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Opportunities for dust experiment & applications in highly-ionized plasmas & magnetic fusion

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Opportunities for dust experiment & applications in highly-ionized plasmas & magnetic fusion

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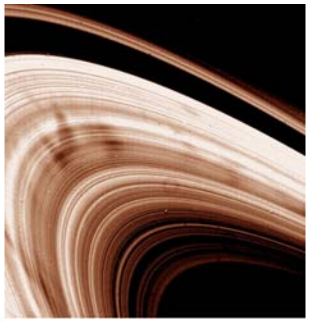
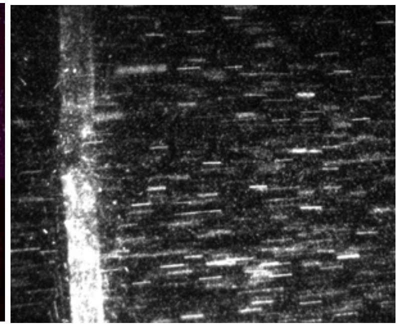
Summer College in Plasma Physics
ICTP, Trieste, Italy
Aug. 21, 2007



Outline

- **Some milestones of dust-in-plasma research**
  - Recognition of dust in interstellar medium
  - Threat to the Moore's law
  - Discovery of dust crystal
  - Discovery of dust acoustic waves
- **Motivations for new research directions**
  - To understand astrophysical phenomena
  - To harvest magnetic fusion energy
  - Opportunities for new technologies
- **Two dust-in-plasma experiments**
  - Study of dust behaviors in flowing plasmas
  - Acceleration of dust to hypervelocities
- **Opportunities and perspectives**
  - Dust study of fusion plasmas
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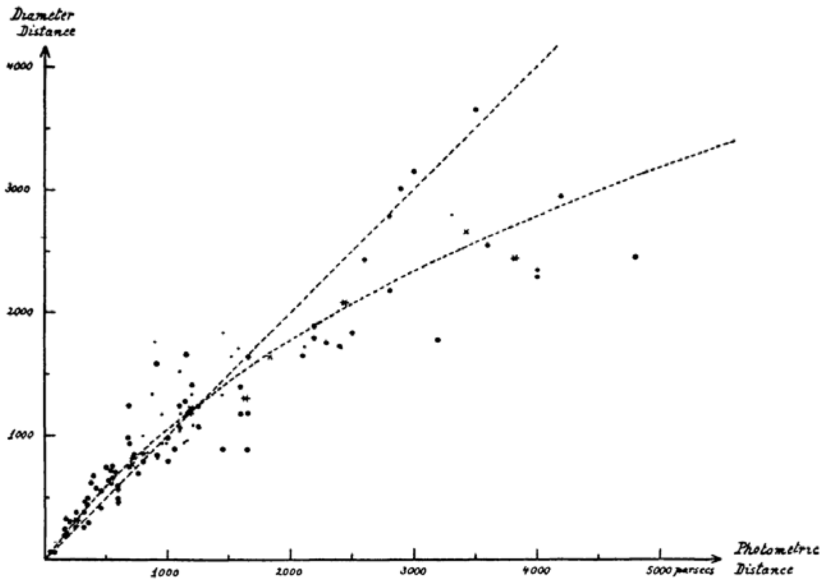
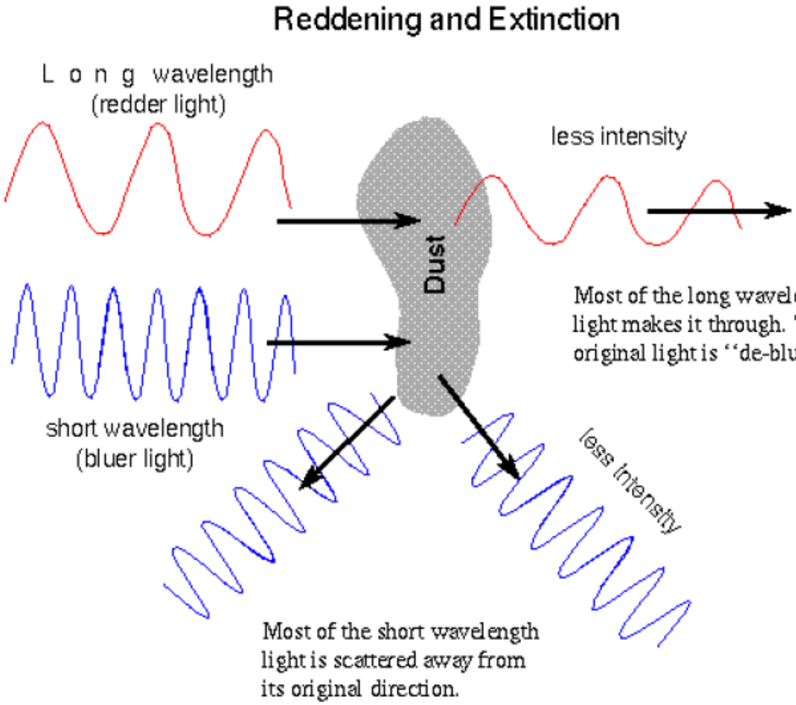
  - Understanding dust transport

Discovery of interstellar dust

Robert J. Trumpler (1930)





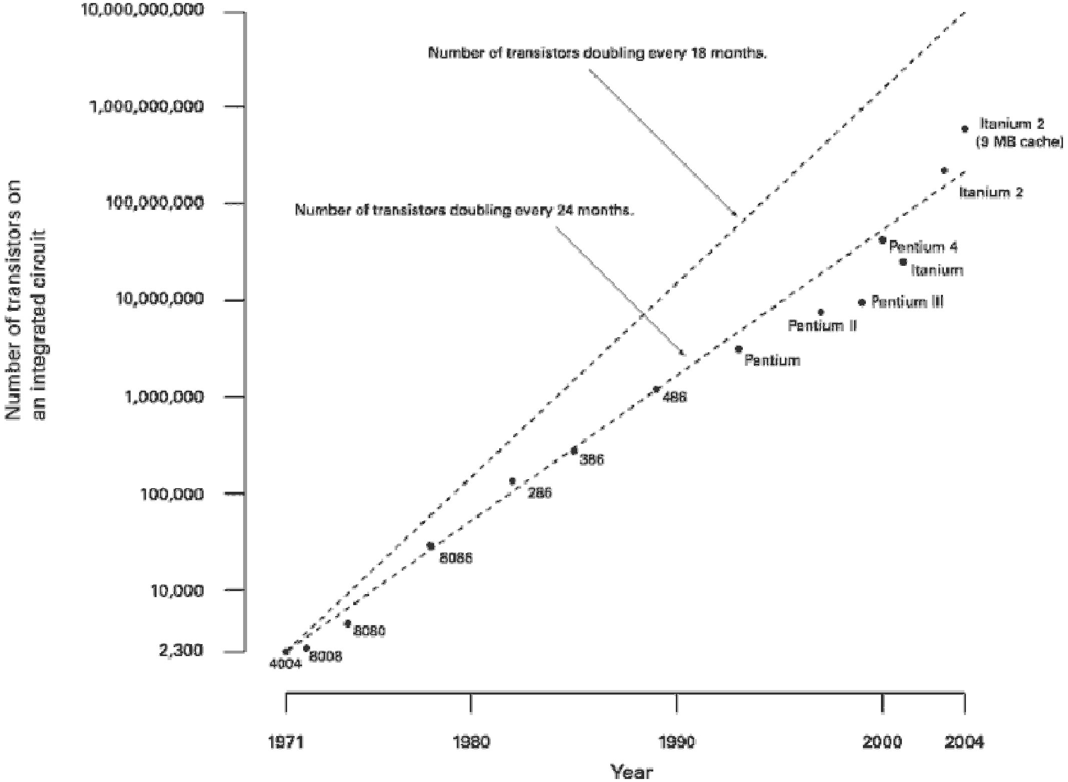
1 parsec = 2.06×10^5 AU = 3.26 ly

Rayleigh scattering

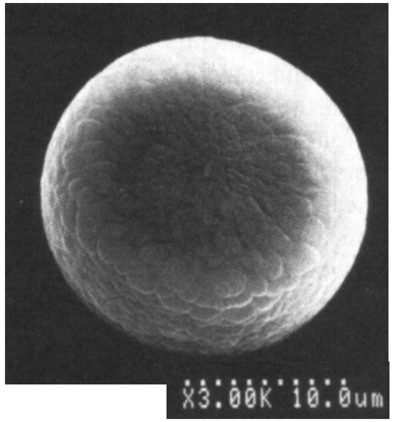
$$I_{scat.} \propto \lambda^{-4}$$

Dust threat to Moore's law

Gordon Moore (1965)



G. S. Selwyn, *et al*. JVST (1989)



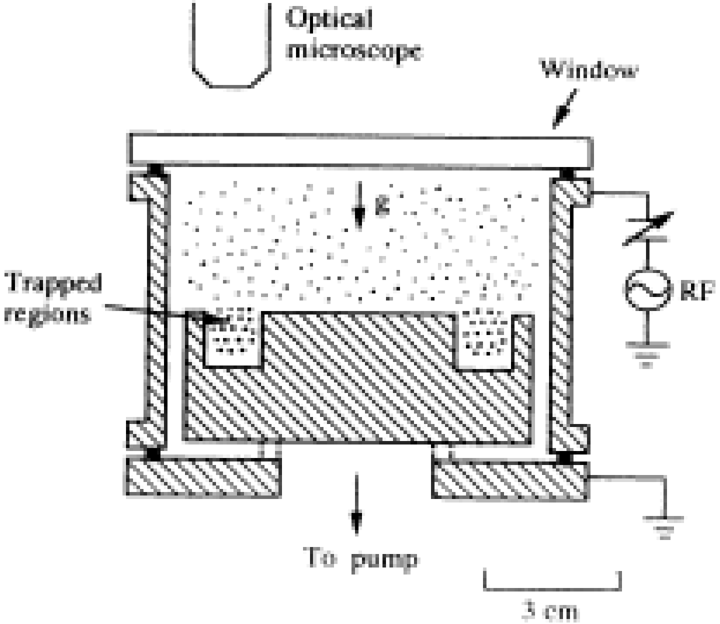
In-situ production of dust by processing plasma observed and analyzed.

