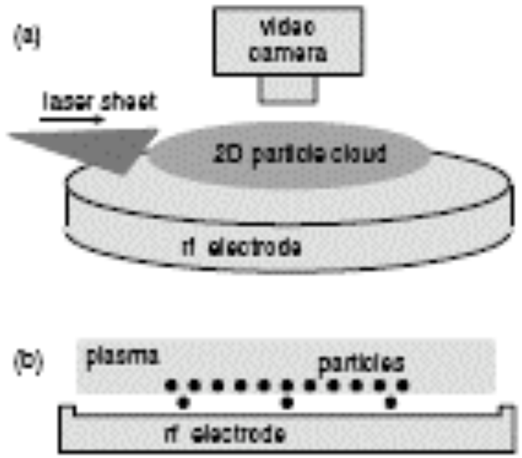
$$g(r) = \left\langle \frac{1}{N} \sum_{i \neq j}^{N} \delta(r - r_i - r_j) \right\rangle,$$

$N = \#$ particles, r_r, r_j *positions*

represents the probability of finding 2 particles separated by a distance r.

- It is a measure of the translational order in structures.
- For a crystal at T = 0, g(r) is a series of equally spaced delta functions.

Melting a crystal by heating



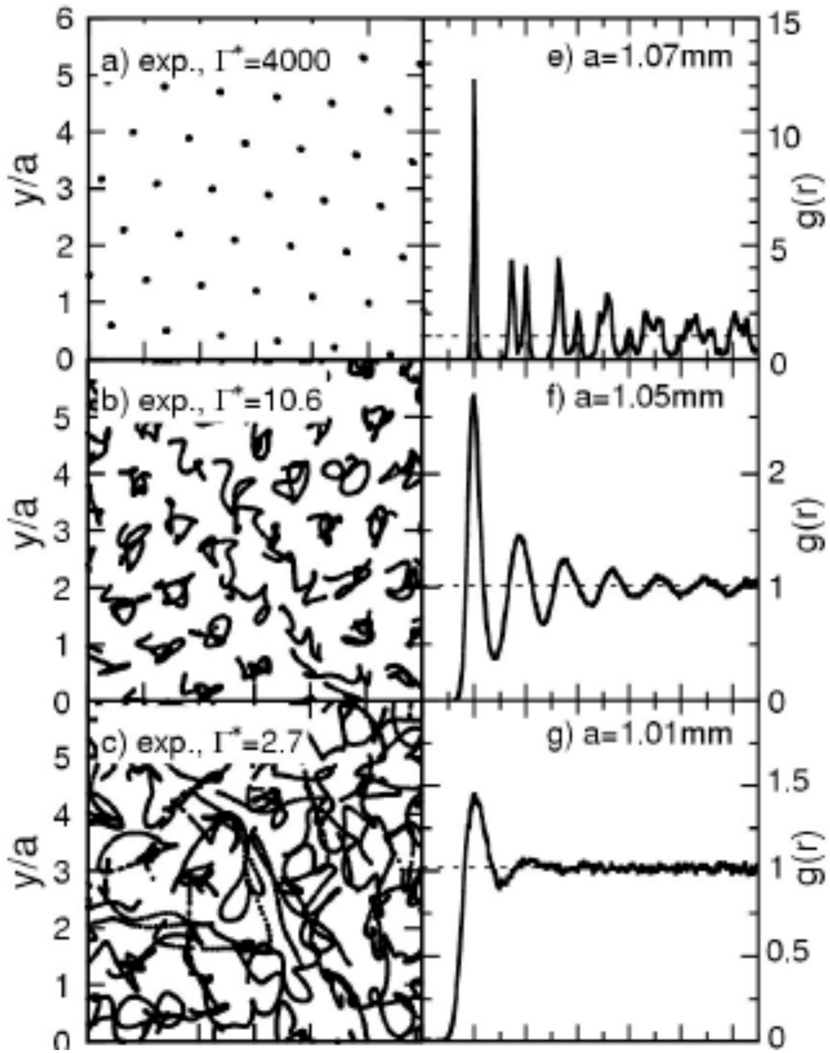
Γ* = 400(

Γ* = 10.6

Γ* = 2.7

$$\Gamma^* = \Gamma e^{-\kappa}$$

$$\kappa = \Delta / \lambda_D$$

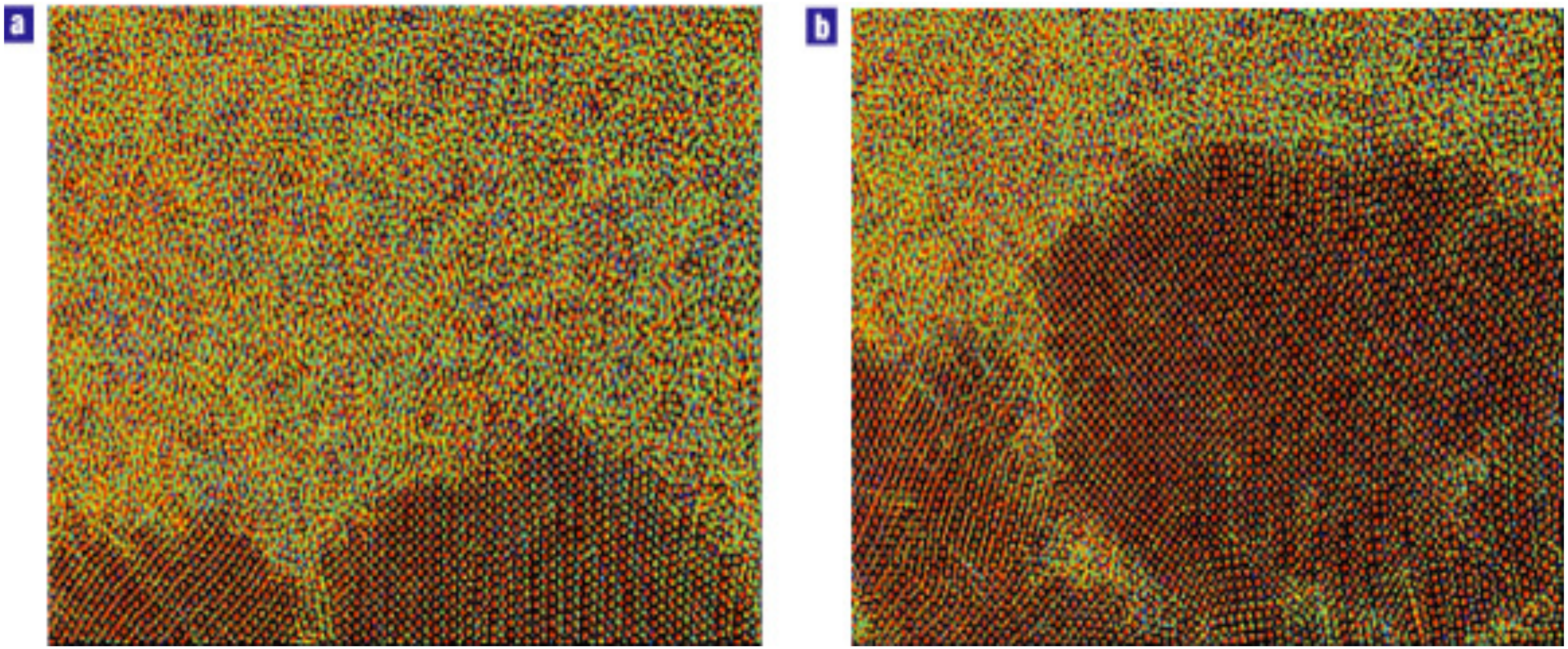


Nonomura at al, PRL 94, 045001, 2005

It is possible to diagnose dusty plasmas down to the particle level

- In a dusty plasma, it is possible to follow the position and velocity of all the particles as a function of time $\rightarrow$ [$\mathbf{r}(t)$, $\mathbf{v}(t)$].
- This is not possible in ordinary plasmas where, at best we can determine the distribution function of the ions and electrons

Crystallization fronts in complex plasmas (Rubin-Zuzic et al Nature physics 2, 181, 2006)

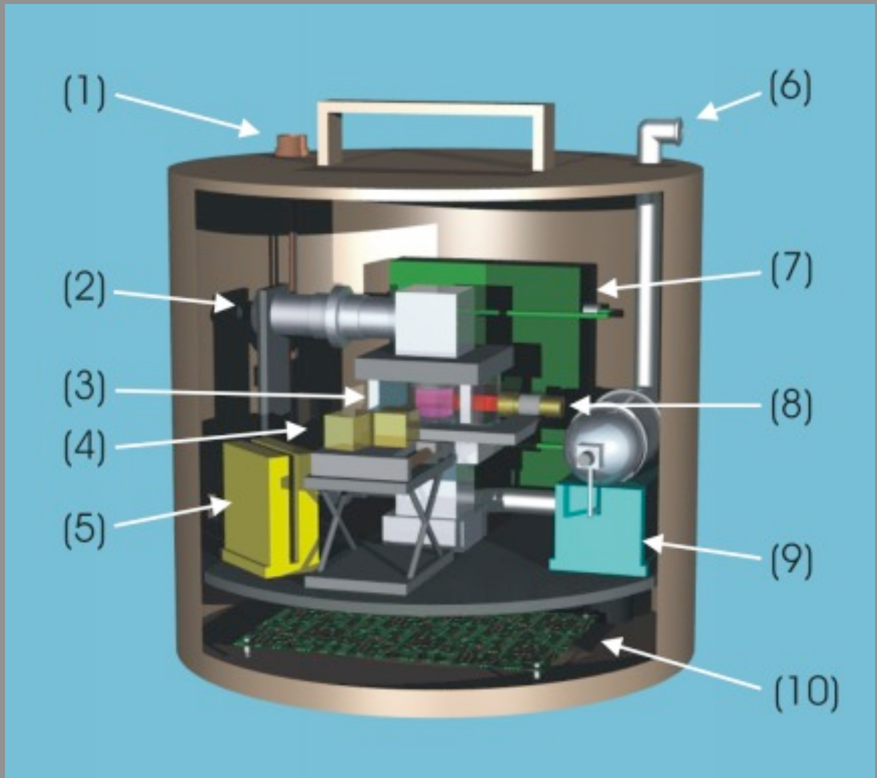


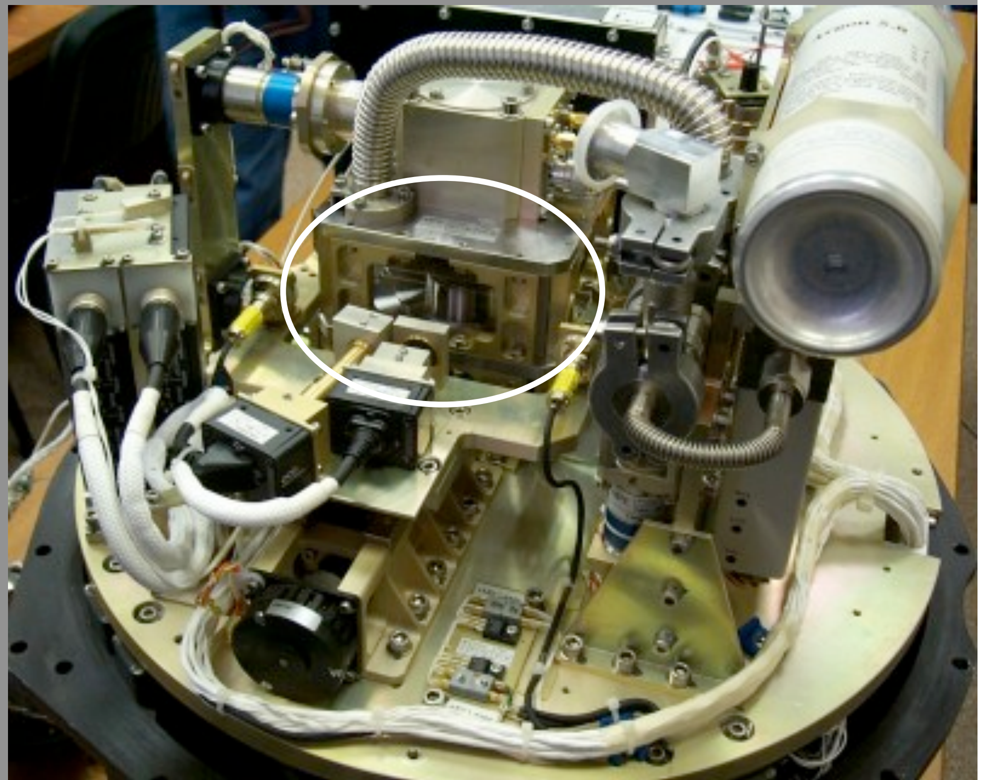
10^7 melamine formaldehyde particles (1.28 μm) in an rf discharge at 173 mTorr. Images are 16 s apart. The crystal was melted down by a sudden decrease in the rf power and subsequently allowed to re-freeze.

E. Dusty plasmas under microgravity (F20,21,34,37)

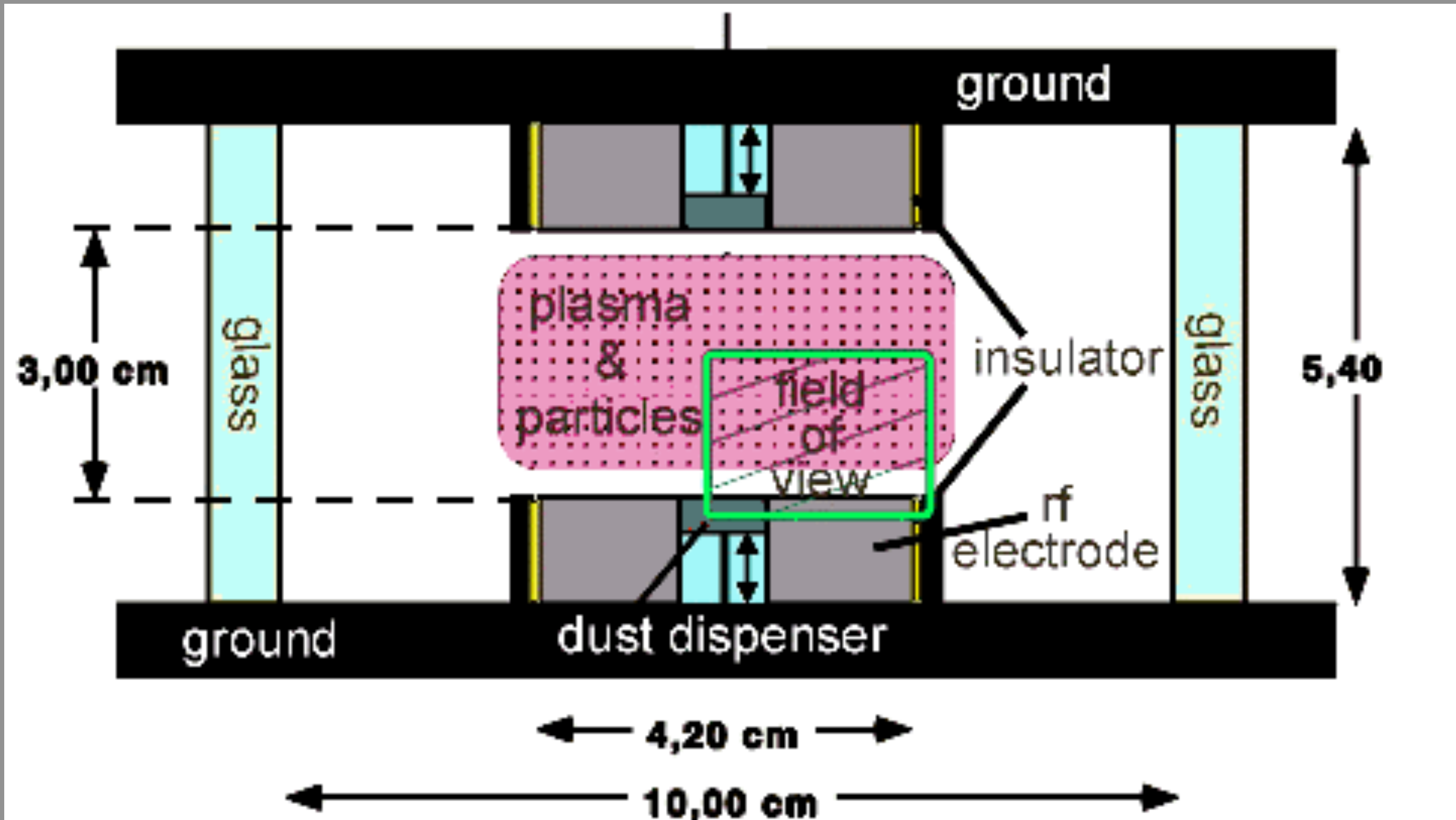
- In the earth-based laboratory, it is necessary to use a levitation method to keep microparticles from falling.
- In the RF dusty plasma devices, the particles always reside in the sheath region and usually in 2D structures.
- The PKE Nefedov device is an RF plasma system operating in the microgravity environment on the International Space Station (ISS)

