Dust transport in magnetic fusion plasmas

Experimental challenges and opportunities

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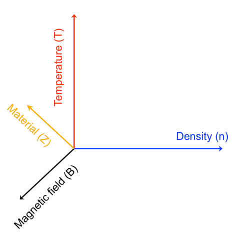
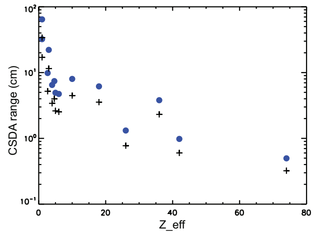
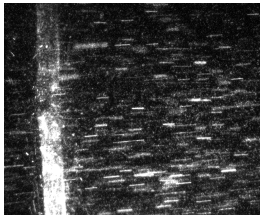
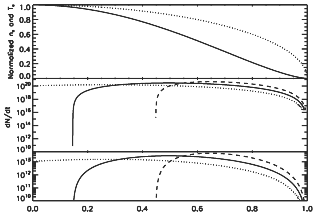
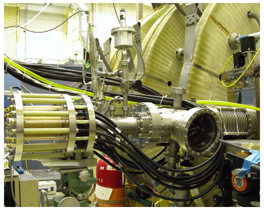
(14th WPDP, May 29, 2015)



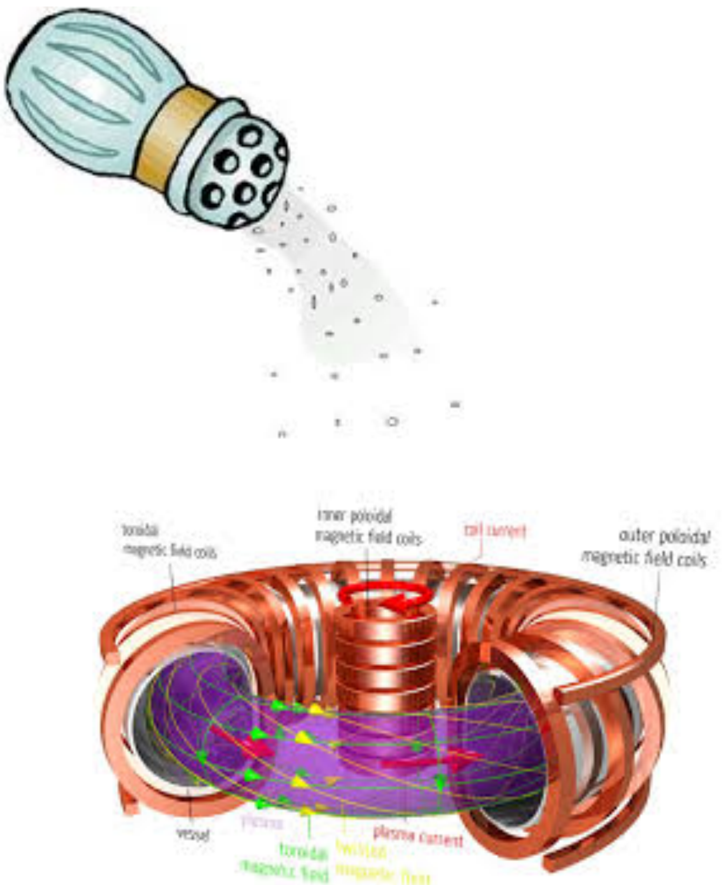






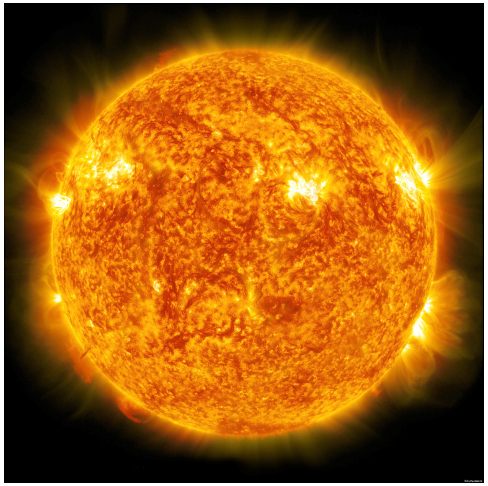


Dust & Donut

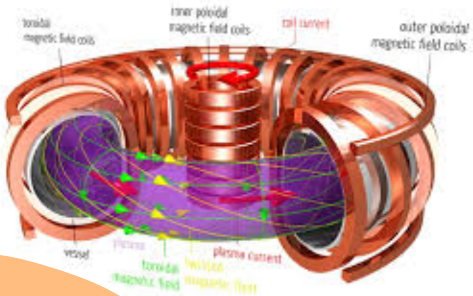

toroidal magnetic field coils
inner poloidal magnetic field coils
coil current
outer poloidal magnetic field coils
vessel
plasma
toroidal magnetic field
twisted magnetic field
plasma current