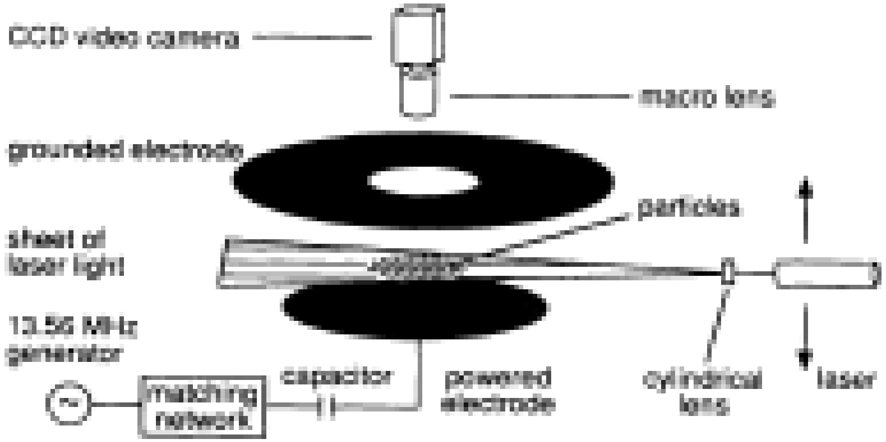
☛ clean room is not a solution

Discovery of dust crystal

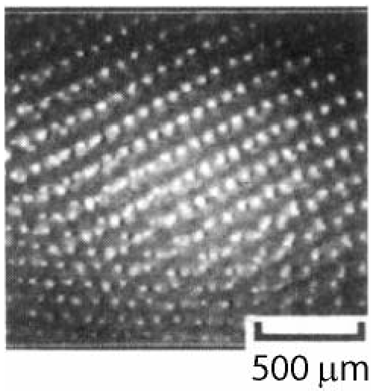
Chu & I, *PRL* (1994)

Thomas *et al.*, *PRL* (1994)



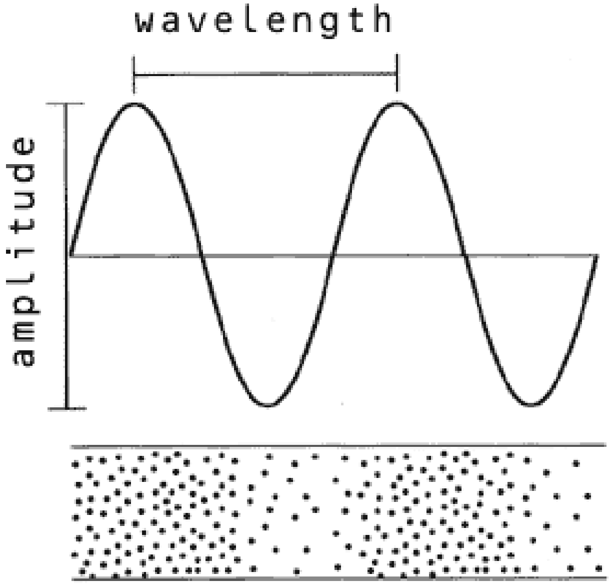


Similar phenomenon ☛



Prediction of dust acoustic wave

Familiar sound waves



$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \quad \text{(a)}$$

$$\rho \frac{Du}{Dt} + \frac{\partial P}{\partial x} = 0 \quad \text{(b)}$$

$$P = P_o \left(\frac{\rho}{\rho_o}\right)^{\gamma} \quad \text{(c)}$$

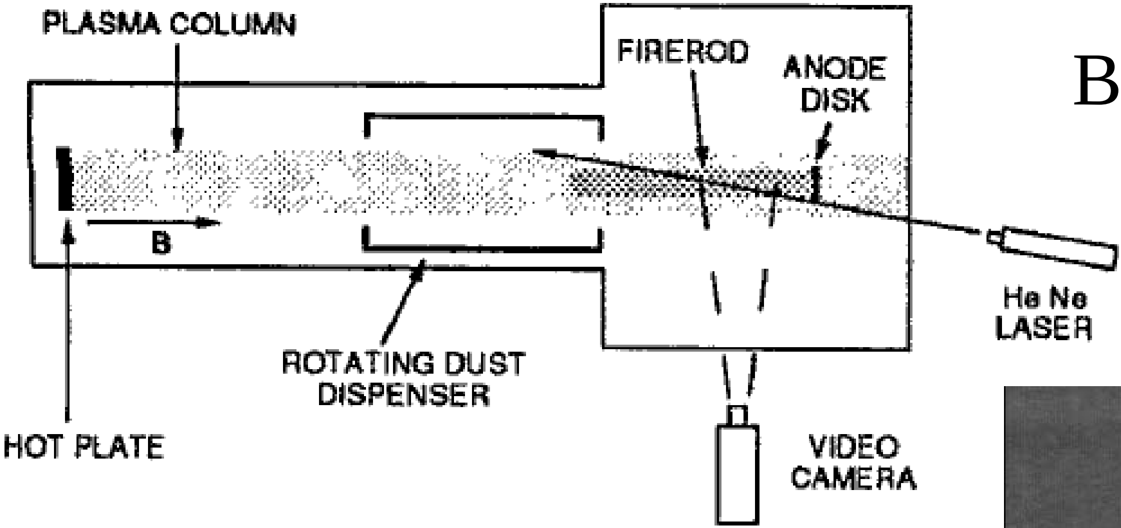
$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv) = 0, \quad (1)$$

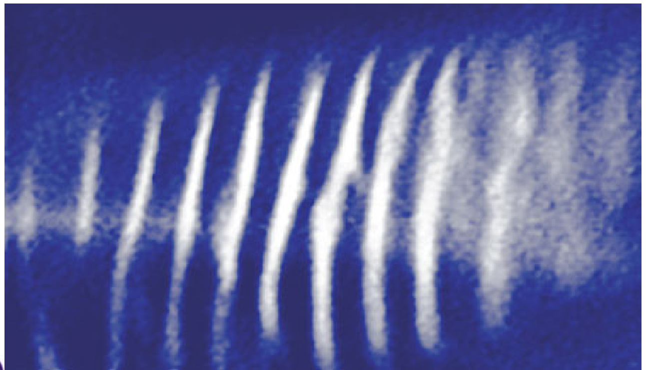
Rao *et al*. PSS (1990) ☛

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{Ze}{m}\frac{\partial \phi}{\partial x}, \quad (2)$$

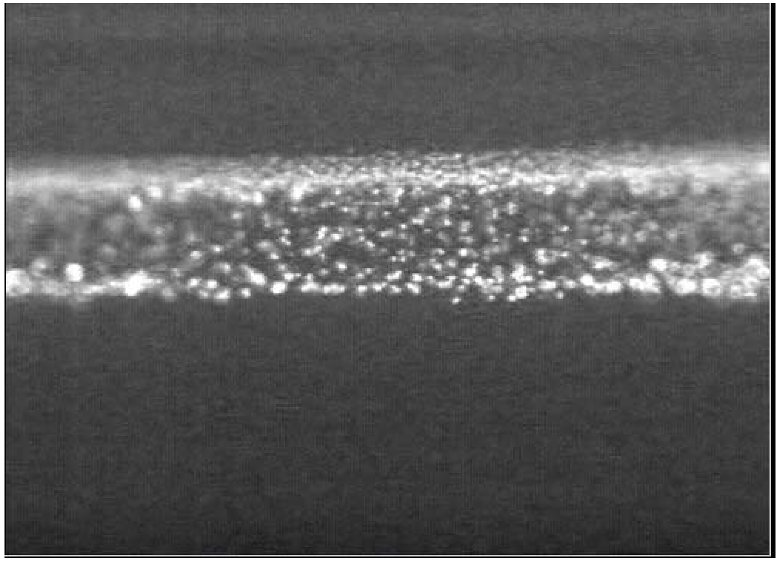
$$\frac{\partial^2 \phi}{\partial x^2} = -4\pi e(n_i - n_e - Zn), \quad (3)$$

Observation of dust acoustic wave





Barkan *et al.* PoP(1995)



Ticos *et al.* PPCF (2004)

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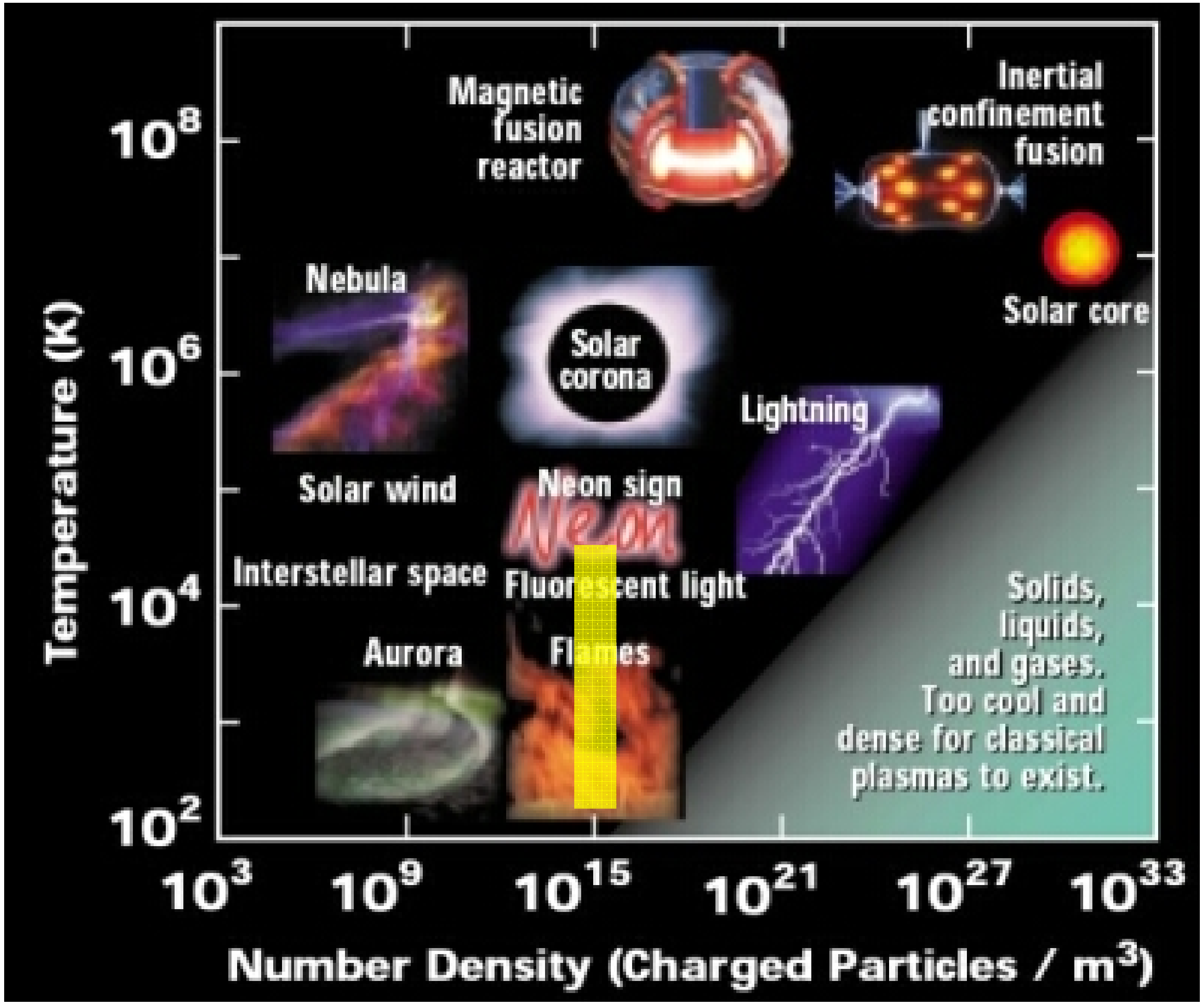
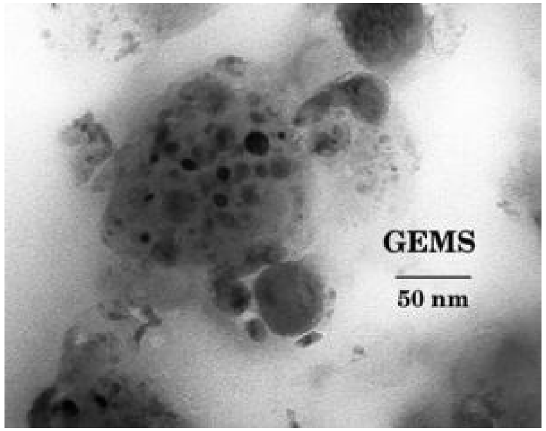
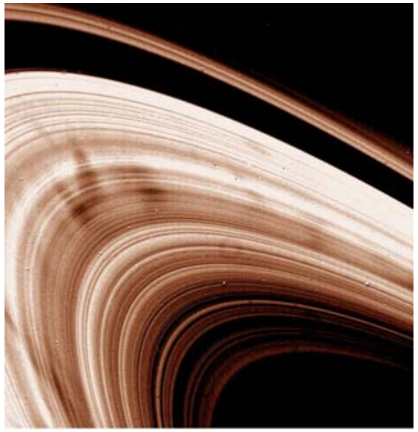
‘Dusty plasmas’ only occupy a small parameter space