PKE Nefedov device on ISS

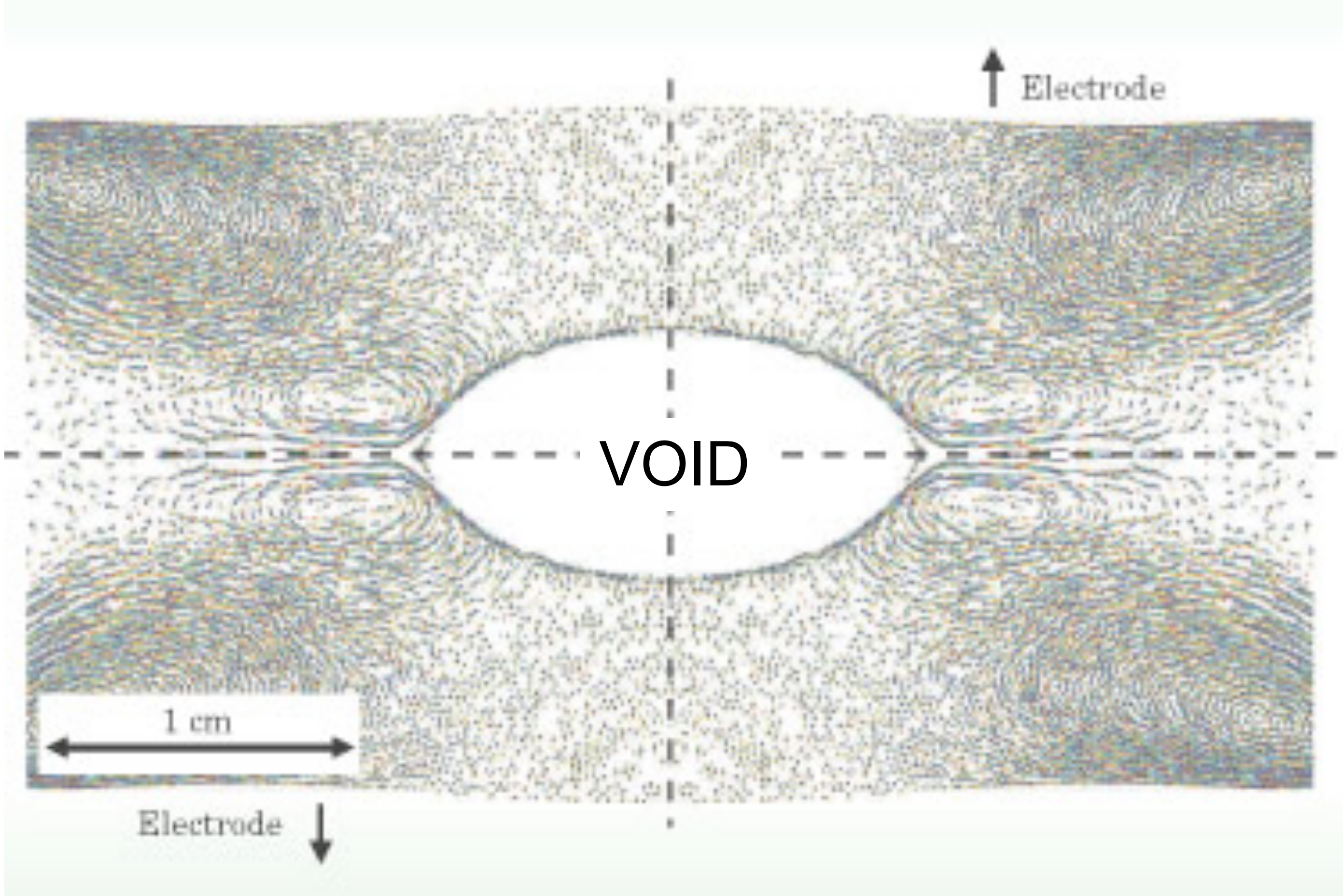




PKE Nefedov schematic



Voids in dusty plasmas under microgravity



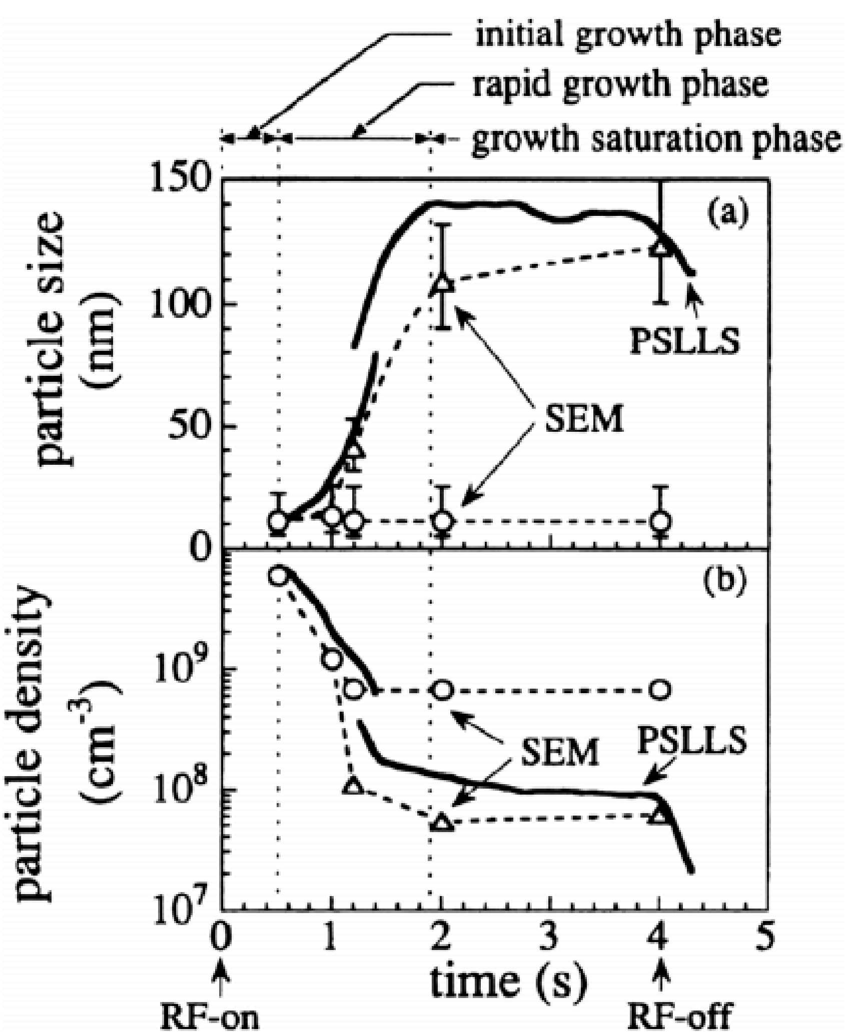
Void is due to the outward ion drag force on the microparticles

F. Particle growth in plasmas
(PSST, B)

- Nanoparticles and microparticles can be grown in a plasma.
- This can occur in plasma reactors used in semiconductor etching and deposition systems using reactive chemical species like silane, SiH_4:
- $e^- + SiH_4 \rightarrow (SiH_4)^* \rightarrow SiH_2 + 2\,H$

- *{Caution: I know less about this topic than all other topics in these lectures. }*

particle growth kinetics



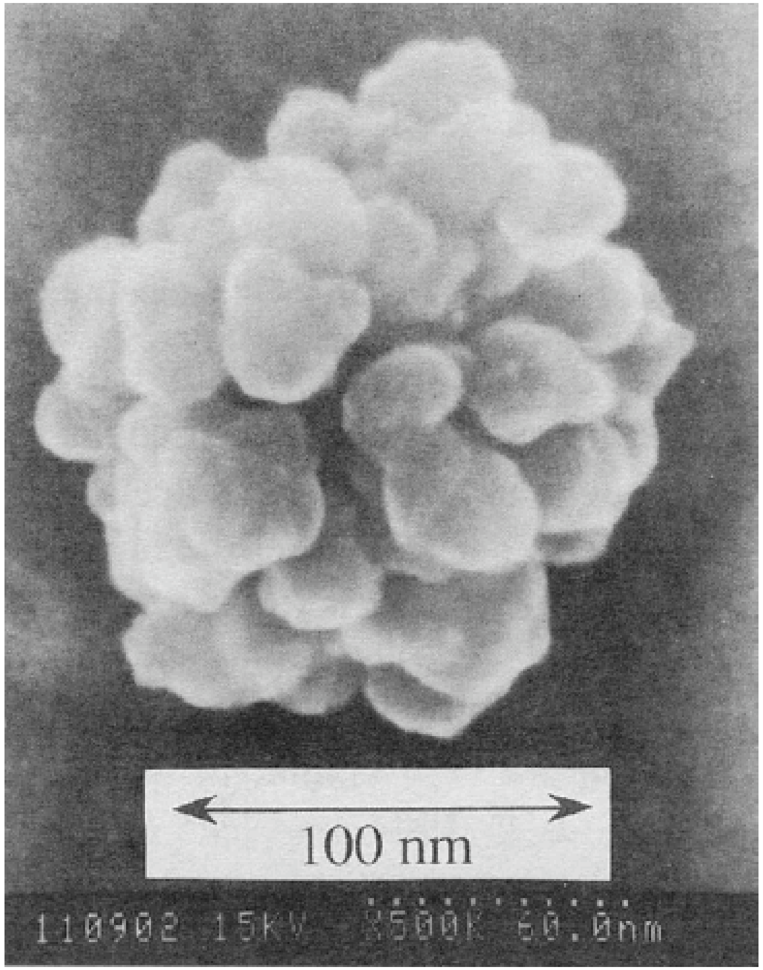
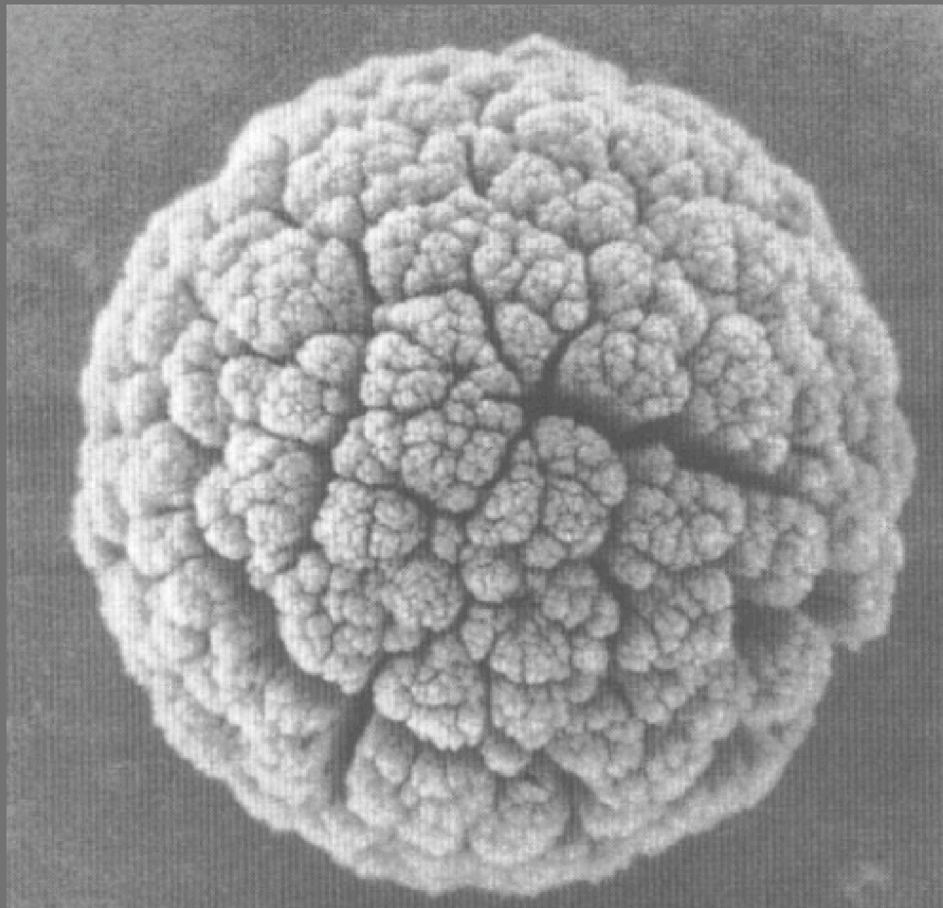
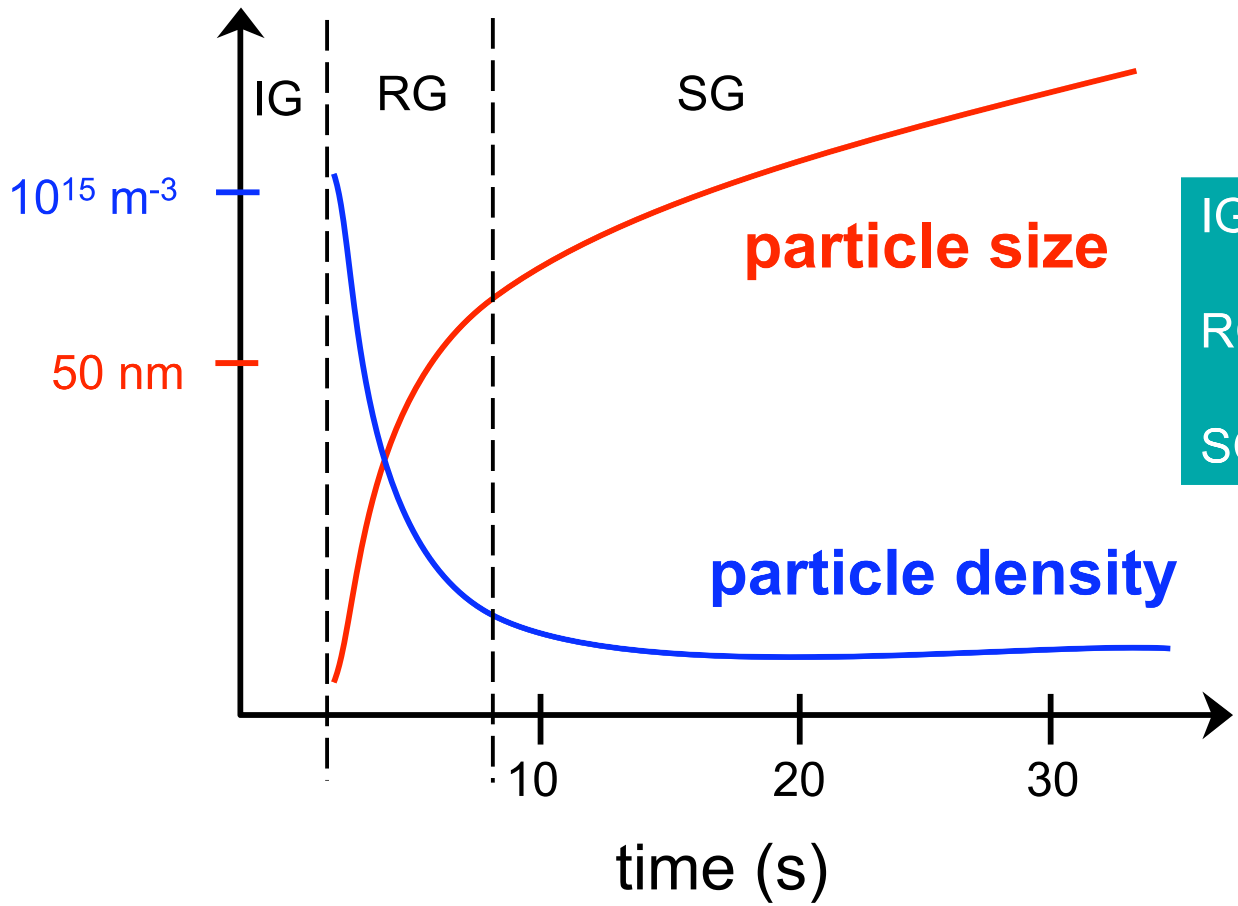


Figure 16. SEM photograph of a particle collected in the GS phase [2]. Experimental conditions: 5% SiH_4 + He, 30 sccm, 80 Pa, 40 W and $T_{on} = 4$ s.