Outline

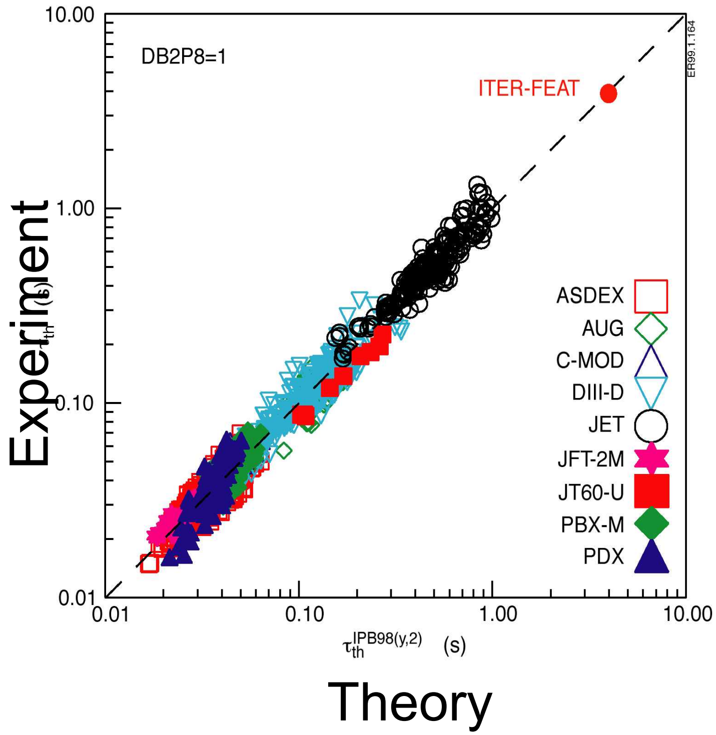
- **Motivations** (ITER → Material issues)
  - Heat: steady-state
  - Transient heat: ELMs & Disruptions
- **Dust in magnetic fusion plasmas**
  - Good, Bad & "Dusty"
  - Dust for transient heat management
- **Experimental opportunities and challenges**
  - Technological advances & new facilities
  - Simulations of fusion plasma environment –
    - Magnetic field, Te ~ Ti, hot dust, hot surfaces