Dust is ubiquitous in astrophysical and solar plasmas



GEMS = glass with embedded metal and sulphides

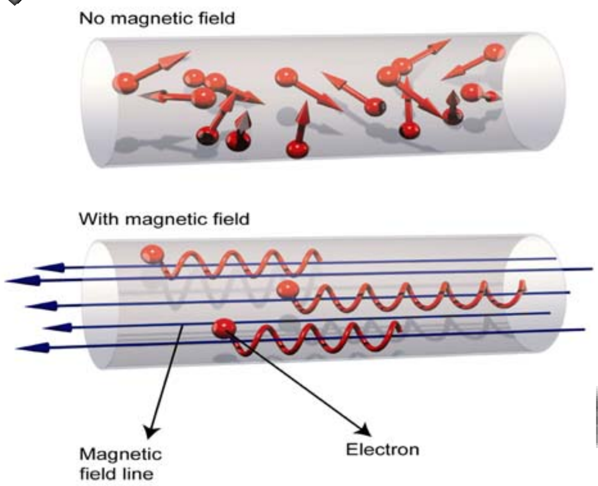


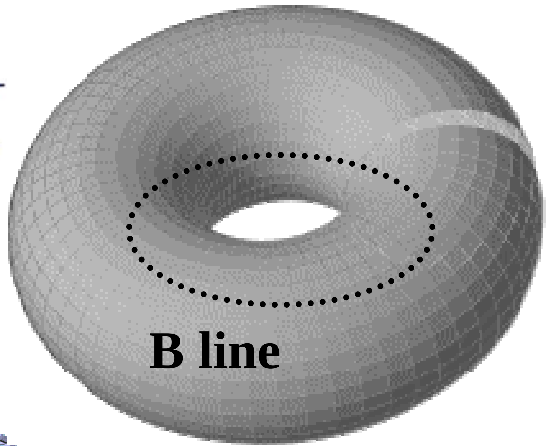
Saturn's dusty rings

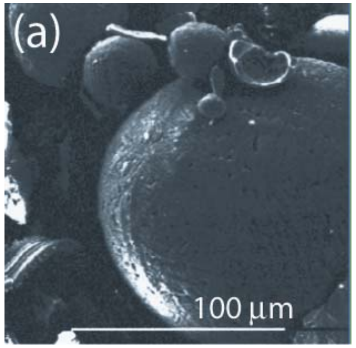
Dusty galaxy

- Physical, chemical properties of dust and its origin
- Dust effects on the structure of the universe (H_2 production)

Dust may cause safety and operational problems to magnetic fusion, such as ITER

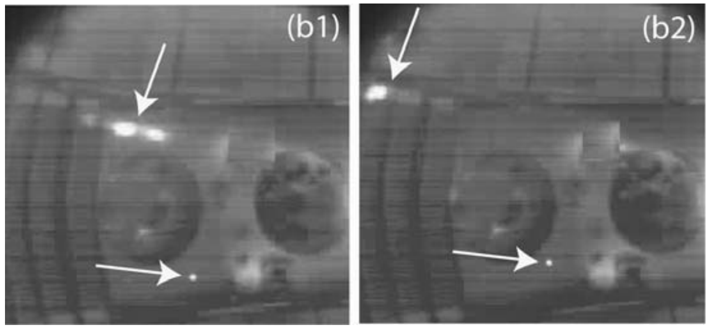


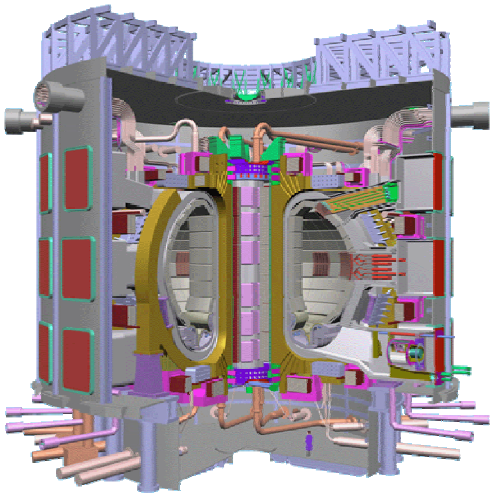




Winter, PoP (2000)

Roquemore et al. (2006)





ITER

- Fire hazard, radioactive material transport
- Cooling of fusion reactor

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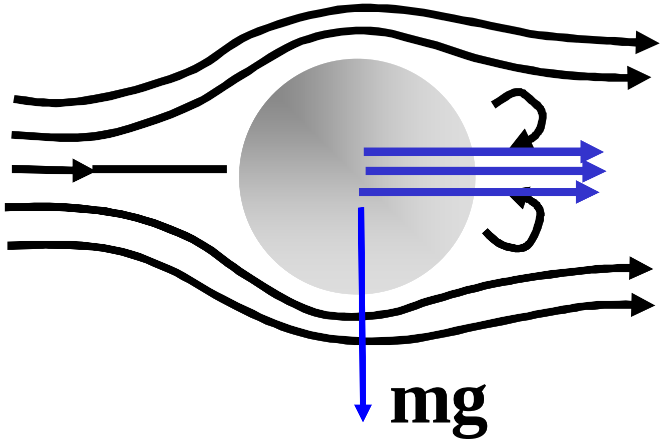
I. Dust studies in Flowing Magnetized Plasma (FMP) experiment

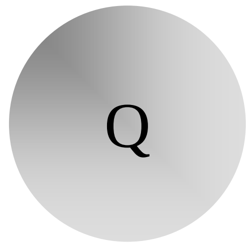
The primary purpose is
to study dust motion in flowing plasmas
'Dust *plasmo*-dynamics'

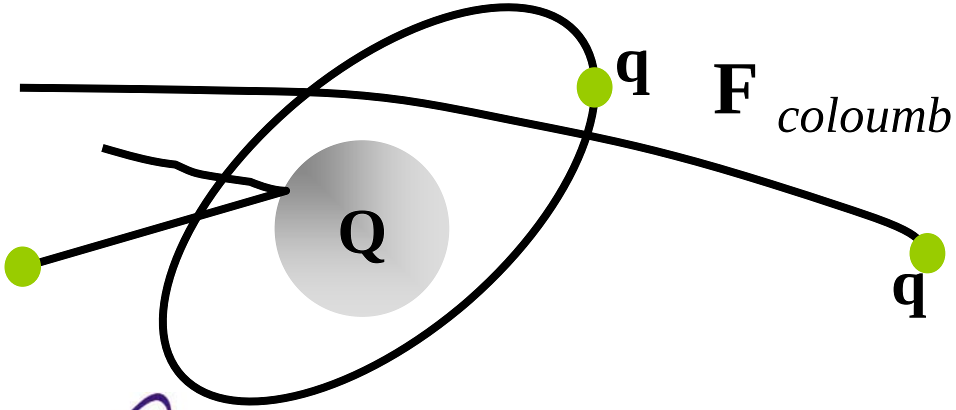
Many forces may affect dust motion in flowing plasmas simultaneously

$\mathbf{F}_{drag}$ (n) , $\mathbf{F}_{drag}(e^{-}, M_i^{+})$



$\mathbf{F}_{Lorentz} = Q\,(\mathbf{E}+\mathbf{V}\times\mathbf{B})$





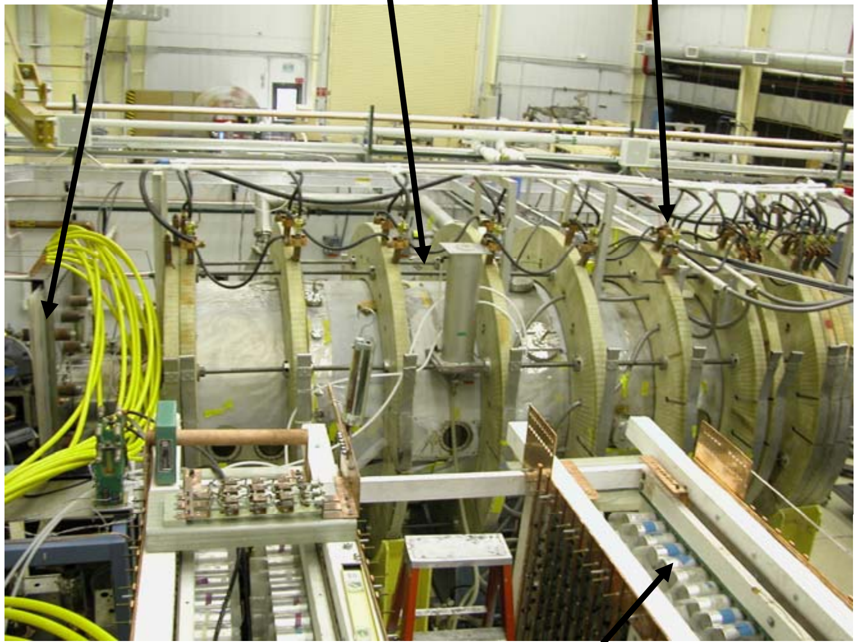
- $Q = Q\,(t, \mathbf{r})$
  $m = m\,(t, \mathbf{r})$

FMP experiment uses a coaxial plasma gun to produce flowing plasmas

Vacuum tank (L=457 cm, ϕ = 150 cm)