A 650 nm particle grown in an helium rf plasma with carbon electrodes



particle growth kinetics

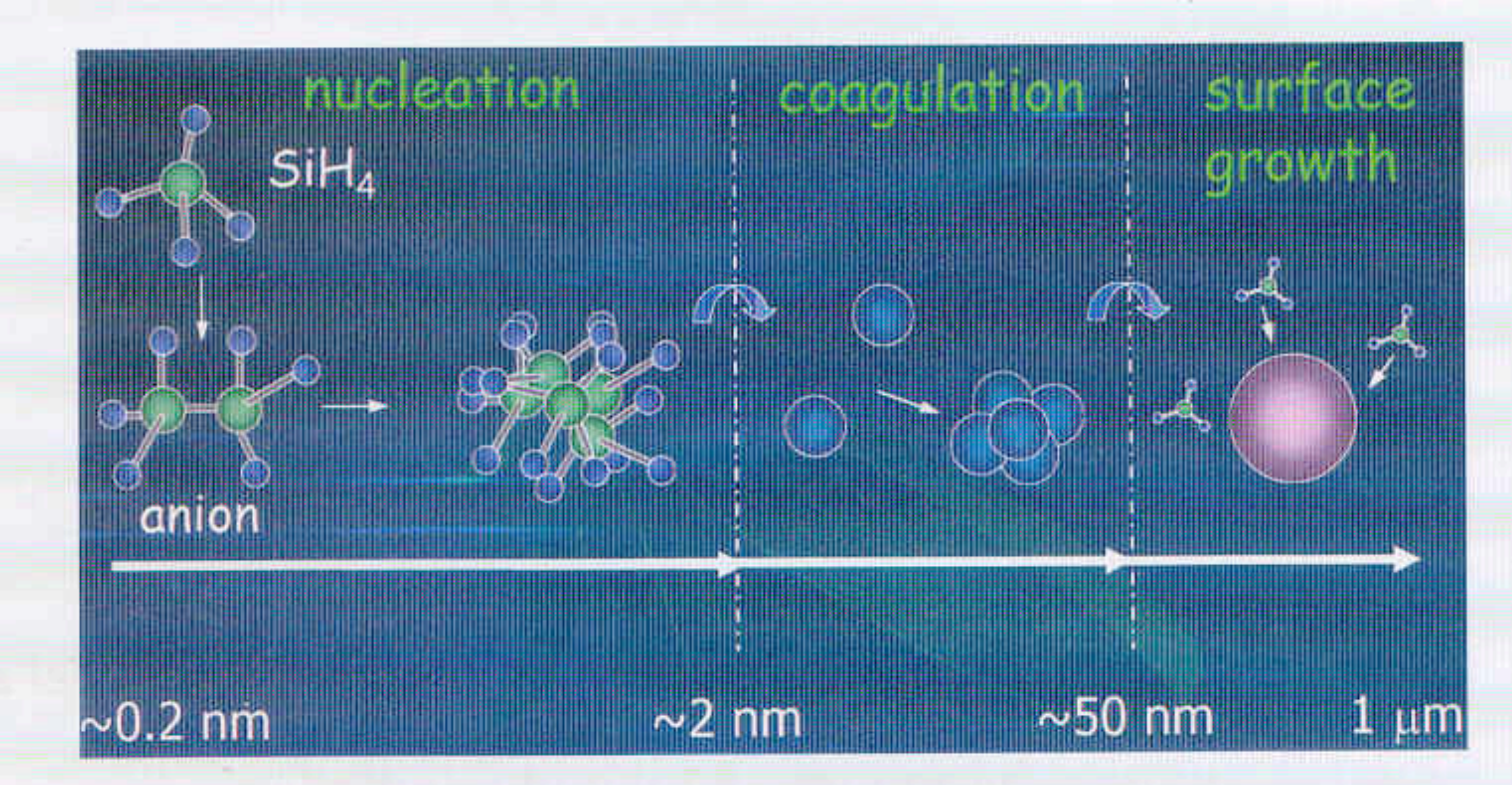


IG: initial growth phase

RG: rapid growth phase

SG: saturated growth phase

three phases of particle growth in silane plasmas



particle growth mechanisms

- Initial growth: nucleation of reactive anions, cations and neutrals in the gas phase (stoms & molecules)

  from < nm → few nm

- Rapid growth: agglomeration or coagulation phase, this qualifies as *dusty plasma*

  10 nm → 100 nm,

- Saturated growth: growth at constant density by surface deposition of SiH_x

  100 nm → μm

reactions involved in IG phase

	Reaction	Threshold energy (eV)	Reaction type
1.	$SiH_4 + e^- \rightarrow SiH_3^+ + H + 2e^-$	11.9	dissoc. ioniz.
2.	$SiH_4^{(2-4)} + e^- \rightarrow SiH_3^+ + H + 2e^-$	11.8	dissoc. ioniz.
3.	$SiH_4^{(1-3)} + e^- \rightarrow SiH_3^+ + H + 2e^-$	11.7	dissoc. ioniz.
4.	$Si_2H_6 + e^- \rightarrow Si_2H_4^+ + 2H + 2e^-$	10.2	dissoc. ioniz.
5.	$SiH_4^{(0)} + e^- \rightarrow SiH_4^{(2-4)} + e^-$	0.11	vibr. exc.
6.	$SiH_4^{(0)} + e^- \rightarrow SiH_4^{(1-3)} + e^-$	0.27	vibr. exc.
7.	$SiH_4 + e^- \rightarrow SiH_3 + H + e^-$	8.3	dissoc.
8.	$SiH_4^{(2-4)} + e^- \rightarrow SiH_3 + H + e^-$	8.2	dissoc.
9.	$SiH_4^{(1-3)} + e^- \rightarrow SiH_3 + H + e^-$	8.1	dissoc.
10.	$SiH_4 + e^- \rightarrow SiH_2 + 2H + e^-$	8.3	dissoc.
11.	$SiH_4^{(2-4)} + e^- \rightarrow SiH_2 + 2H + e^-$	8.2	dissoc.
12.	$SiH_4^{(1-3)} + e^- \rightarrow SiH_2 + 2H + e^-$	8.1	dissoc.
13.	$Si_2H_6 + e^- \rightarrow SiH_3 + SiH_2 + H + e^-$	7.0	dissoc.
14.	$SiH_4 + e^- \rightarrow SiH_3^- + H$	5.7	dissoc. attach.
15.	$SiH_4^{(2-4)} + e^- \rightarrow SiH_3^- + H$	5.6	dissoc. attach.
16.	$SiH_4^{(1-3)} + e^- \rightarrow SiH_3^- + H$	5.5	dissoc. attach.
17.	$SiH_4 + e^- \rightarrow SiH_2^- + 2H$	5.7	dissoc. attach.
18.	$SiH_4^{(2-4)} + e^- \rightarrow SiH_2^- + 2H$	5.6	dissoc. attach.
19.	$SiH_4^{(1-3)} + e^- \rightarrow SiH_2^- + 2H$	5.5	dissoc. attach.
20.	$H_2 + e^- \rightarrow H_2^+ + 2e^-$	15.4	ioniz.
21.	$H_2 + e^- \rightarrow H_2^{(\nu=1)} + e^-$	0.54	vibr. exc.
22.	$H_2 + e^- \rightarrow H_2^{(\nu=2)} + e^-$	1.08	vibr. exc.
23.	$H_2 + e^- \rightarrow H_2^{(\nu=3)} + e^-$	1.62	vibr. exc.
24.	$H_2 + e^- \rightarrow H + H + e^-$	8.9	dissoc.

The initial precursors for particle growth are thought to be heavy, singly charged negative ion clusters.

Cosmic dust growth by coagulation

- coagulation is a random growth process whereby particles can stick together via mutual collisions forming larger particles.
- this can occur in the presolar nebula, circumstellar, circumplanetary, cometary, etc. environments
- however, if the grains all have the like charge, coagulation can not take place unless the grains can overcome their mutual Coulomb repulsion

overcoming Coulomb repulsion

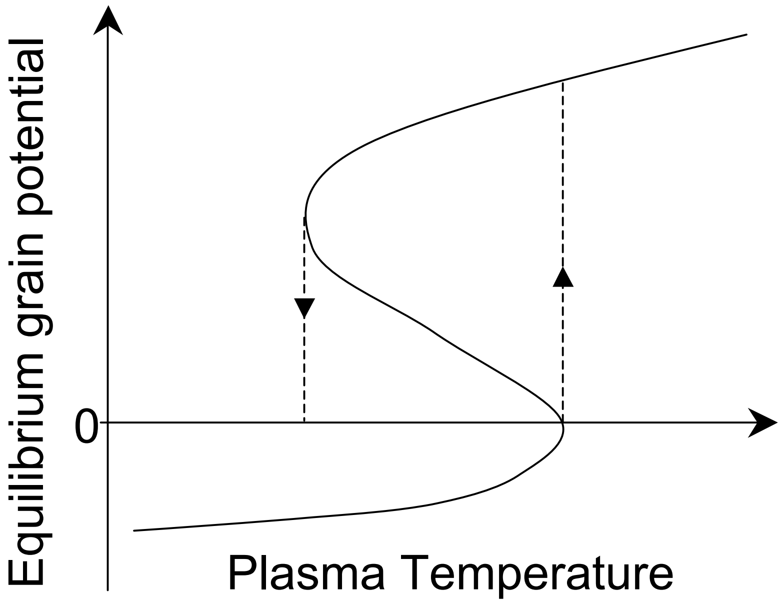
- relative velocity v of two grains of charge q, mass m, radius a required:
- $$\mathrm{v} = \left(\frac{q^2}{2\pi\varepsilon_o a m} \right)^{\frac{1}{2}}$$
- for H plasma with T = 2 eV, a = 0.5 μm
- $\Rightarrow$ $\mathrm{v} \simeq 2\, m/s$
- for dust at $\mathrm{T_d} = 1\, eV$, $\mathrm{v}_{d,T} \simeq 10^{-2}\, m/s$,
- $\Rightarrow$ coagulation is impossible

A cosmic dust growth scenario

M. Horanyi and C. Goertz *(Ap. J. 361, 155, 1990)*

- found a scenario in which grains of opposite polarity might be formed leading to enhanced coagulation
- How to get positively charged grains:
  - photoemission in radiative environment
  - secondary electron emission → energetic electrons
- need a mechanism that gives *both* positive and negative gains

effect of secondary electron emission (SEE) and temperature fluctuations



N. Meyer-Vernet, Astron Astrophys. 105, 98 (1982)

- in presence of SEE, grain potential is multi-valued (Meyer-Vernet 1982)
- charging time ~ a^{-1}
- consider case of grains of various sizes in plasma with temp. fluctuations
  - big grains → positive
  - small grains → negative
- enhanced coagulation

Electrostatic disruption (MR)

- Dust growth must compete with the tendency of highly charged grains to be blown apart by the electrostatic tension
- Electrostatic disruption will occur unless the tensile strength of the material exceeds the electric force $F_t > F_e$ ($\sim \varphi^2/a^2$)
- Disrupting grains will continue to do so
- Effect is circumvented by field emission of electrons from *negative* grains

Part III.—Waves and instabilities in dusty plasmas (SM, MR, F)

F.Verheest, *Space Sci. Rev., 77, 267, 1996*)

A. effect of dust on collective processes

B. methods of analysis of dusty plasma waves

C. fundamental wave modes in dusty plasmas

   (1) unmagnetized plasma

      (a) dust ion acoustic wave (DIA)

      (b) dust acoustic wave (DAW)

   (2) magnetized plasma

      (a) electrostatic dust ion cyclotron wave (EDIC)

      (b) electrostatic dust cyclotron wave (EDC)

Part III.—Waves and instabilities in dusty plasmas

D. New wave damping mechanisms

(1) “Tromsø damping”

(2) “creation damping”

E. Waves in strongly coupled dusty plasmas

(1) compressional modes

(2) shear modes

(3) Mach cones

Effect of dust on collective processes in plasmas -1

- consider the case in which there is a significant amount of dust in the plasma
- the presence of negatively charged dust can affect the properties of plasma waves even for waves with frequencies high enough that the dust *does not participate* in the wave motion (dust is an immobile neutralizing background)
- this is because the dust affects the *charge neutrality condition*: $en_+ = en_e + Q_d n_d$

Effect of dust on collective processes in plasmas -2

- the presence of charged dust leads to modifications in the wave dispersion relations [real $\omega(K)$]
- the dust can also affect instability conditions (growth rates, critical drifts, etc.)
- for frequencies below the characteristic plasma frequencies, new *"dust modes"* emerge, these are modes in which the dust participates in the wave motion.

Effect of dust on collective processes in plasmas -3

- Although the effect of dust on plasma waves is similar to the effects that occur in plasmas with negative ions, *there are important differences:*
  - the charge on the dust may not be constant
  - there may be a distribution of dust sizes, leading to a distribution of mass and charge.
  - the dust may be in a liquid or crystalline state

Analysis of dusty plasma waves

- the theoretical analysis of wave modes and major instabilities in a dusty plasma can be performed by considering the dust species as another fluid component which obeys the usual continuity and momentum equations

$$\frac{\partial n_d}{\partial t} + \frac{\partial \left(n_d \mathrm{v}_d \right)}{\partial x} = 0$$

$$m_d n_d \left(\frac{\partial \mathrm{v}_d}{\partial t} + \mathrm{v}_d \frac{\partial \mathrm{v}_d}{\partial x} \right) + kT_d \frac{\partial n_d}{\partial x} + e n_d Z_d \frac{\partial \phi}{\partial x} = -\sum_{\alpha} \nu_{d\alpha} \left(\mathrm{v}_d - \mathrm{v}_{\alpha} \right)$$

kinetic theory of dusty plasma waves

- the standard Vlasov analysis of plasma waves and instabilities can also be applied to dusty plasmas
- the dust is assumed to have a Maxwellian velocity distribution
- instability analyses can also be carried out by using drifting Maxwellians

Fundamental wave modes in a dusty plasma

- unmagnetized plasma
  - dust ion acoustic (DIA) mode
  - dust acoustic wave (DAW)
- magnetized plasma
  - electrostatic dust ion cyclotron wave (EDIC)
  - electrostatic dust cyclotron wave (EDC)

R. L. Merlino, et. al., Phys. Plasmas 5, 1607, 1998

Dust ion acoustic mode (DIA)

Shukla and Silin, Physica Scripta 45, 508, 1992

$K\lambda_D << 1,$ long wavelength limit

IONS
$$\begin{cases} \dfrac{\partial n_{+1}}{\partial t} + n_{+0}\dfrac{\partial \mathrm{v}_{+1}}{\partial x} = 0 \\ m_+ n_{+0}\dfrac{\partial \mathrm{v}_{+1}}{\partial t} + kT_+\dfrac{\partial n_{+1}}{\partial x} + en_{+0}\dfrac{\partial \phi_1}{\partial x} = 0 \end{cases}$$

ELECTRONS: $n_{e1} / n_{e0} = e\phi_1 / kT_e$

$n_{e1} = n_{+1}, \quad n_{d1} = 0$ (dust immobile)

$n_{+0} = n_{e0} + Zn_{d0}, \quad \varepsilon \equiv n_{d0} / n_{+0}$

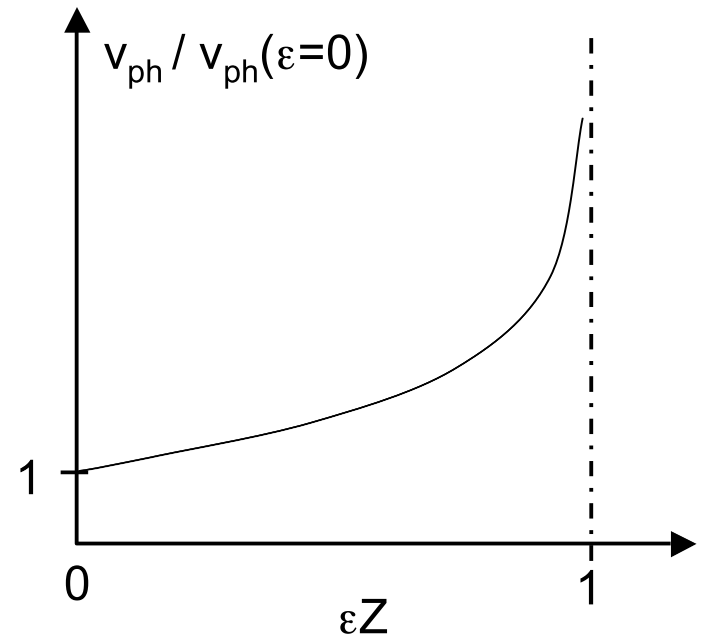
phase velocity of DIA wave

$$\left[\frac{\omega}{K}\right]_{DIA} = \left[\frac{kT_+ + kT_e/(1-\varepsilon Z)}{m_+}\right]^{\frac{1}{2}}$$

εZ = percentage of negative charge on the dust

$$\left[\frac{\omega}{K}\right]_{DIA} = \left[\frac{kT_+ + kT_{e,eff}}{m_+}\right]^{\frac{1}{2}} \equiv C_{DIA}$$

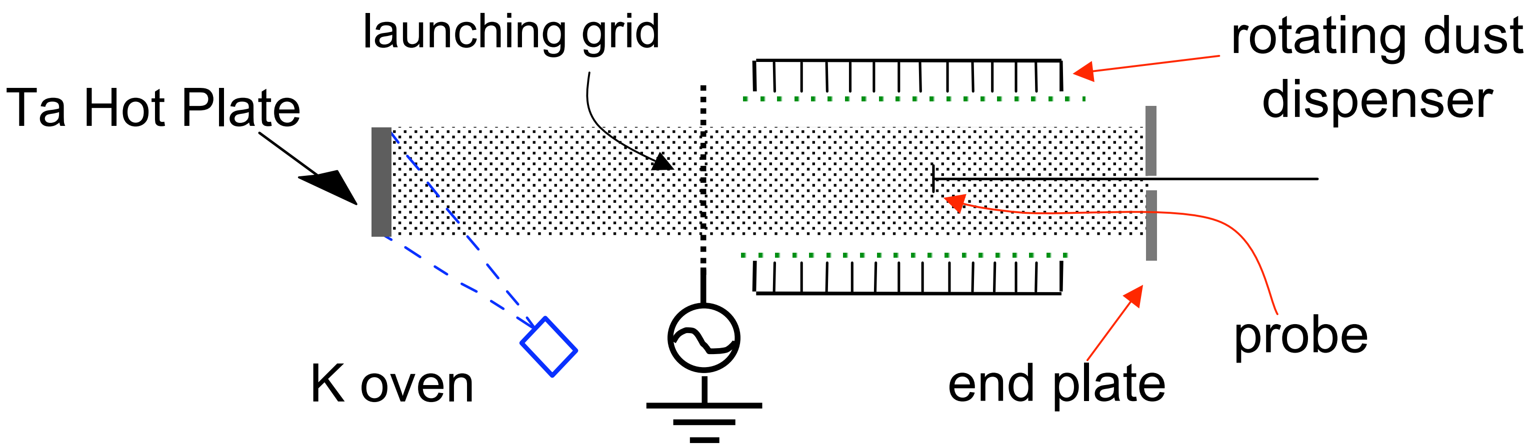
$$T_{e,eff} = \frac{T_e}{1-\varepsilon Z}$$

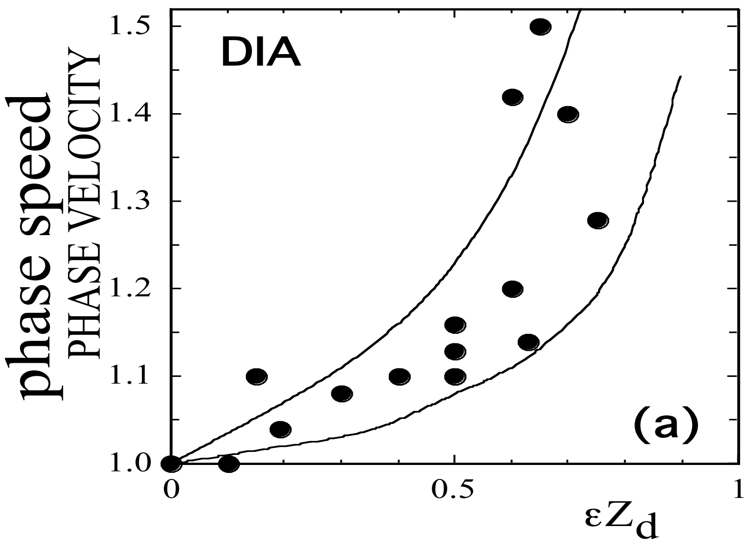


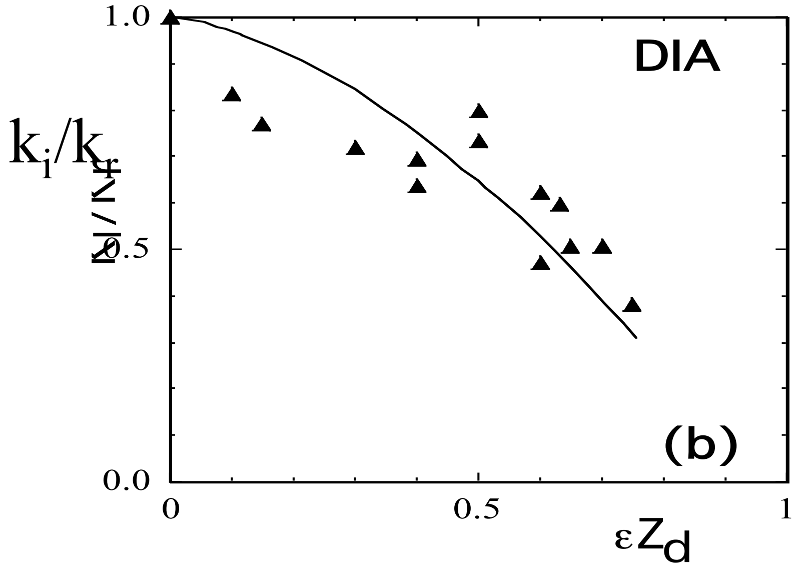
DIA -comments

- the effect of dust is to *increase the phase velocity* of the ion acoustic waves
- this can be interpreted formally as an increase in the *effective electron temperature* which has important consequences for wave excitation
- Ion acoustic waves are subject to ion Landau damping, which is severe for $T_e \sim T_+$, however the effect of the dust is to increase the phase speed which has the effect of *decreasing the Landau damping*, since now the wave-particle resonance at $v_{+,th} \sim v_{ph}$ no longer holds with $v_{ph} >> v_{+,th}$

Dust Ion Acoustic Wave Experiment



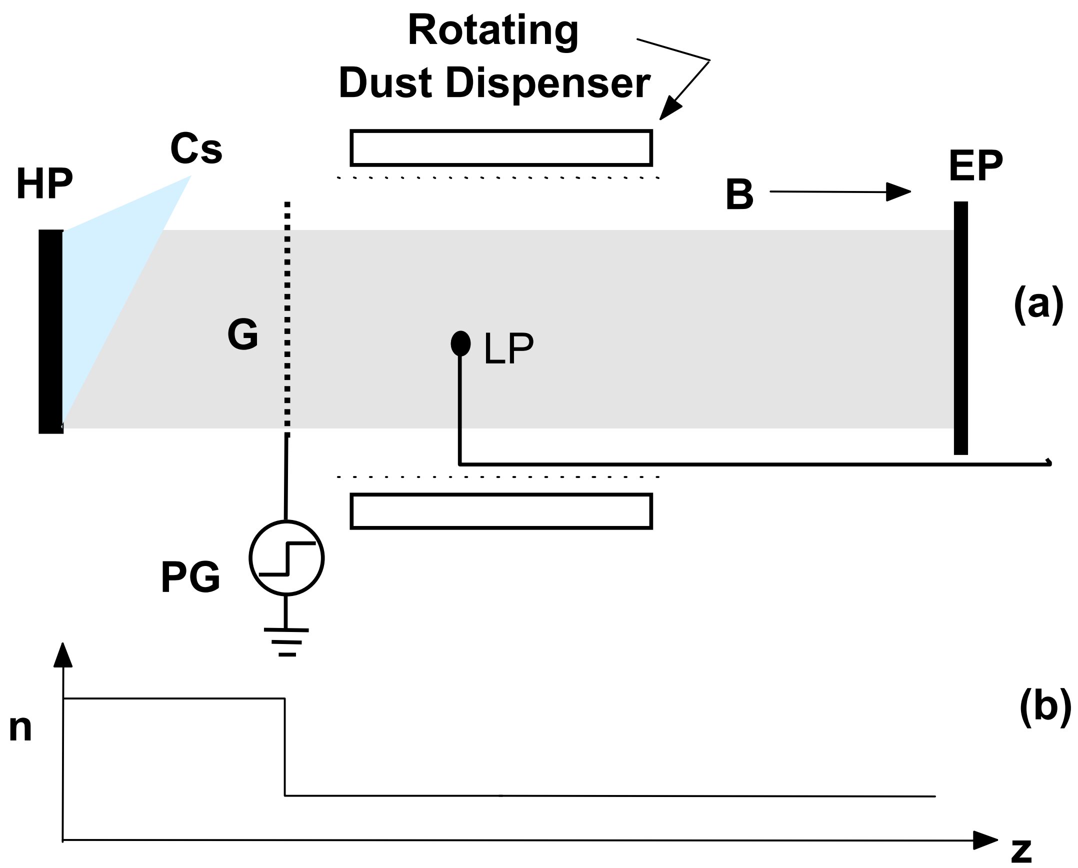




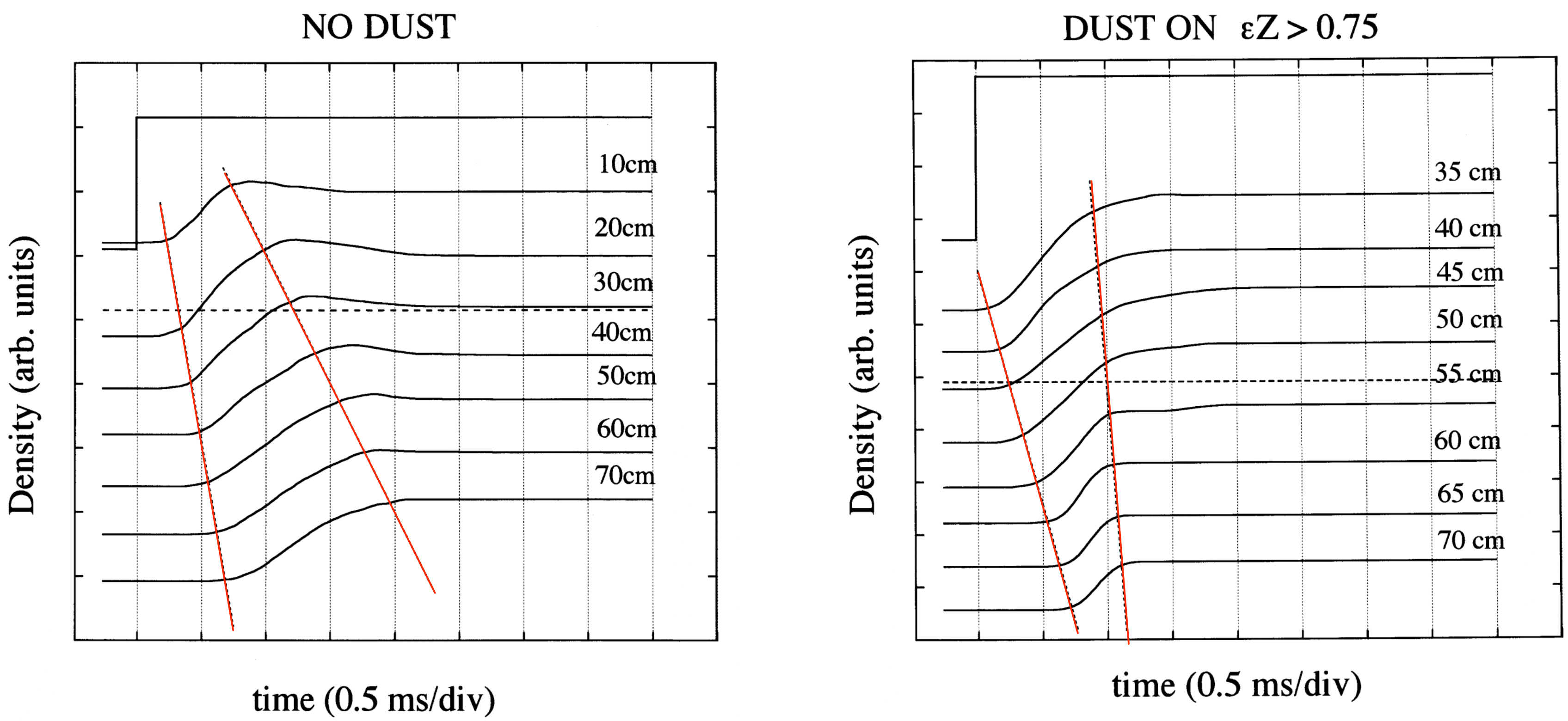
Dust ion acoustic shocks

- Normally in a plasma with $T_e = T_+$ a compressive pulse will not steepen into a shock-like structure because of Landau damping
- However, in a dusty plasma, DIA waves are subject to insignificant Landau damping, so that shock formation should be possible

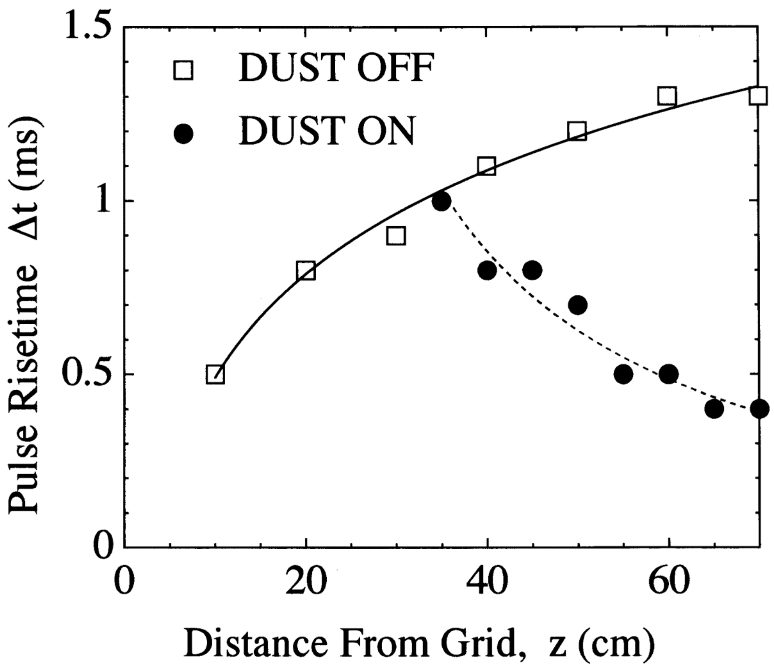
Experimental setup

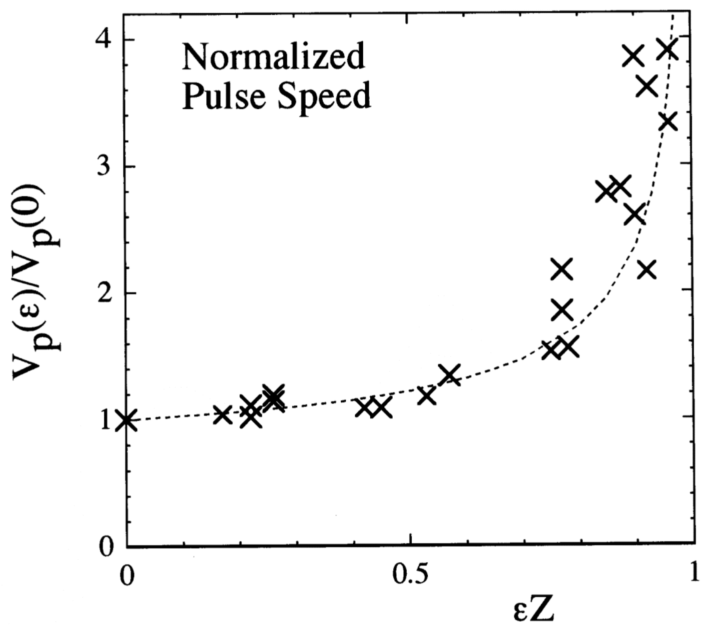


DIA Shocks – results



DIA Shocks – results





Dust acoustic (DA) waves

(Rao, Shukla, Yu, Planet. Space. Sci. 38, 543, 1990)

- very low frequency (<< ω_{p+}, phase speed C_{sd} << $v_{+,th}$) longitudinal *compressional disturbances* in a *fluid-like* dusty plasma
- the dust particles participate in the wave dynamics – it is a *“dust wave”*
- phase speed (dust acoustic speed)

$$C_{DA} \sim \sqrt{Z^2 \frac{kT_+}{m_d}}$$

Dust acoustic waves: fluid theory

Dust dynamics

$$\frac{\partial n_d}{\partial t} + \frac{\partial (n_d v_d)}{\partial x} = 0$$

$$m_d n_d \left[\frac{\partial v_d}{\partial t} + v_d \frac{\partial v_d}{\partial x} \right] + kT_d \frac{\partial n_d}{\partial x} - eZ_d n_d \frac{\partial \varphi}{\partial x} = 0$$

Electrons & Ions

$$kT_e \frac{\partial n_e}{\partial x} - en_e \frac{\partial \varphi}{\partial x} = 0; \qquad kT_+ \frac{\partial n_+}{\partial x} + en_+ \frac{\partial \varphi}{\partial x} = 0$$

Quasineutrality

$$\nabla^2 \varphi = -(e/\varepsilon_o)(n_+ - n_e - Zn_d)$$

$K\lambda_{Dd} << 1$

$$n_+ = n_e + Z_d n_d$$

Combining the dust momentum equation with the plasma equations we see that *(for the case of cold dust, $T_d = 0$).*

$$m_d n_d \frac{\partial v_d}{\partial t} = -\frac{\partial}{\partial x}(P_e + P_+)$$

where $P_e + P_+$ is the total pressure due to electrons and ions.