Coaxial plasma gun

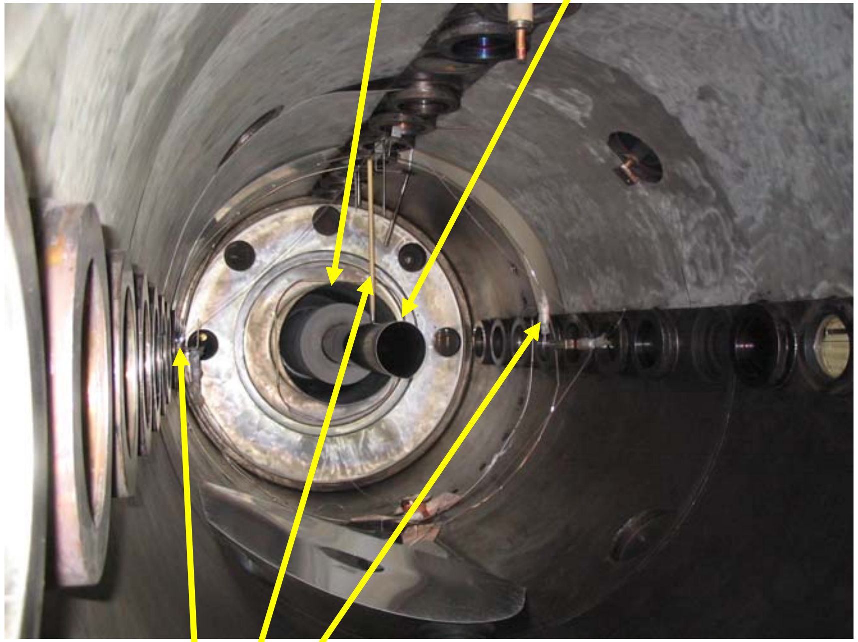
Water-cooled solenoids



0.76 F, 900 V main bank

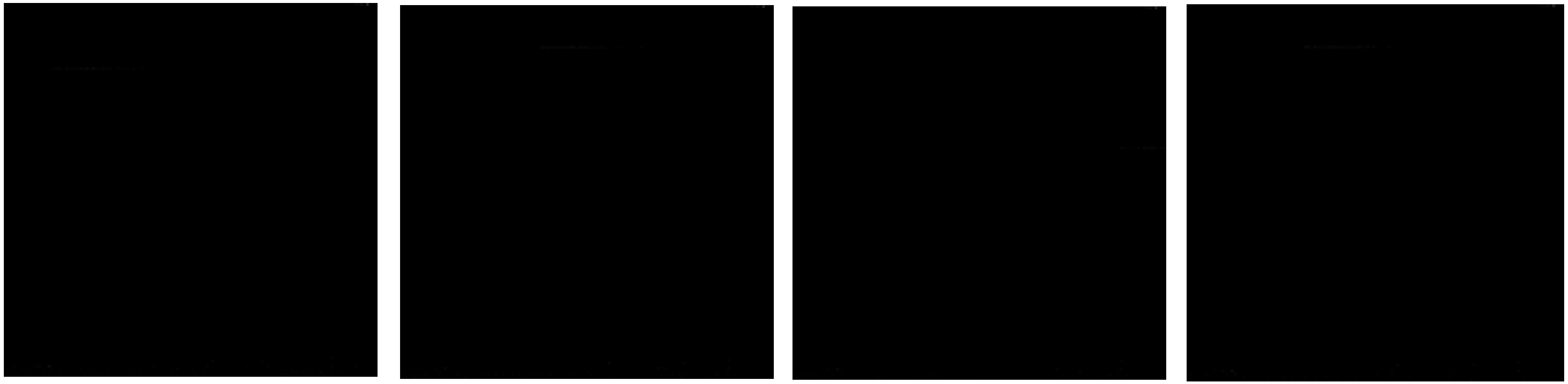
Coaxial gun (57 cm OD, 37 cm ID)

Biasing electrode



Probe diagnostics

Dynamic features of FMP plasmas

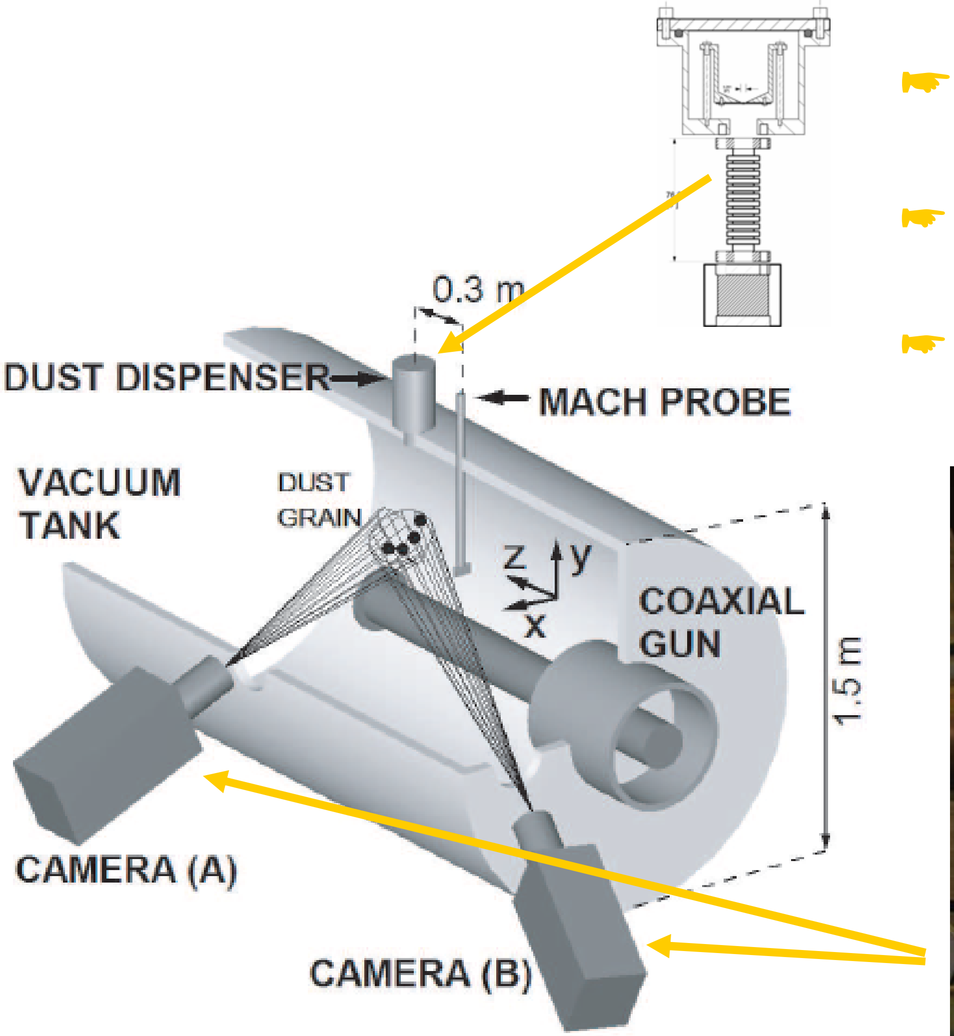


0 (G) 100 300 -300

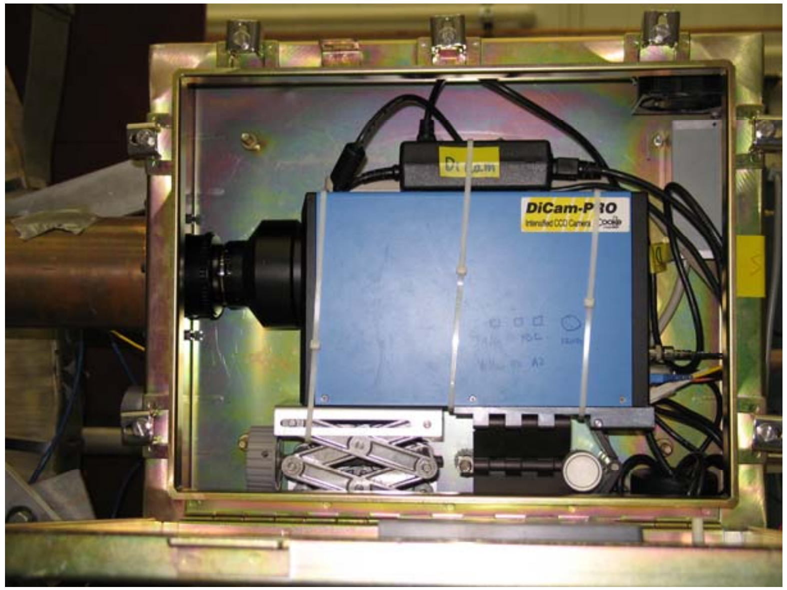
Bz ⊙ ⊗

☛ **rotation direction is determined by J ×B torque**

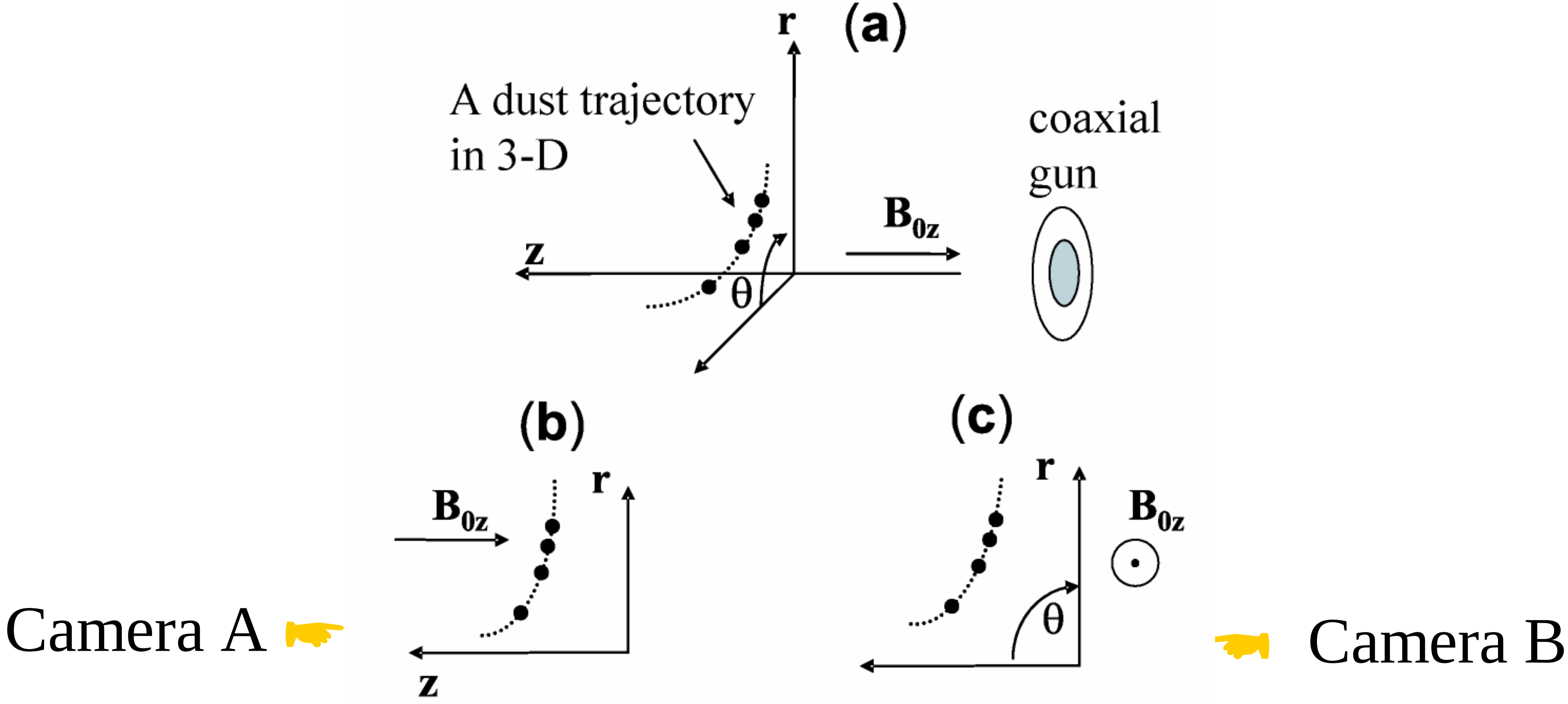
Setup for dust studies in FMP plasmas



- The falling time (0.1-0.2 s) >> $\tau_{pl.}$ (~ 10 ms)
- Dust were pre-dropped before the plasma shot/discharge,
- The dust grains are ~ *at rest* relative to the rapid moving plasma.