In the dust acoustic wave the inertia is provided by the massive dust particles and the electrons and ions provide the restoring force

excitation of dust acoustic waves

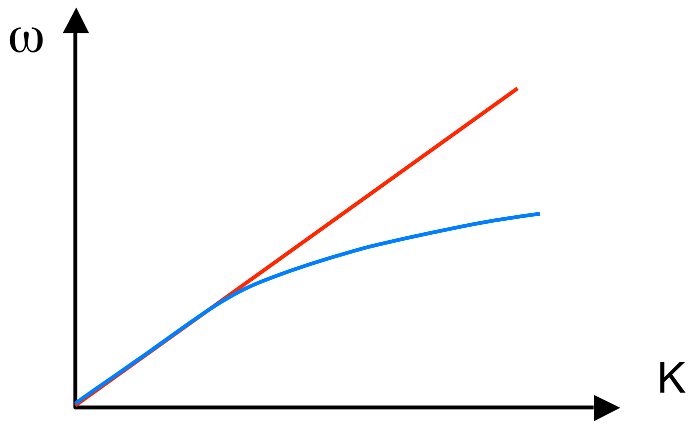
- dust acoustic waves can be driven by an ion-dust streaming instability *(Rosenberg, JVST A 14, 631, 1996)*
- a relatively modest drift $u_o \sim v_{ith}$ of the ions through the dust is sufficient for instability
- DAWs are spontaneously excited in dusty plasmas produced in gas discharges
- are observed visually by laser light scattering

dust acoustic dispersion relationship ($T_d \sim 0$)

acoustic modes (long wavelength)

$$\frac{\omega}{K} = \left[\left(\frac{kT_+}{m_d}\right)\left(\frac{\varepsilon Z^2}{1+\left(\frac{T_+}{T_e}\right)(1-\varepsilon Z)}\right)\right]^{1/2} = C_{DA}$$

where: $\varepsilon = n_d / n_i$



Finite $K\lambda_D$ effects:

$$\frac{\omega}{K} = \left[\frac{C_{DA}^2}{1+K^2\lambda_D^2}\right]^{1/2}$$

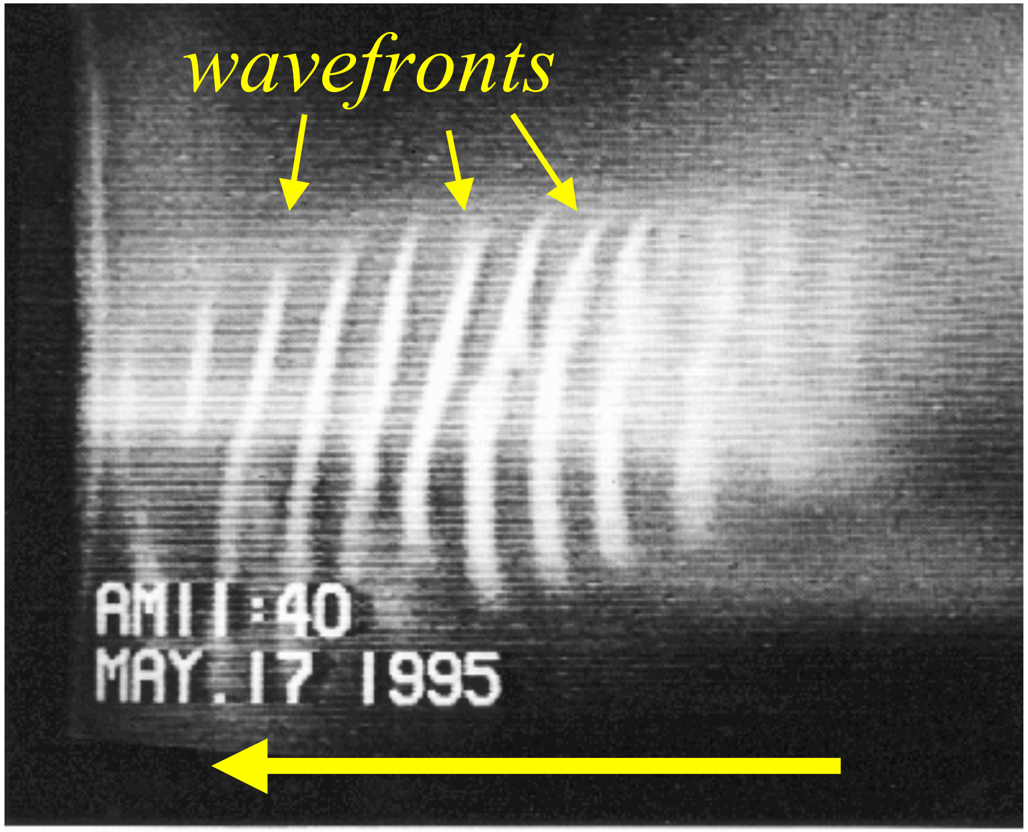
where: $\frac{1}{\lambda_D^2} = \frac{1}{\lambda_{De}^2} + \frac{1}{\lambda_{Di}^2}$

Effect of dust-gas collisions:

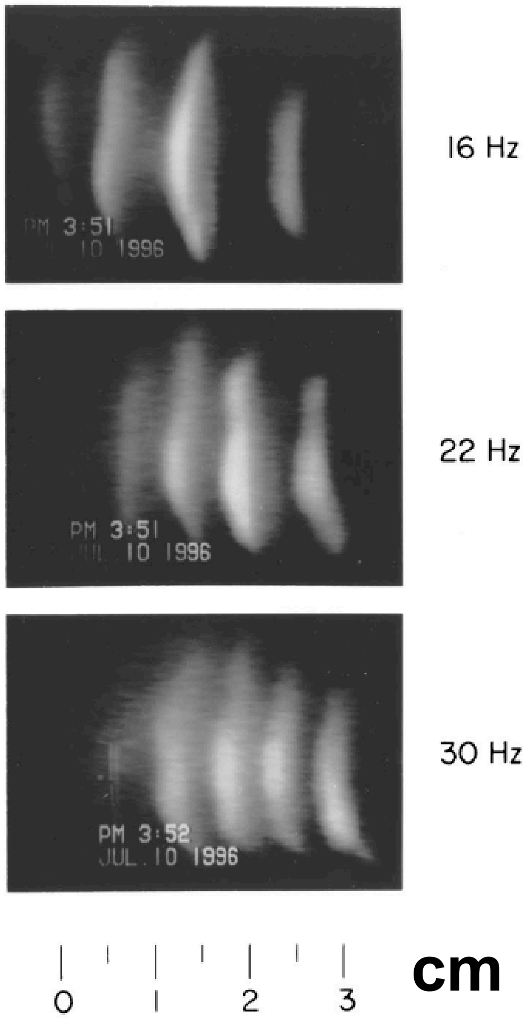
$$\omega(\omega + i\beta) = K^2 C_{DA}^2$$

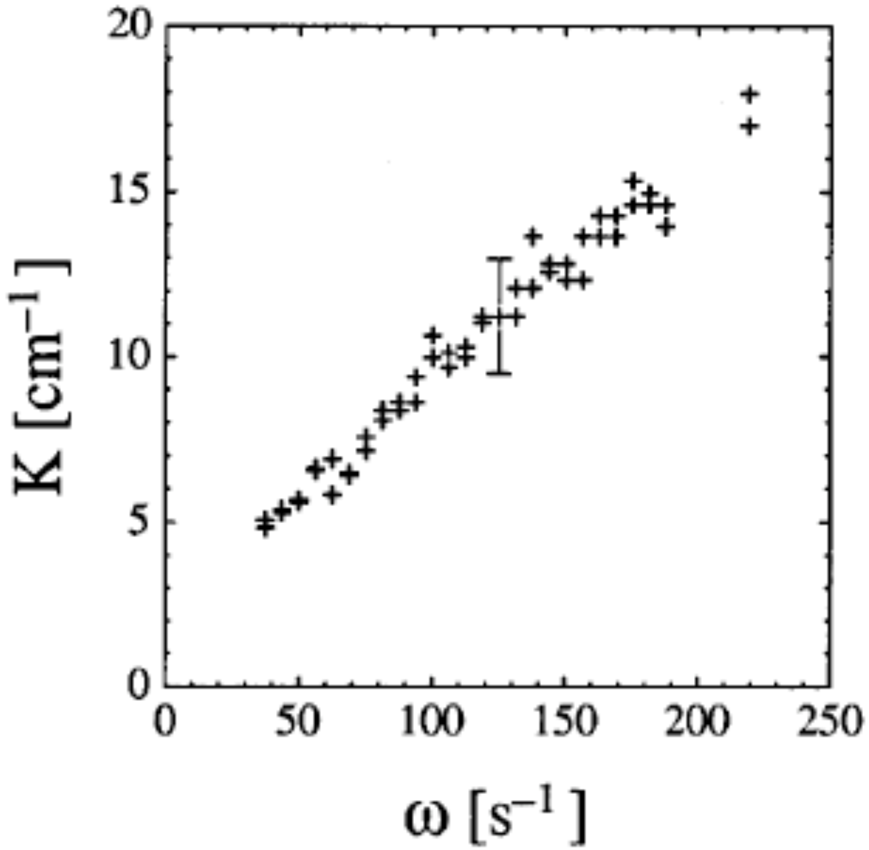
β is the dust-neutral collision frequency

Dust Acoustic Wave Image



Dust acoustic waves





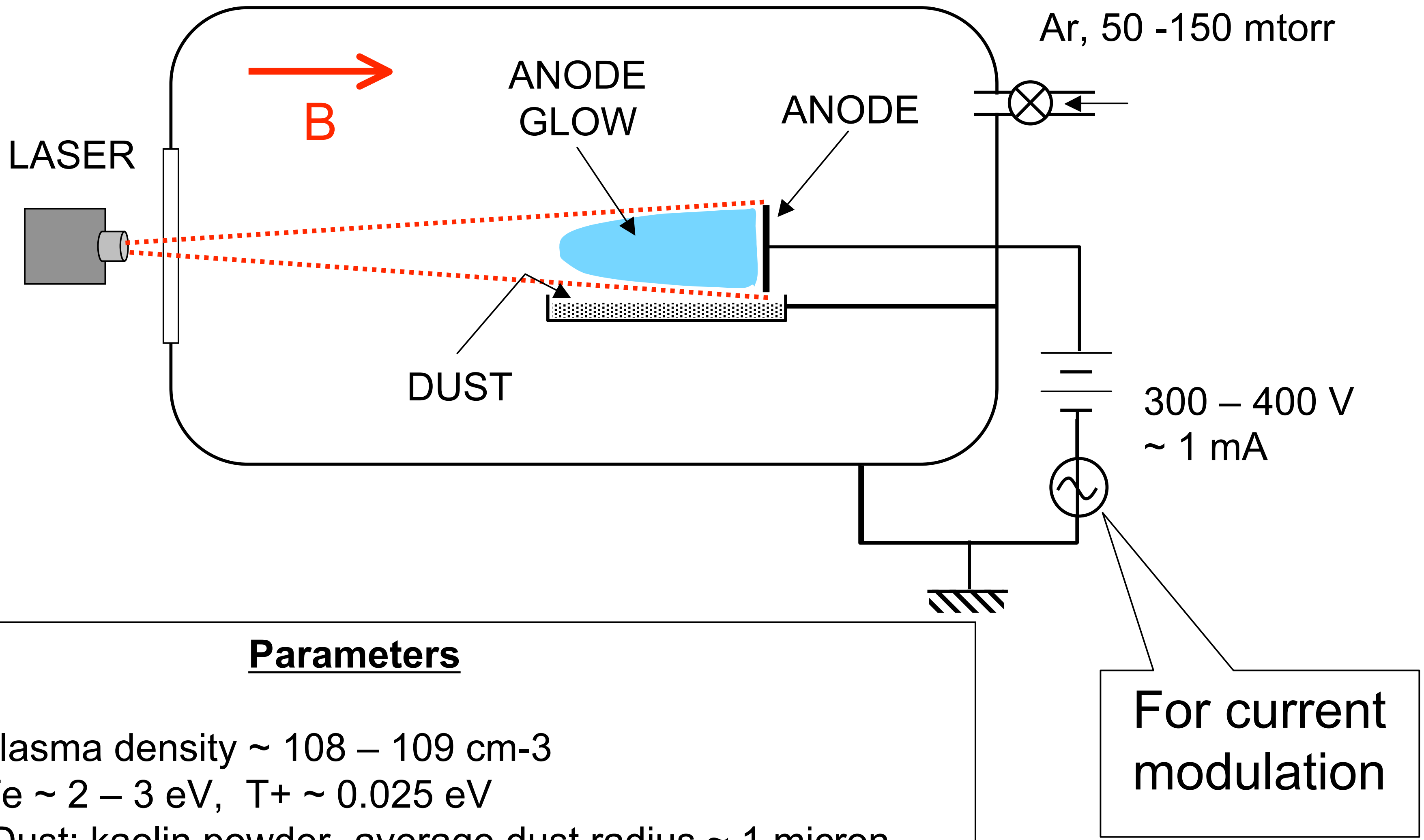
Measurement of the dispersion relationship of the dust acoustic wave

Original Experiments

A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Plasmas, 2, 3563 (1995).

C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Plasmas, 4, 2331 (1997).

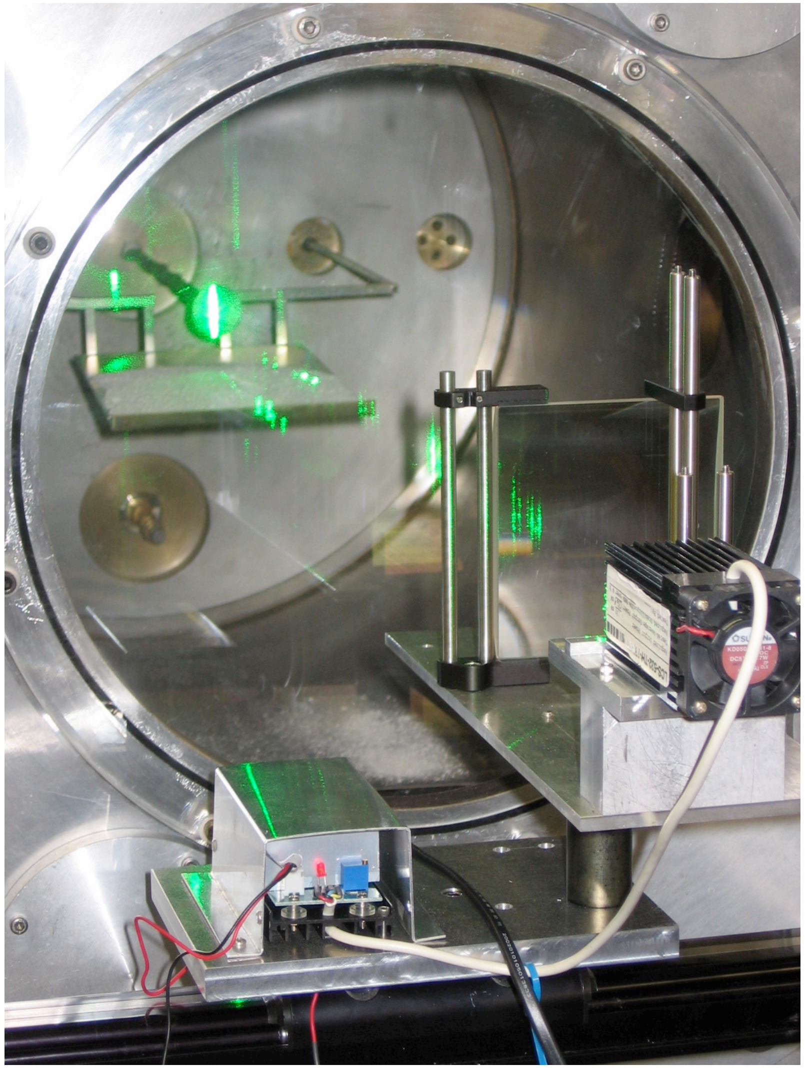
UI dusty plasma device

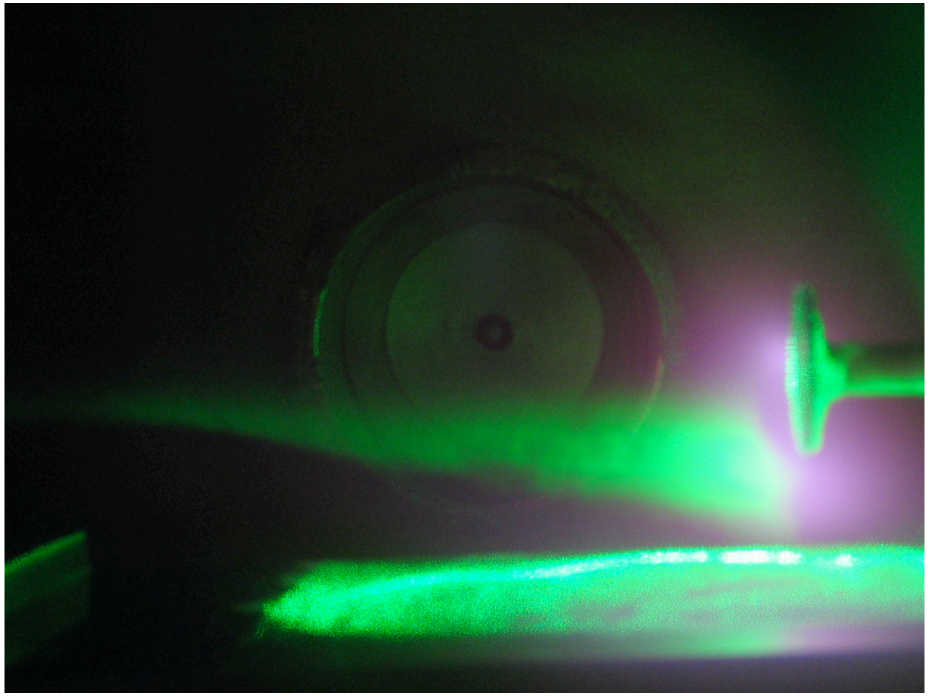


Parameters

plasma density ~ 108 – 109 cm-3
Te ~ 2 – 3 eV, T+ ~ 0.025 eV
Dust: kaolin powder -average dust radius ~ 1 micron
average dust charge Z ~ – (1000 – 2000)
dust density nd ~ 105 cm-3, ω_{pd} ~ 300 - 500 s^{-1}

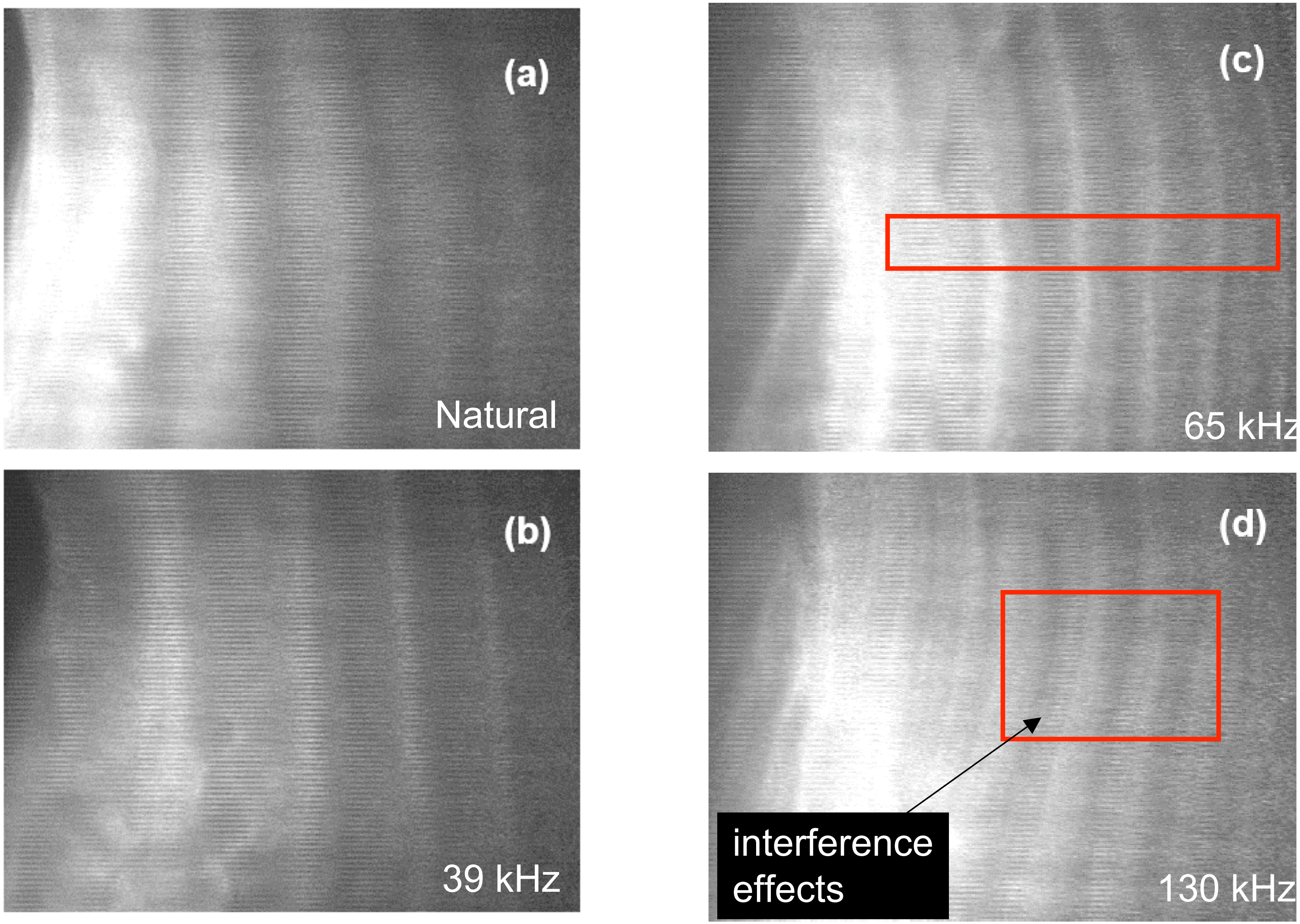
Experiment at Univ. of Iowa, Fall, 2006





60 cm dia. x 80 cm long vacuum vessel
dc glow discharge plasmas (N_2, Ar)
50 - 100 G axial magnetic fields

Dust acoustic waves are captured using a 30 fps digital camera



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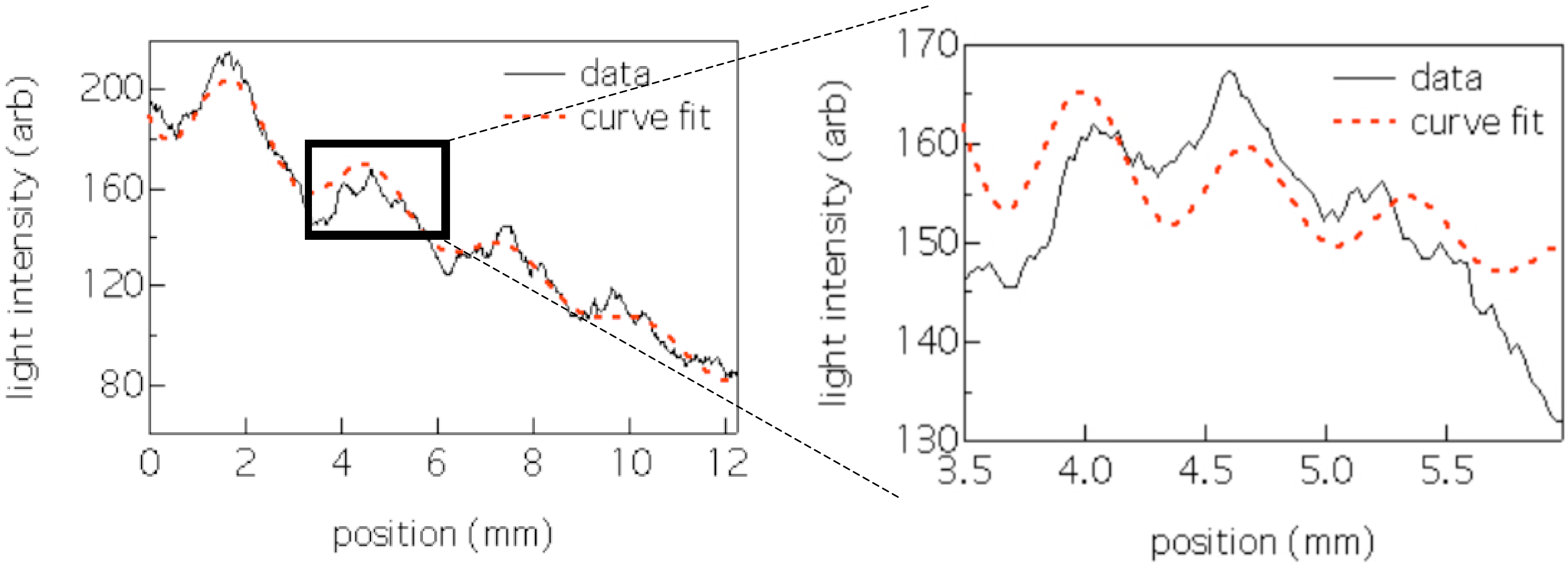
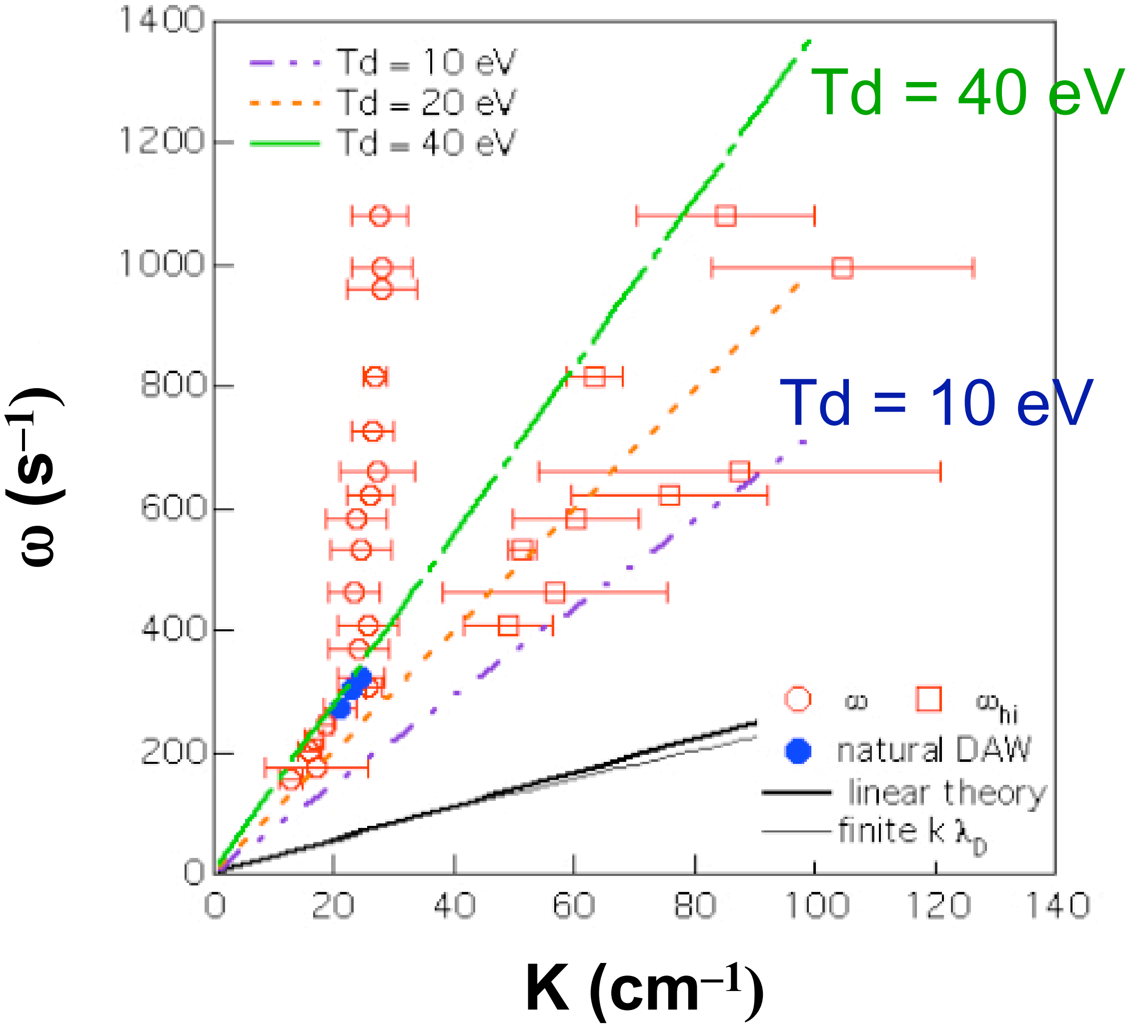
video analysis



About 100 images were analyzed for each frequency

dispersion relation — short wavelengths



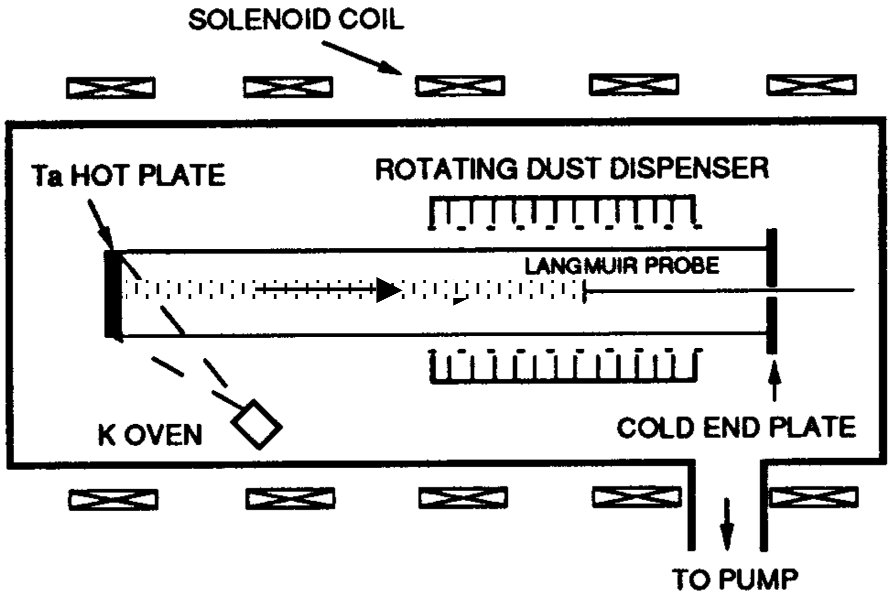
Magnetized plasma—Electrostatic dust ion cyclotron waves (EDIC)

- Electrostatic ion-cyclotron waves excited by electron current along the magnetic field
- dust is treated as an immobile charge neutralizing background
- waves propagate at large angle to **B** $(K_\perp >> K_{||})$

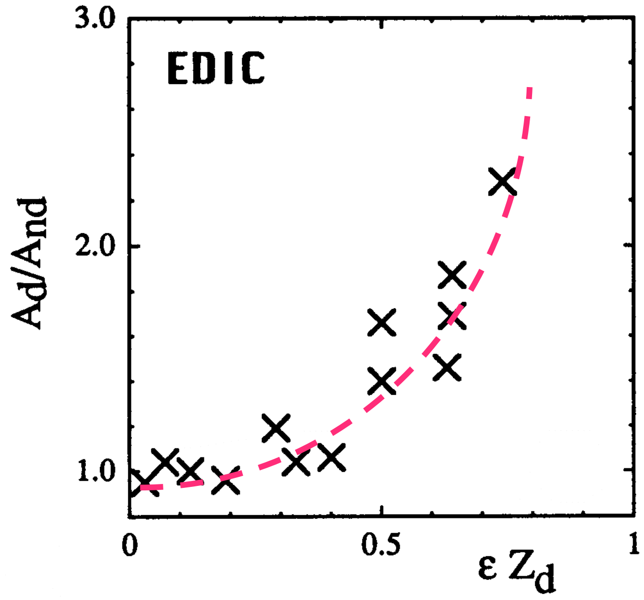
$$\omega^2 = \Omega_{ci}^2 + K_\perp^2 \left(\frac{kT_i}{m_i} + \frac{kT_e}{m_i(1 - \varepsilon Z_d)} \right)$$

$$= \Omega_{ci}^2 + K_\perp^2 C_{DIA}^2$$

Electrostatic dust ion-cycloton instability (EDIC)

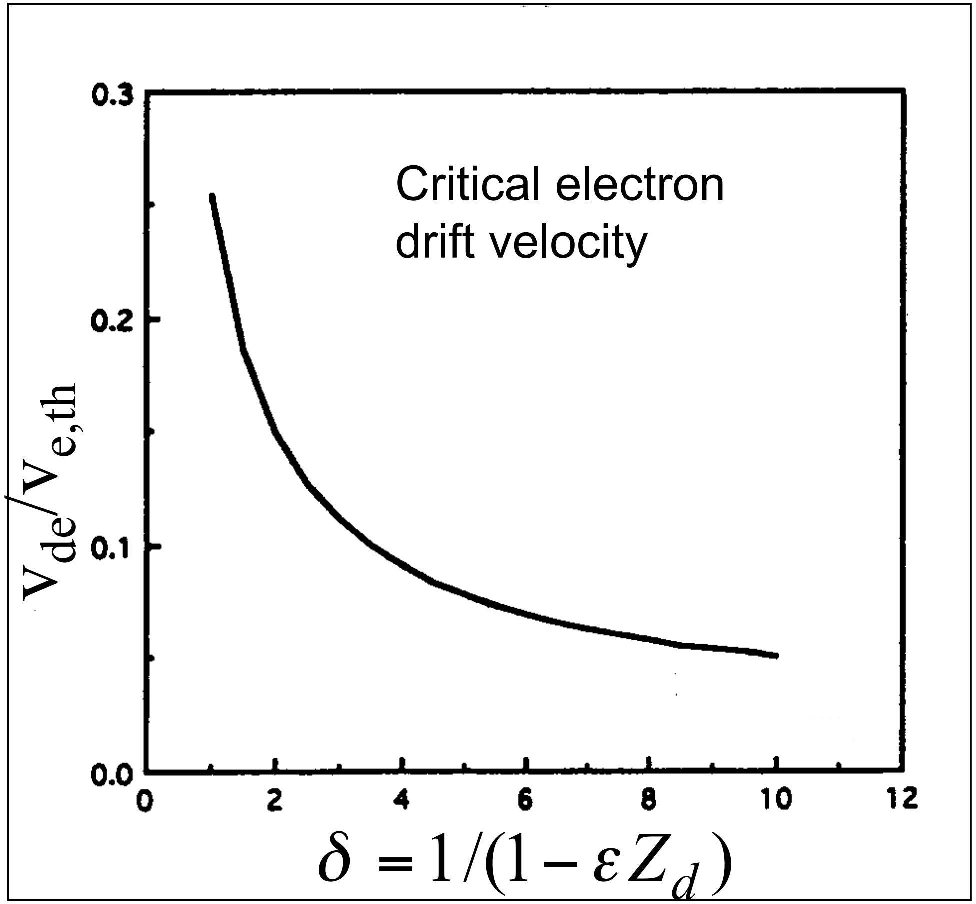


Amplitude of EIC Wave relative to case with no dust



EDIC- kinetic theory results

- EIC instability driven by current along B
- As more negative charge is carried by the dust, the critical drift needed to excite the instability decreases
- *the instability is easier to excite in a dusty plasma*