3-D dust trajectory

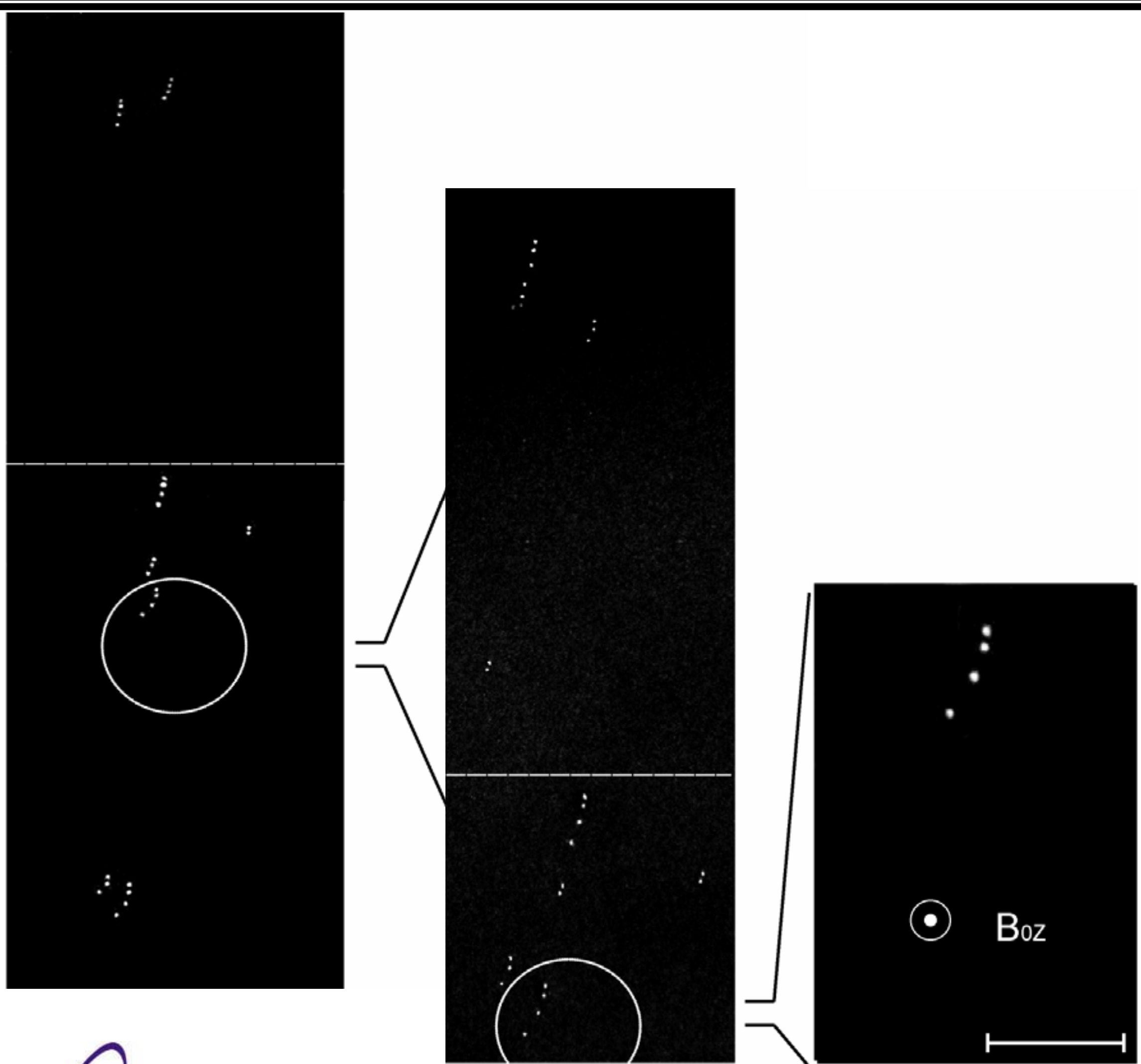


Projection of the 3-D trajectory in the r-z plane.

Projection of the 3-D trajectory in the r-θ plane.

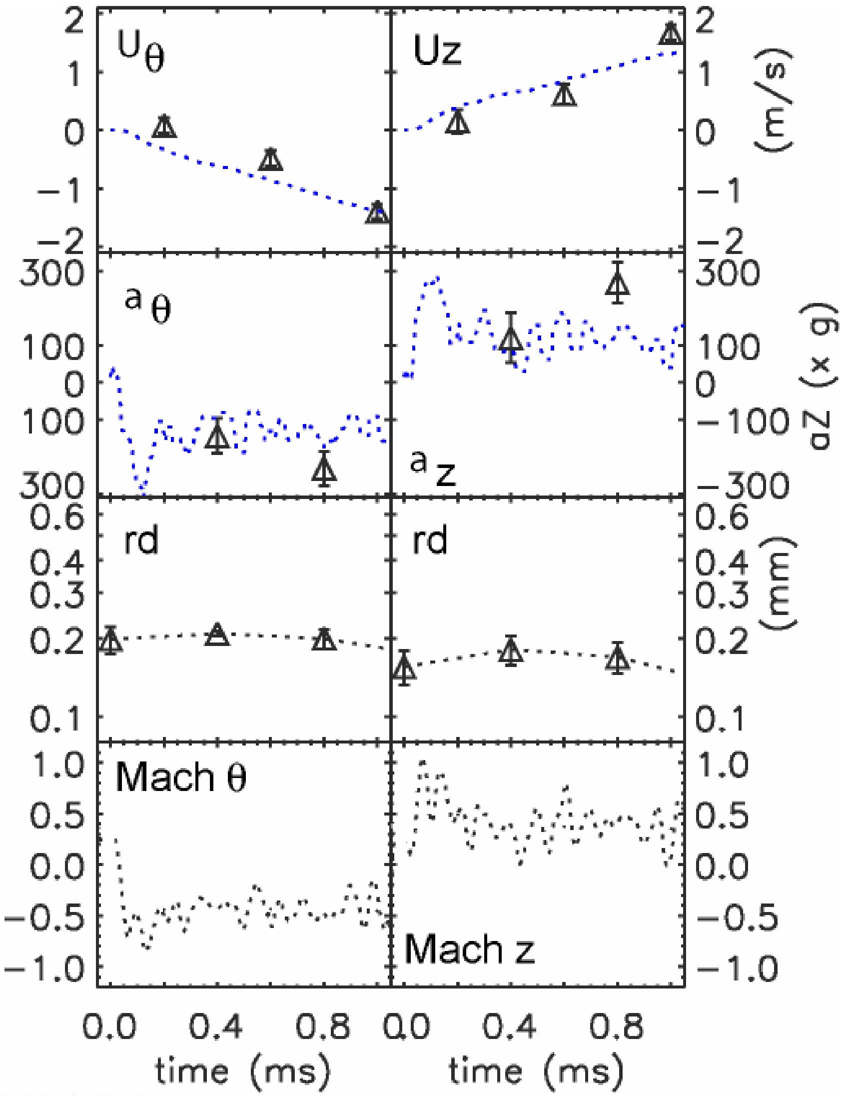
Wang *et al*. accepted PoP (2007)

Dust trajectory recorded



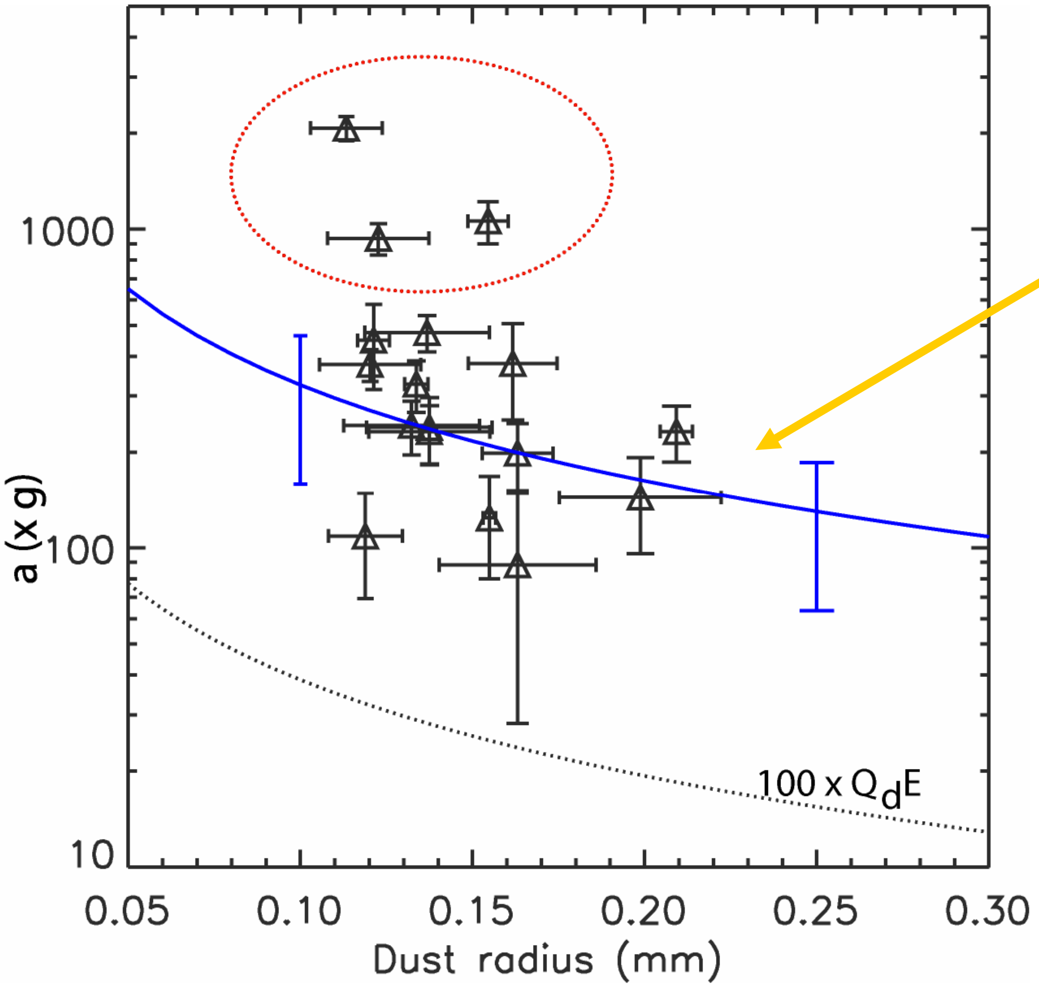
- Camera A
- Camera B

Analysis of dust trajectory



- $U_d << U_{plasma}$
- $U_{plasma} \sim 7$ km/s

Dust motion is dominated by 'impact' drag



$$\mathbf{F}_{pf} = 2\pi r_d^2 k_B T_i n_i \xi \mathbf{w}$$

- other forces are small

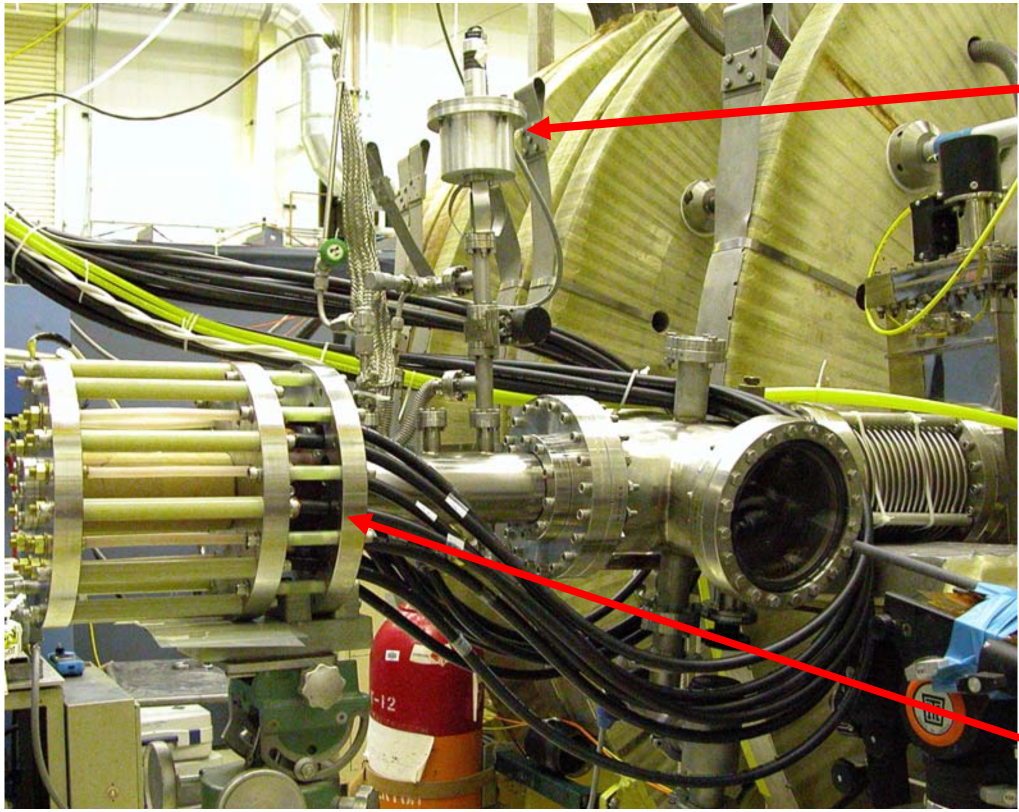
Dust can become a new technique for plasma flow