V. W. Chow & M. Rosenberg, Planet. Space Sci. 44, 465 (1996)

Electrostatic dust cyclotron mode (EDC)

- EDIC – involves cyclotron motion of the dust – *magnetized dust*
- Dispersion relation

$$\omega^2 = \Omega_{cd}^2 + K_\perp^2 \left[\frac{kT_d}{m_d} + \varepsilon Z_d^2 \frac{1}{1 + (T_i / T_e)(1 - \varepsilon Z_d)} \right]$$

$$= \Omega_{cd}^2 + K_\perp^2 C_{DA}^2$$

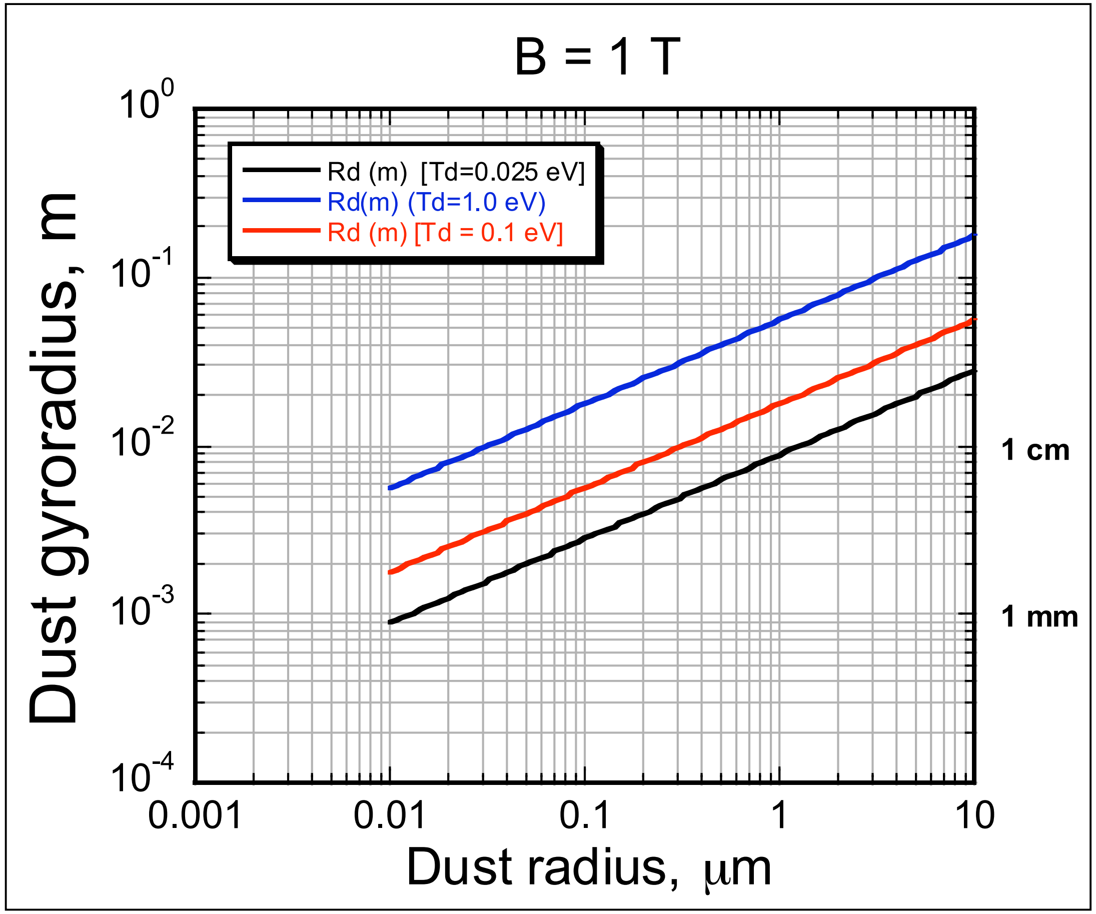
Gyroradius of dust particles

$$r_d = \frac{m_d v_d}{eZ_d B},$$

$$v_{d,T} = \sqrt{\frac{8kT_d}{\pi m_d}}$$

$$m_d \propto a^3, \quad Z_d \propto a,$$

$$r_d \propto a^{\frac{1}{2}}$$



New damping mechanisms for DAW and DIA waves

(1) Tromso damping due to Dust charge fluctuations—[*Melandso, Aslaksen and Havnes, Planet. Space Sci. 41, 321, 1993*]. In the presence of plasma potential oscillations, the charge on the dust will also oscillate. If the frequency of the potential fluctuations is close to the dust charging frequency (inverse of dust charging time) this can lead to a damping. The damping of the wave is due to the delay in charging the particles.

(2) Creation damping — [*D'Angelo, Planet. Space Sci. 42, 507, 1994*]. This is a damping due to the fact that plasma which is absorbed on the dust must be replaced by a continuous injection of new plasma by ionization. The newly created ions do not share initially in the wave motion of the existing ions and hence lower the average momentum of the ion population. This can be an important damping mechanism for the DIA wave.

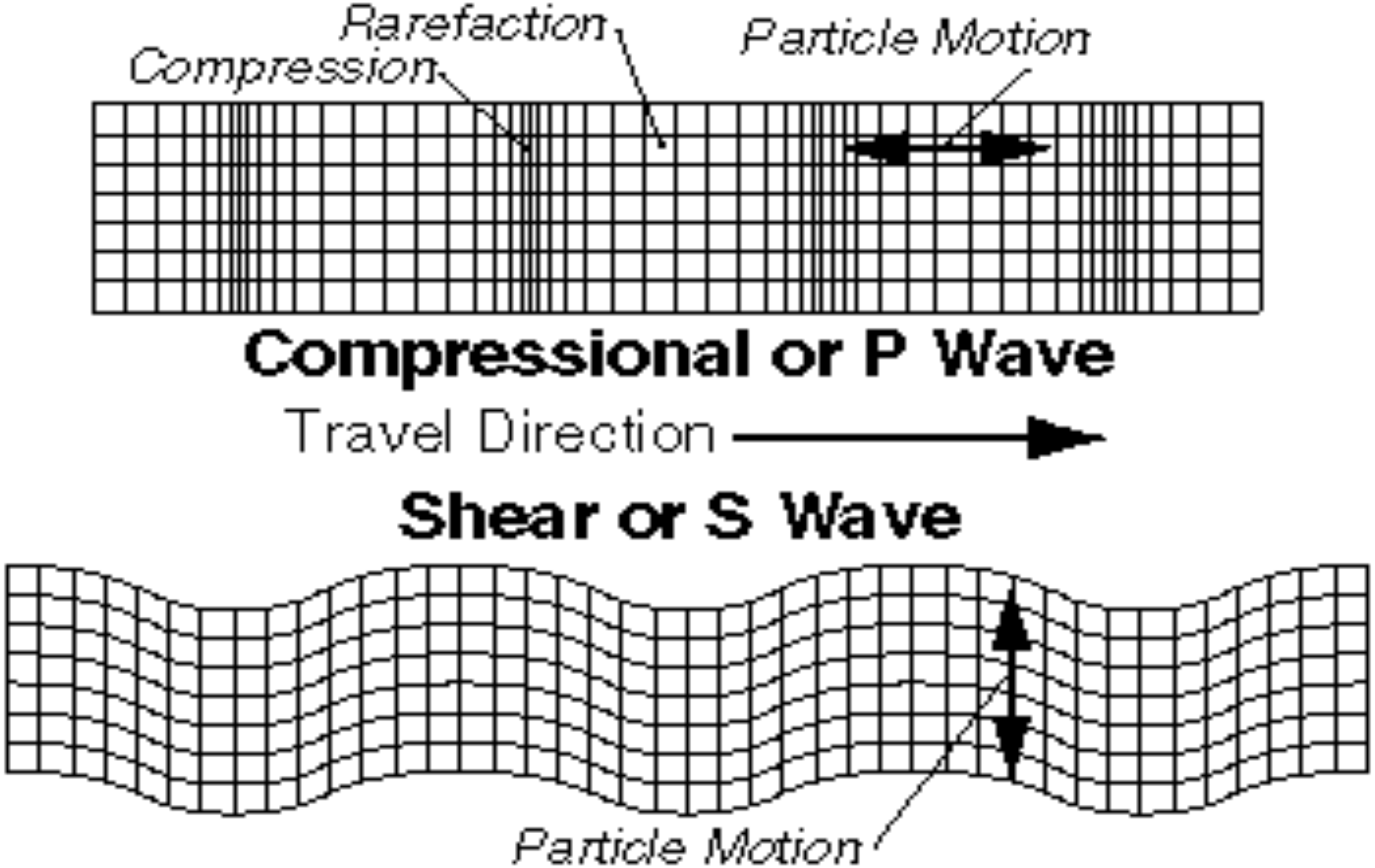
Waves in strongly coupled dusty plasmas (F, p. 58)

- The presence of short scale correlations gives rise to novel modifications of the collective behavior
- Both compressional and transverse shear waves are possible
- dispersion relations are derived from the equations of motion

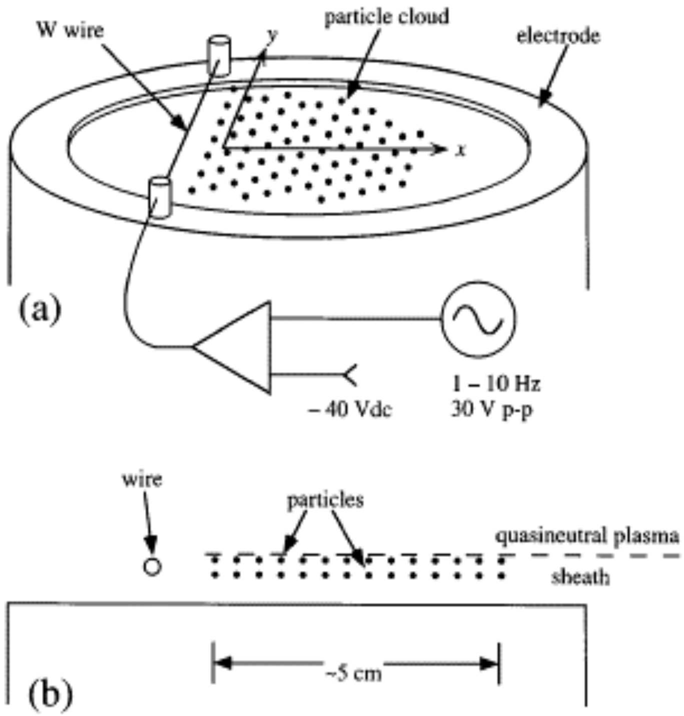
$$m_d \ddot{\xi}^{jk} + m_d \beta \dot{\xi}^{jk} = \sum_{\alpha,\delta}^{N} k_{\alpha\delta}^{jk} (\xi^{jk} - \xi^{\alpha\delta})$$

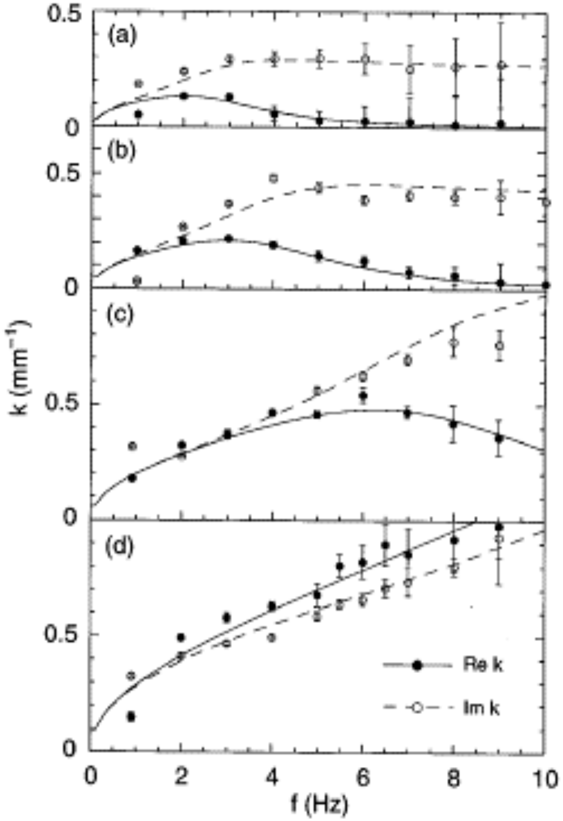
β = neutral drag coeff., k = spring constants

Compressional and shear waves



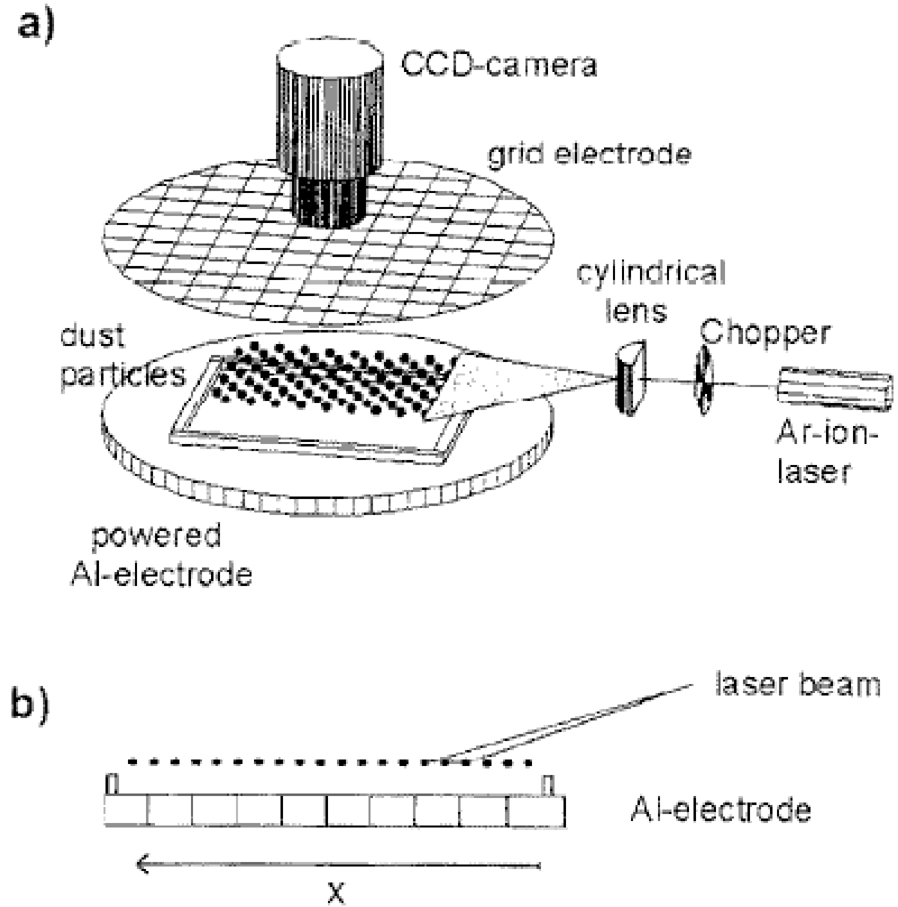
Dispersion of DAW in strong coupling regime *(Piper& Goree PRL 77, 3137, 1996)*

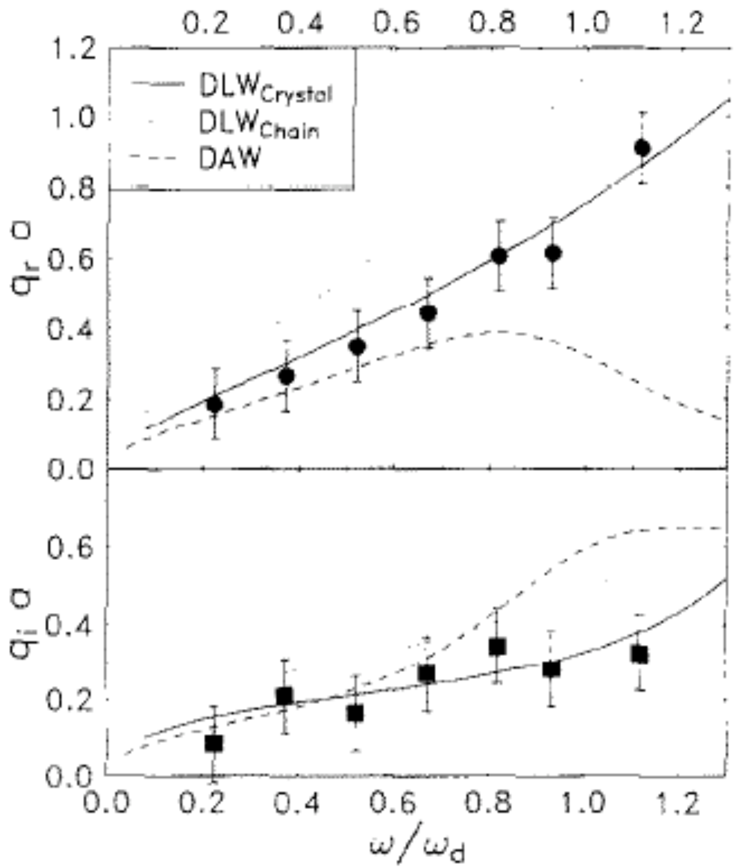




In this case better agreement was obtained with the dispersion relation derived from fluid theory – ignoring the strong coupling.