II. Hypervelocity dust injection (HDI) experiment

The primary purpose is

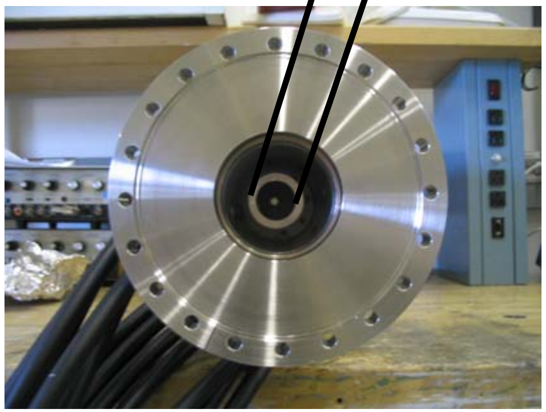
to demonstrate dust acceleration to hypervelocities

The heart of HDI system is a coaxial plasma gun



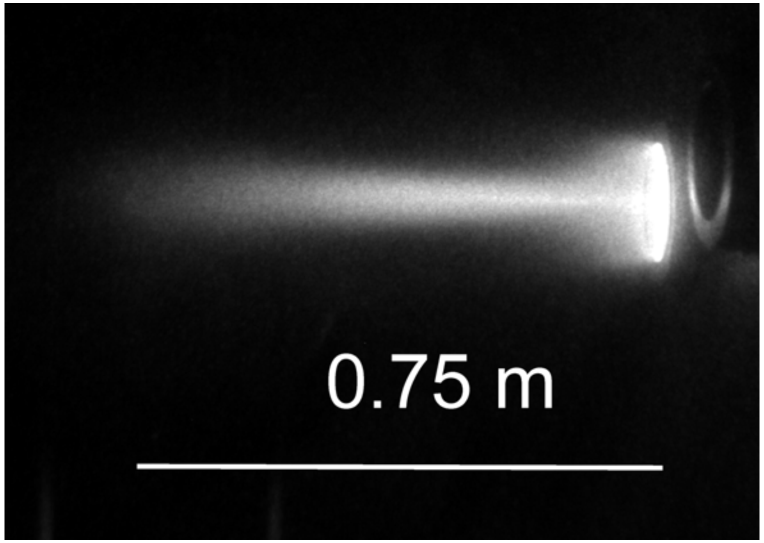
Dust reservoir

ϕ 4.4 cm

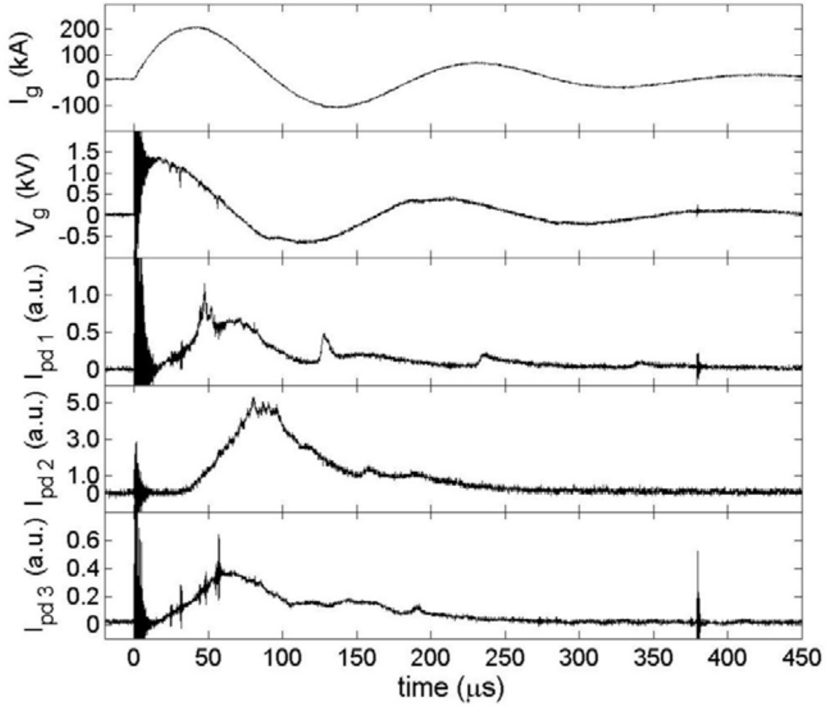


Ticos *et al*. RSI (2006)

HDI performance



5 kV, 30 μs exposure,
4 ms puff gas

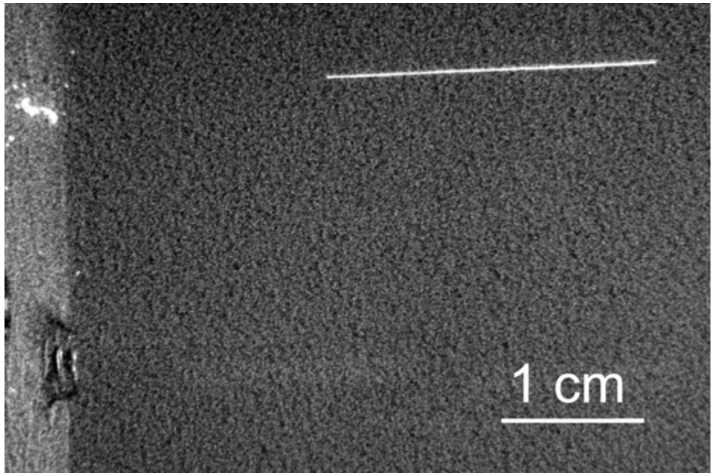


Vplasma ≥ 28 km/s
(≈ 0.9m/ 33μs)

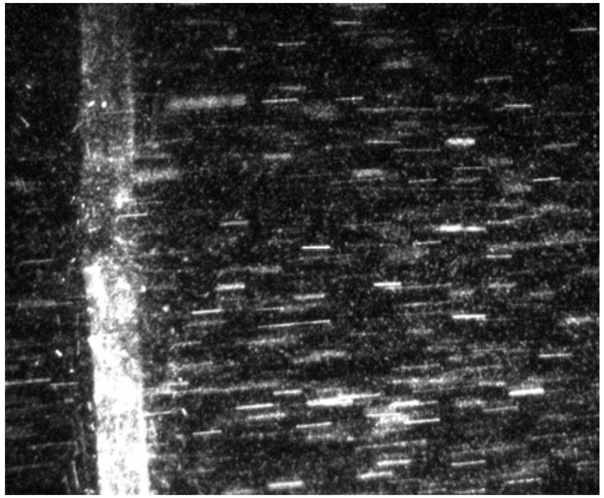
Ticos *et al.* in preparation (2007)

Peak power ~ 200 MW

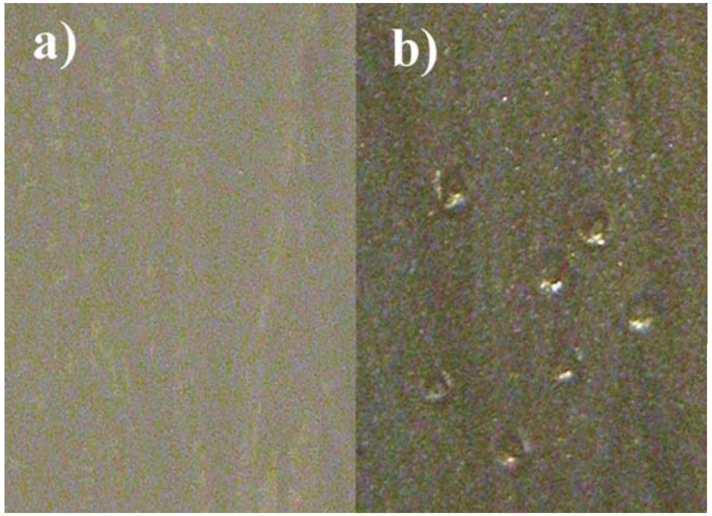
Observation of hypervelocity dust



v_d=2.3 km/s (exp. 10 μs).



HDI Dust storm



Observation of craters

Cosmic Dust storm

Ticos *et al*. in preparation (2007)

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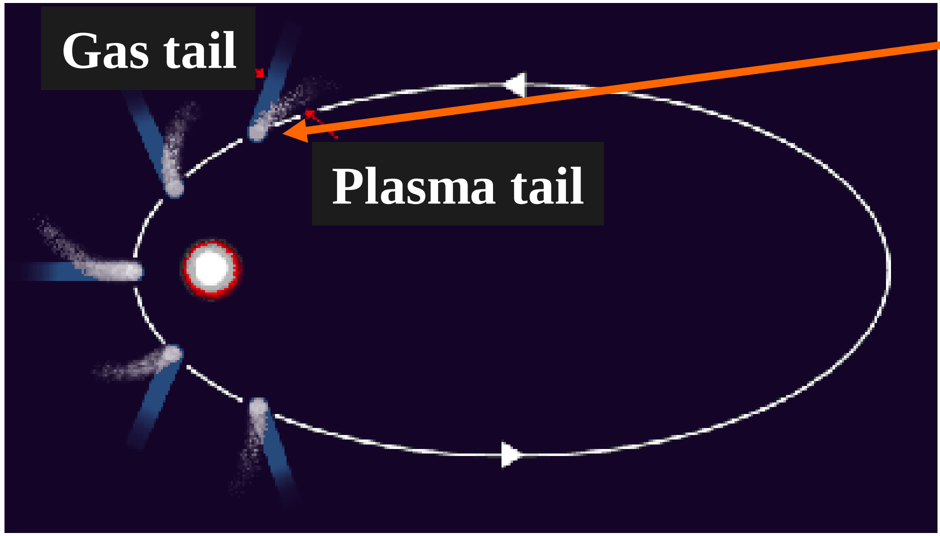
Imaging of internal magnetic field and structures in magnetic fusion



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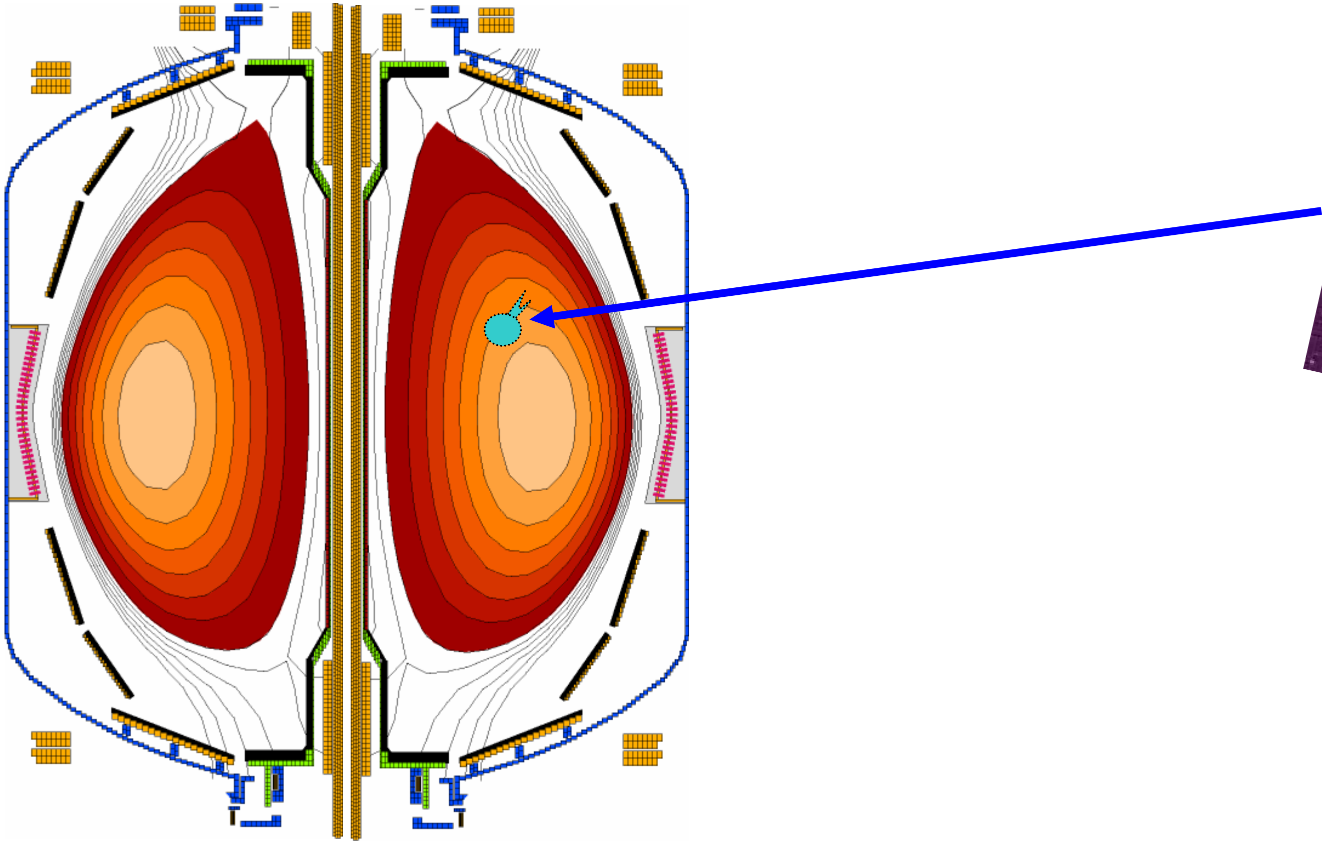
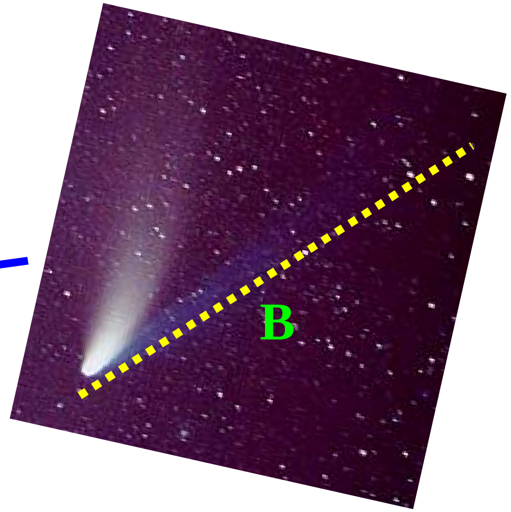
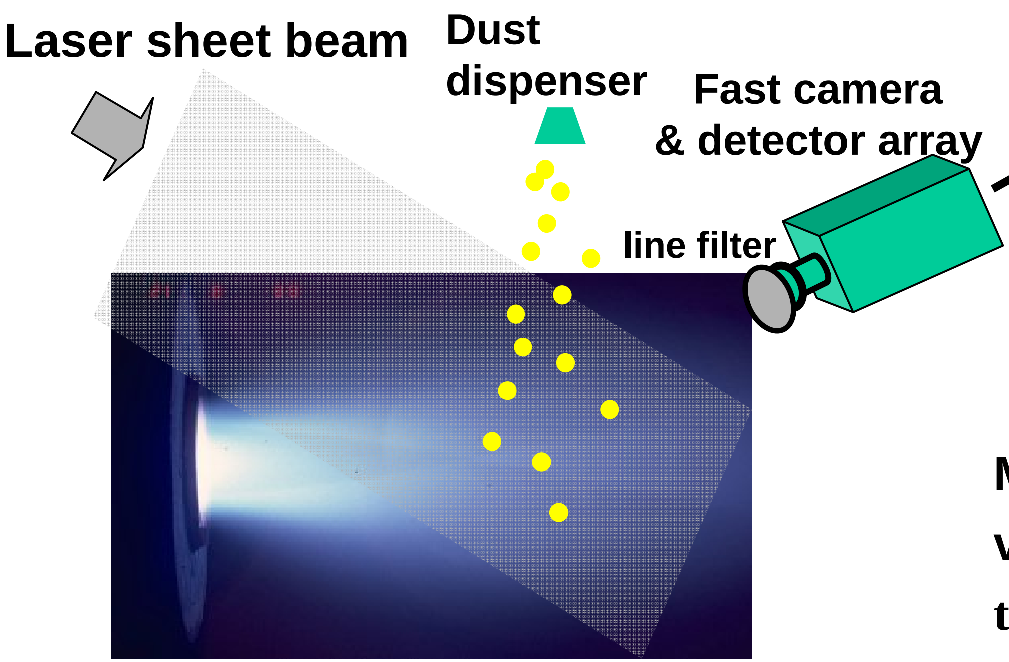
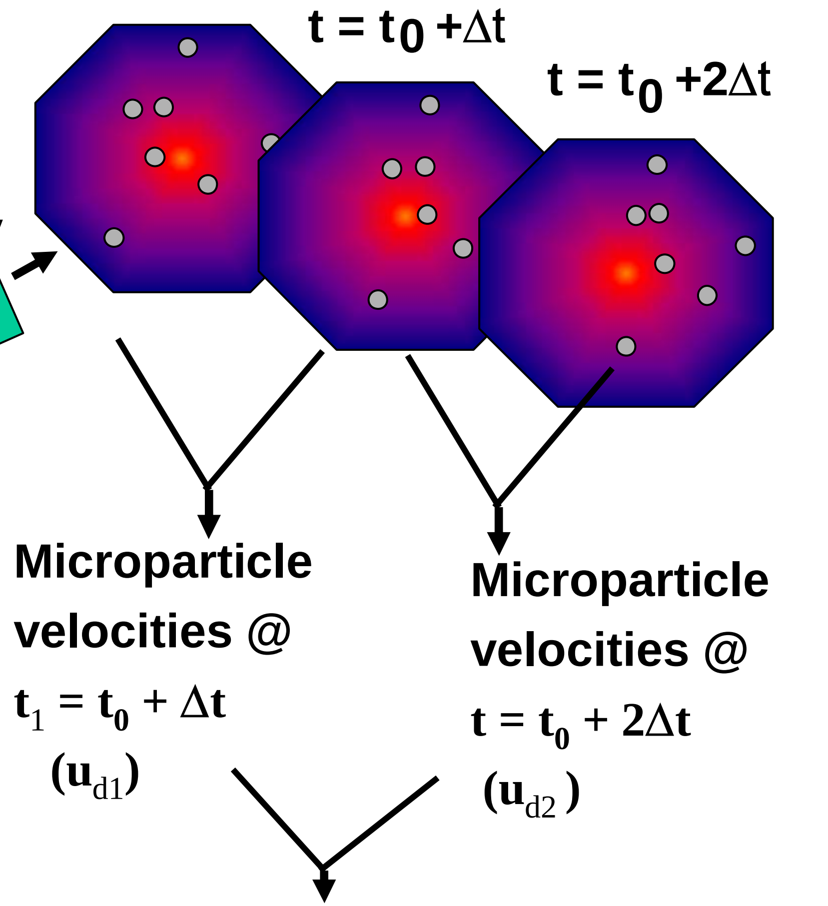




Wang *et al*. RSI (2003), RSI (2004)