Laser excited dust lattice waves in plasma crystals *(Homan et al PLA 242, 173, 1998)*

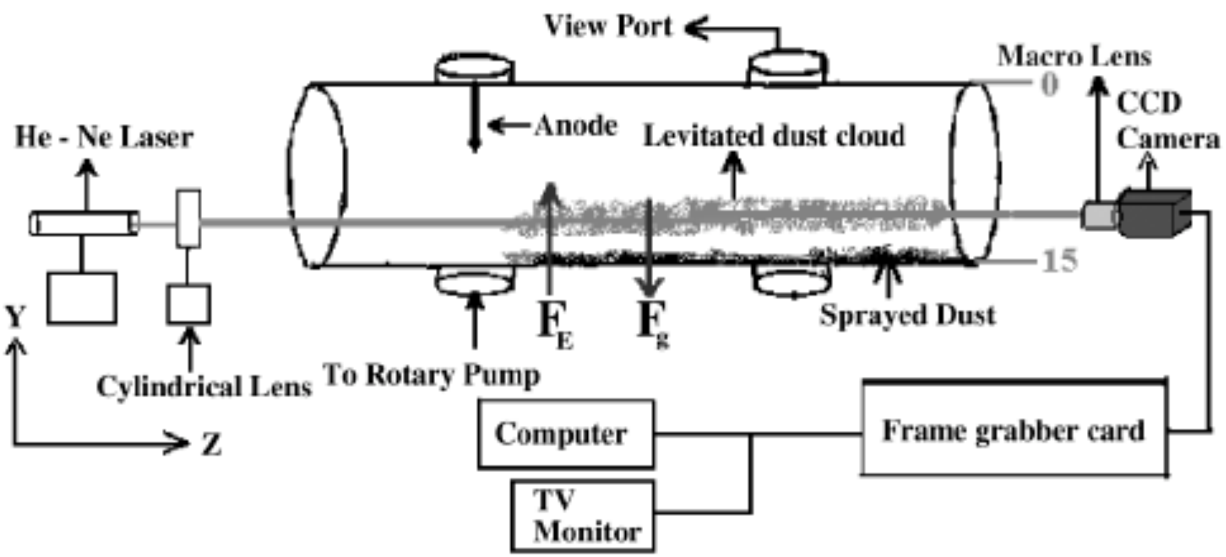


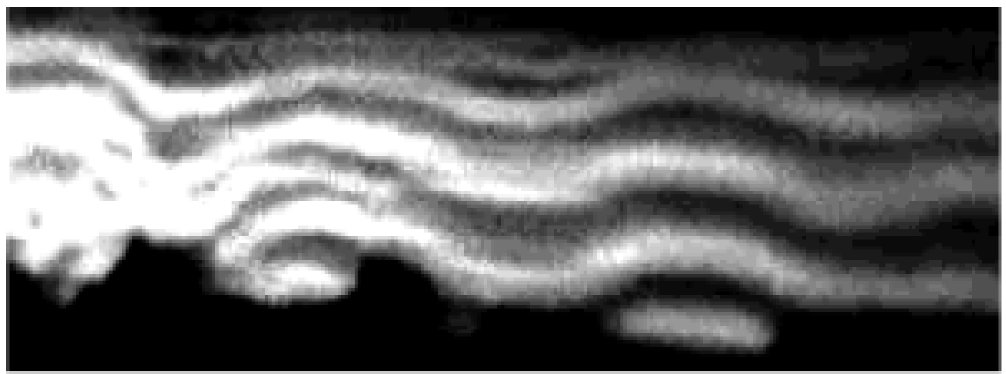


In this case the data agreed with the results of the dust lattice wave. The main difference was that this exp. had a single dust layer not multiple ones.

Observation of the transverse shear wave in a strongly coupled dusty plasma

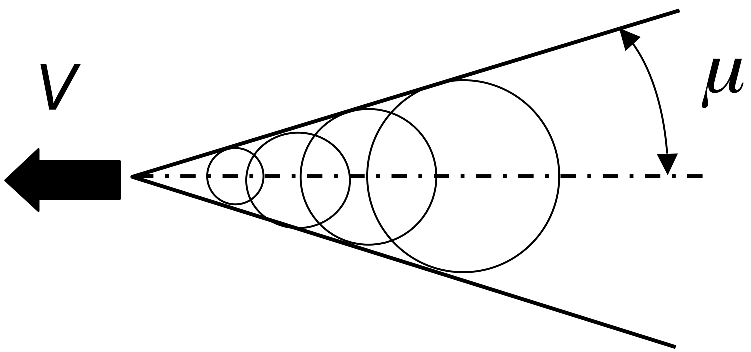
(Pramanik et al, PRL 88, 175001, 2002)





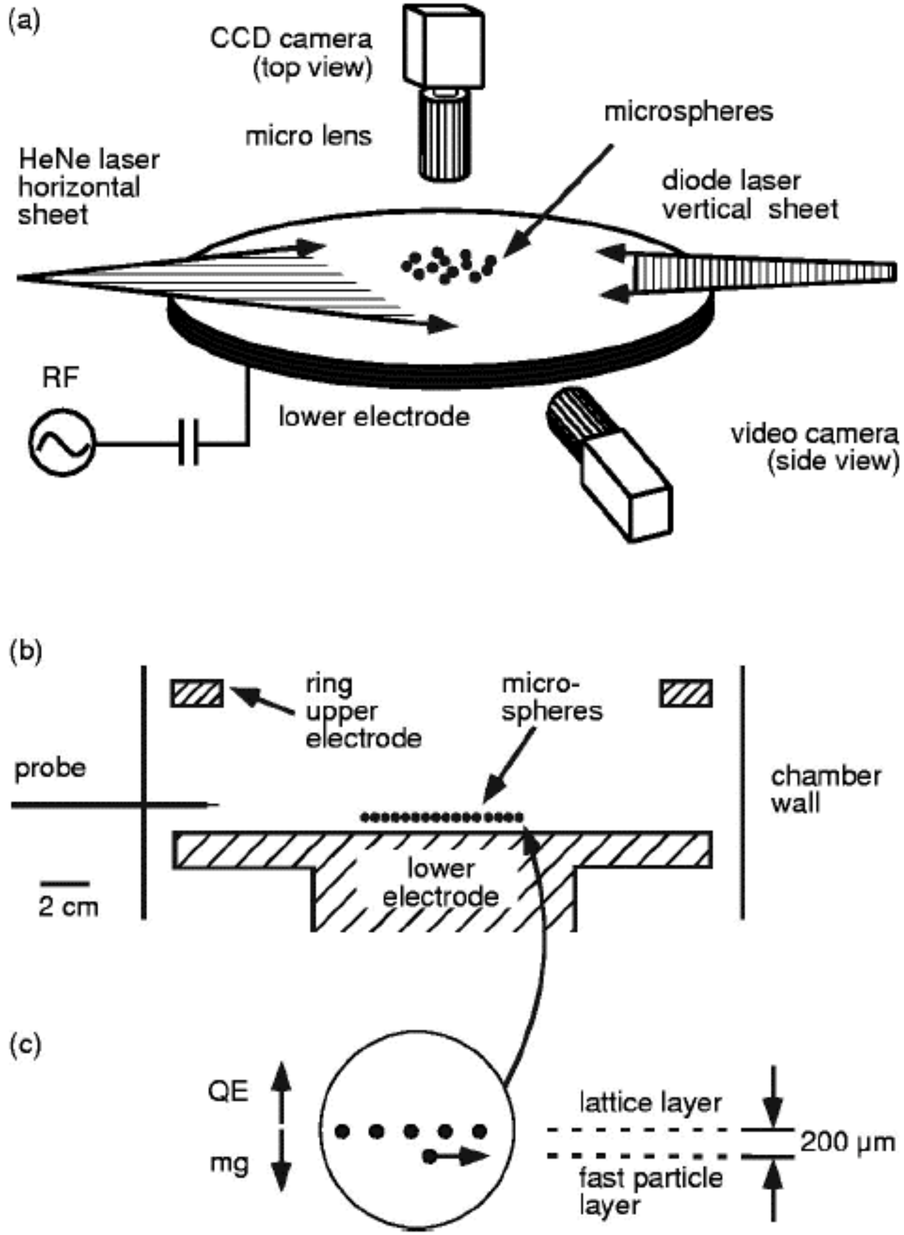
Mach cones in dusty plasmas (F 254, 255)

Mach cones are V-shaped disturbances (shock waves) produced by supersonic a object moving through a medium



$$\sin \mu = \frac{C_s}{V} = \frac{1}{M}$$

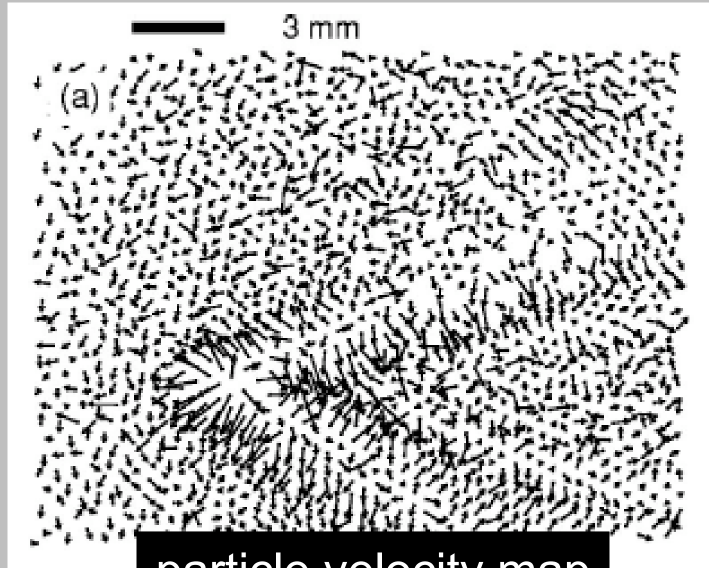
Havnes et. al. (J. Geophys. Res. 100, 1731, 1995) proposed to look for Mach cones in Saturn’s rings during the Cassini mission



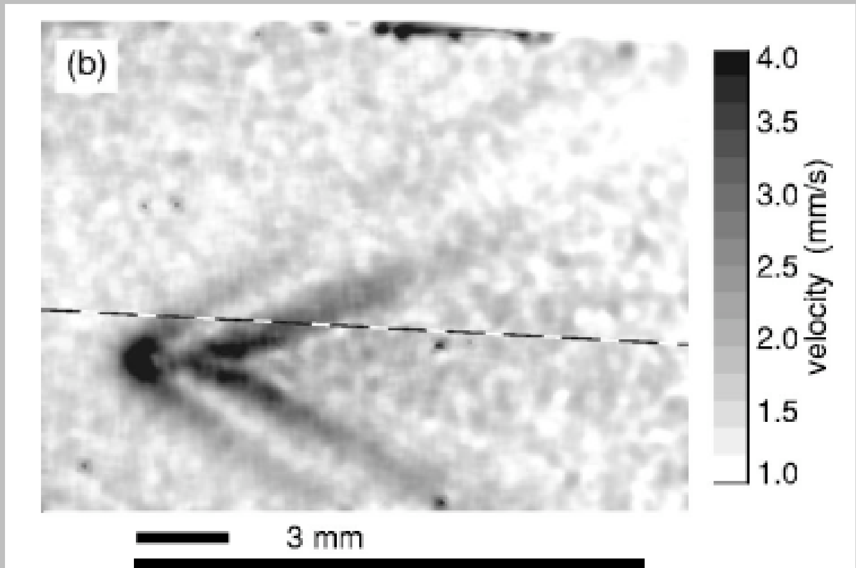
Mach cones observed in the lab *Samsonov, et al., PRE 61, 5557,2000*

The cones were produced by supersonically moving particles just below the dust crystal

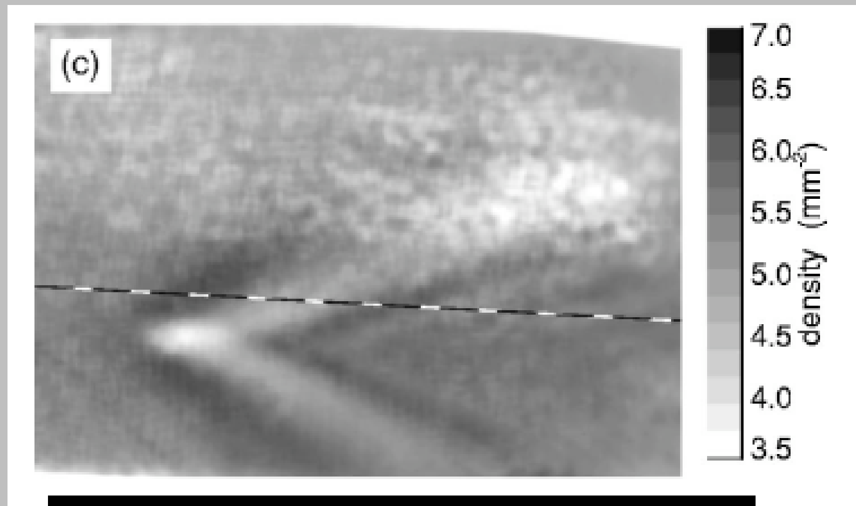
Mach cone observations



particle velocity map

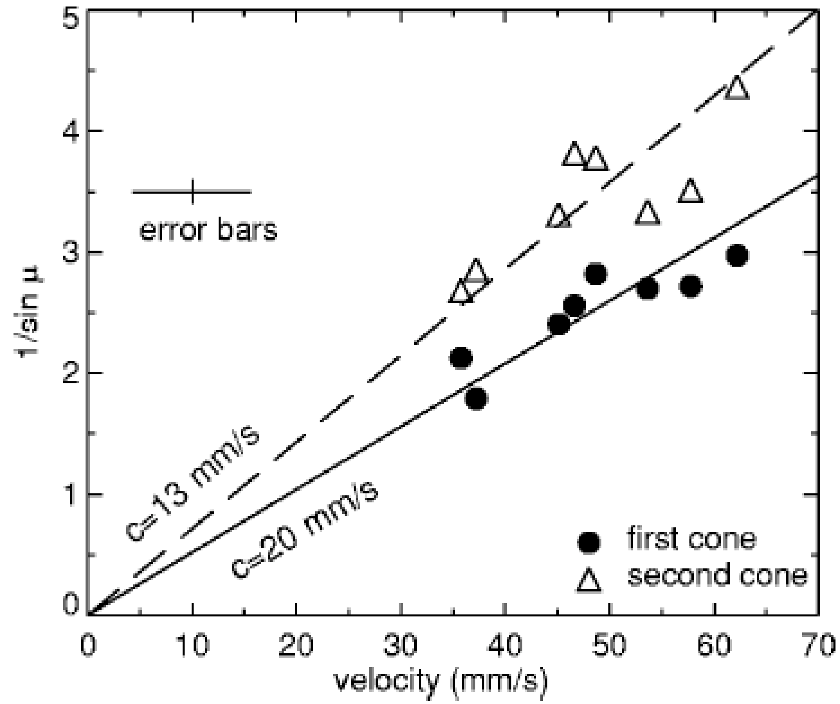


grey-scale speed map



grey-scale number density map

summary of Mach cone data



Future directions in dusty plasma research

- dust does not necessarily have only undesirable consequences
  - use plasma technologies to produce powders with control over size, composition and structure
  - modify surface properties using materials grown in plasmas
- use dusty plasma systems to study “nano-dynamics” - behavior of systems at the kinetic level, e.g., physics of liquids, phase transitions, etc.
- explore consequences of the understanding that particle growth takes place in plasmas both in cosmos and lab
- Transfer our detailed understanding of basic properties of dusty plasmas acquired through theory and in the lab to astrophysical plasmas