Dust study of plasma flow in Laboratory Plasmas



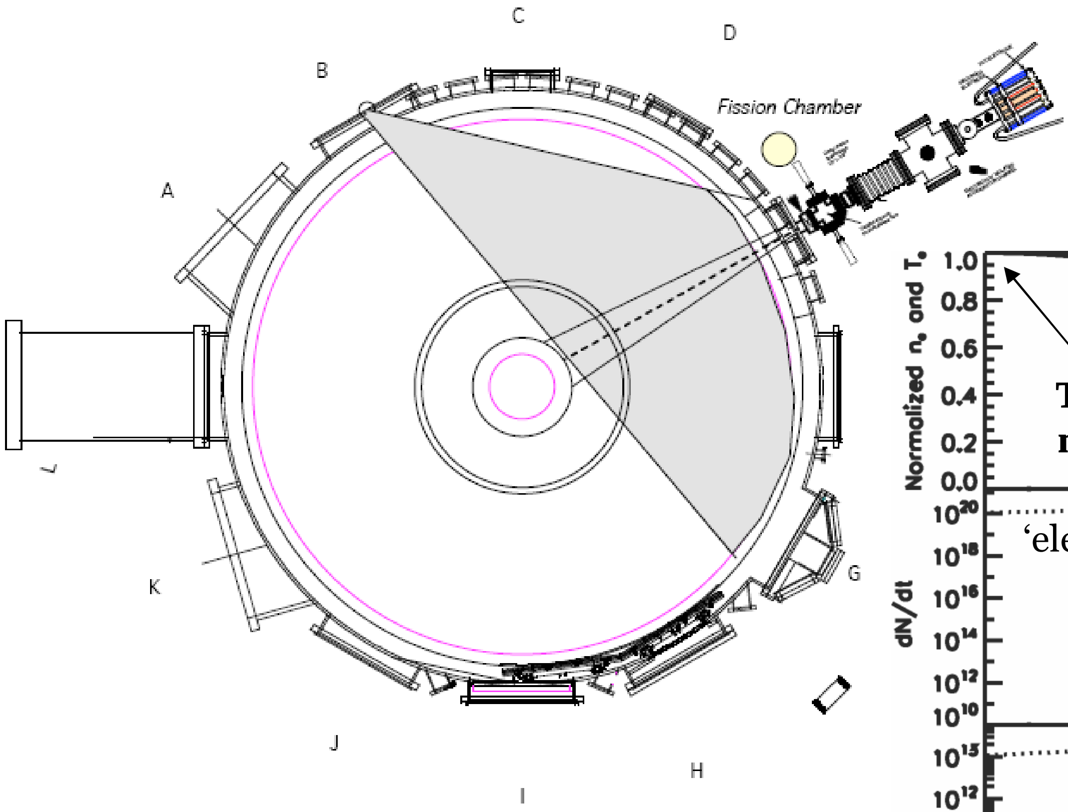


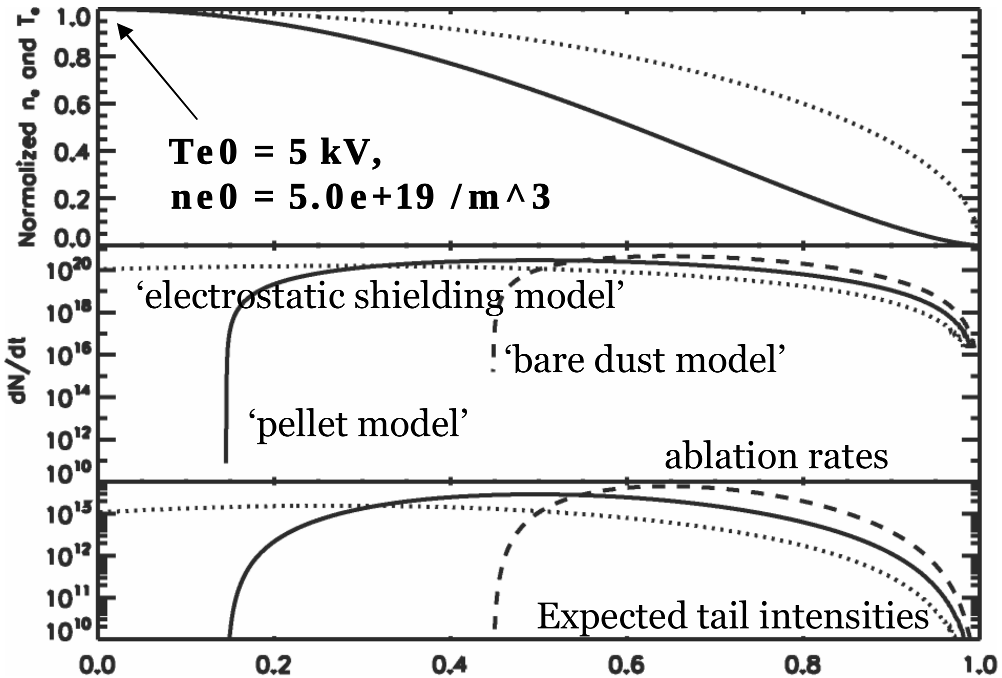
- ✓ Non-invasive
- ✓ Good spatial resolution
- ✓ Flow profile

Microparticle accelerations [$\mathbf{a}_d = (\mathbf{u}_{d2} - \mathbf{u}_{d1})/ \Delta t$]
Plasma flow velocities [$\mathbf{U} = C(n, T, \rho_d, r_d)\, \mathbf{a}_d$]

Wang *et al.* IEEE (2006)

Study of dust transport in magnetic fusion





- Analytical theories
- DUSTT simulation (UCSD)

Z. Wang and G. A. Wurden, *Rev. Sci. Instrum*. **75**, 3436 (2004).

Summary

- Ubiquitous presence of dust in the universe has been recognized since 1930's.
- Extensive R&D on dust in plasmas started in the information age (1980's).
- Emerging opportunities exist for dust-in-plasma R&D
  – astrophysics, magnetic fusion, basic plasma science, etc.
- Two laboratory experiments are described, both are related with plasma flows.
  – flow-drag force dominates dust motion ('dust *plasmo*-dynamics')
  – demonstration of dust acceleration to hypervelocities
- Dust can become important tool to study laboratory flowing plasmas & magnetic fusion plasmas
- A possible set up to study dust transport in fusion experiments is illustrated

Acknowledgement

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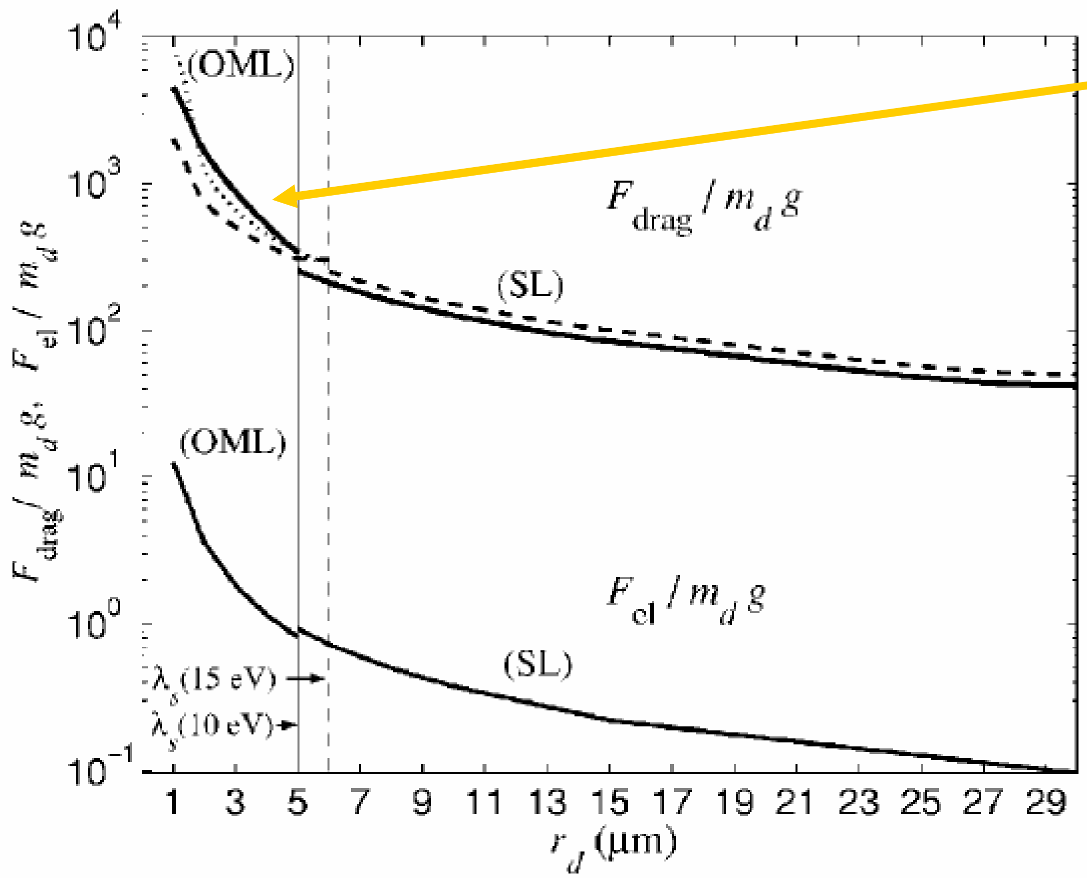
Mrs. Ave Lusenti (ICTP, Trieste, Italy)

Theory predicts that Coulomb drag will be larger than 'impact' drag for smaller dust

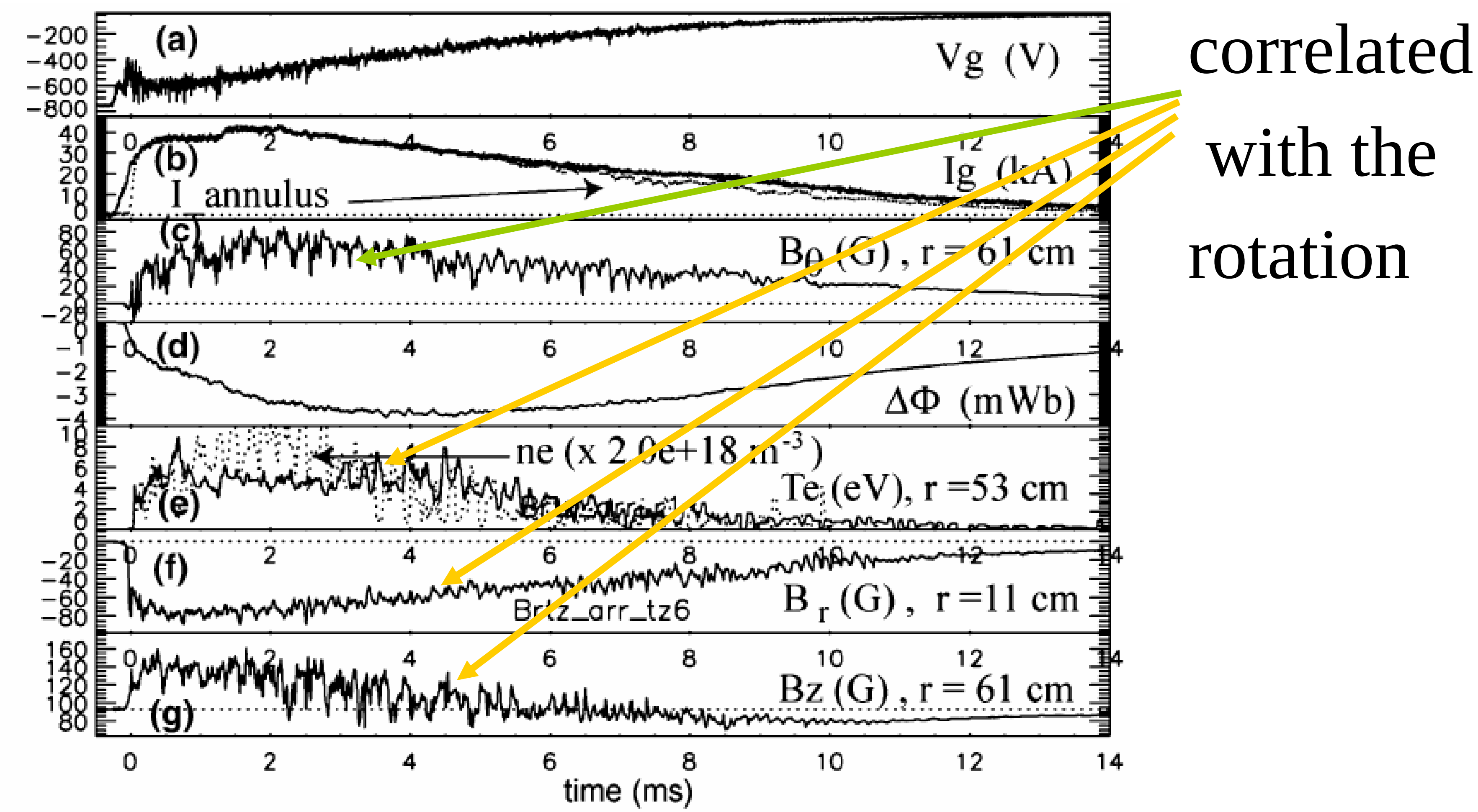


Up to × 10

Exciting* opportunity may exist for advanced propulsion concepts using *dust

Ticos *et al*. PoP (2006)

Probe characterization of FMP plasmas



Wang *et al*. JoFE (2006)

HDI pulsed power system