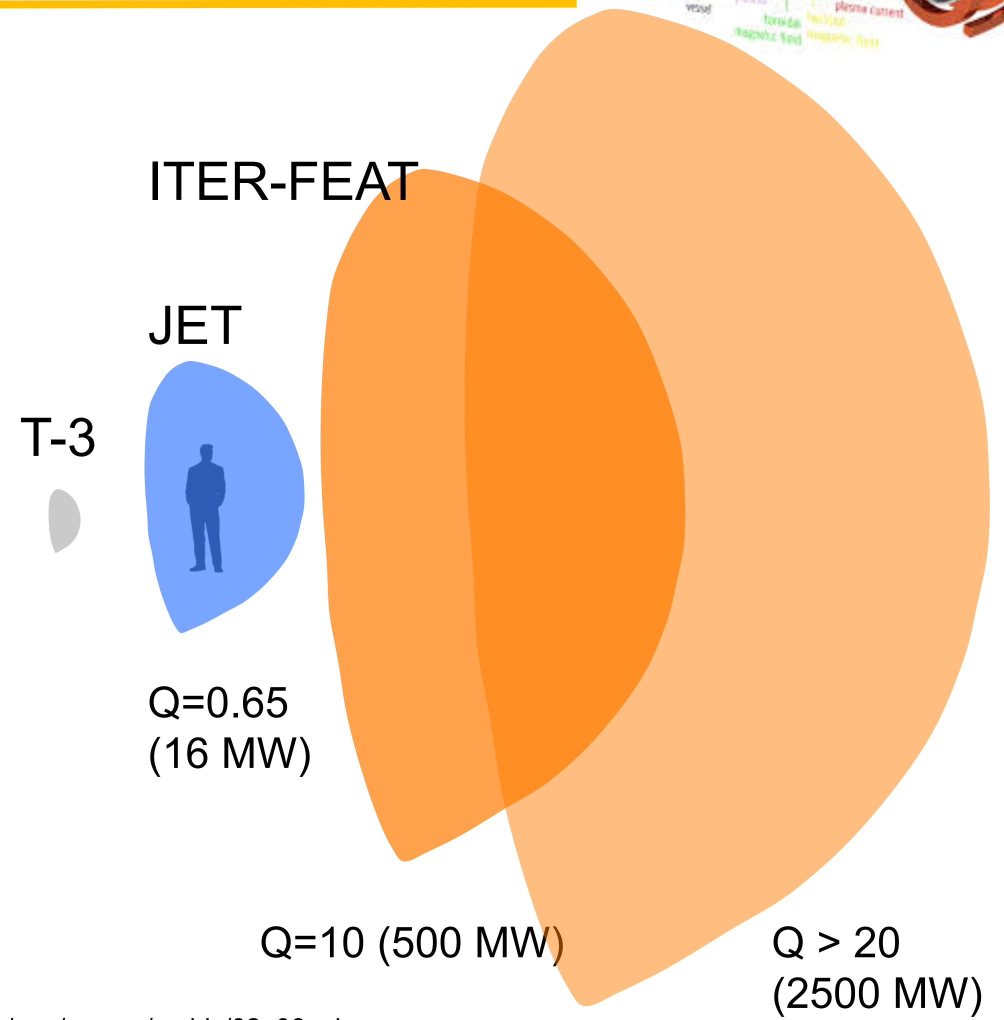


Bigger is better for magnetic fusion



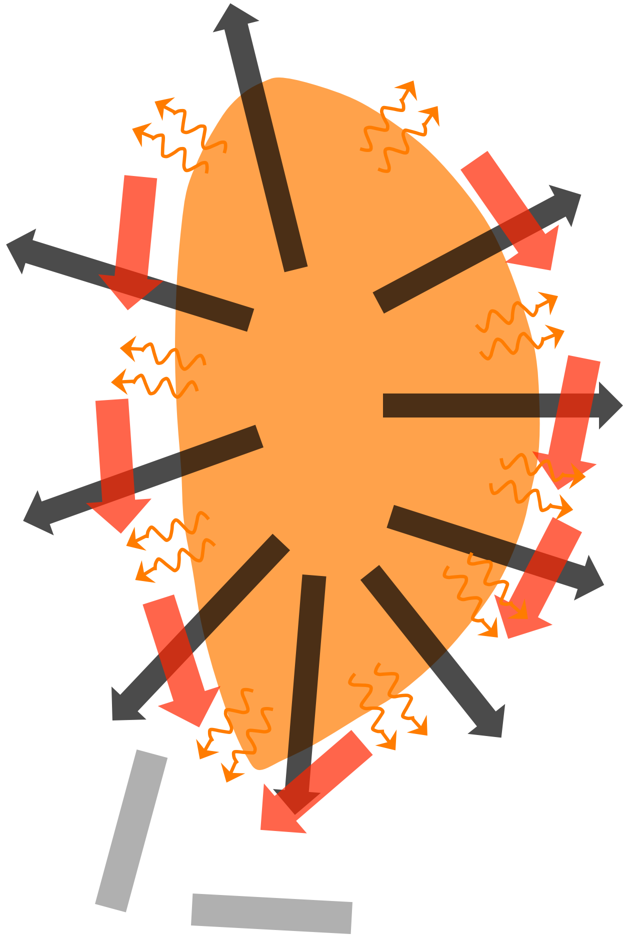
$$\tau \propto R^{1.97}$$





http://www.ipp.mpg.de/ippcms/eng/presse/archiv/02_06_pi

Heating issues for Q > 5: (steady state) $\Gamma_H \sim r P_f / 2b$ (b<1)



Neutrons: (80% E)
~ 1 MW/m^2
(1000 suns)

Alpha's = ¼ neutrons

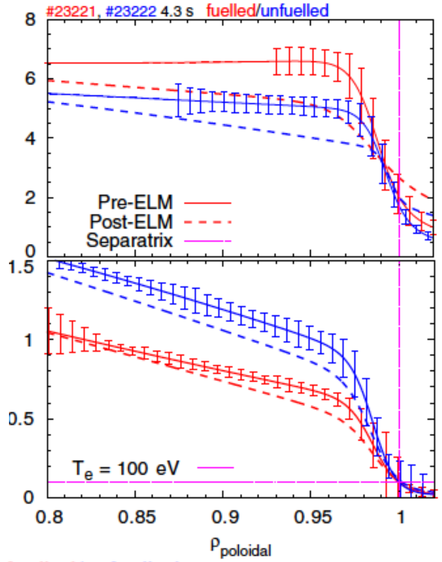
~ 3-30 MW/m^2

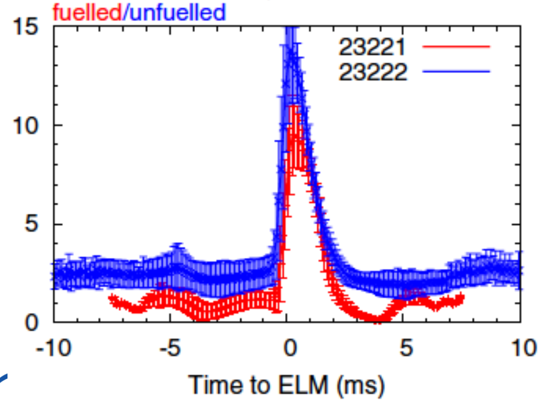
Photons ($h\nu$):
??

(radiative cooling/N_2, Ar)

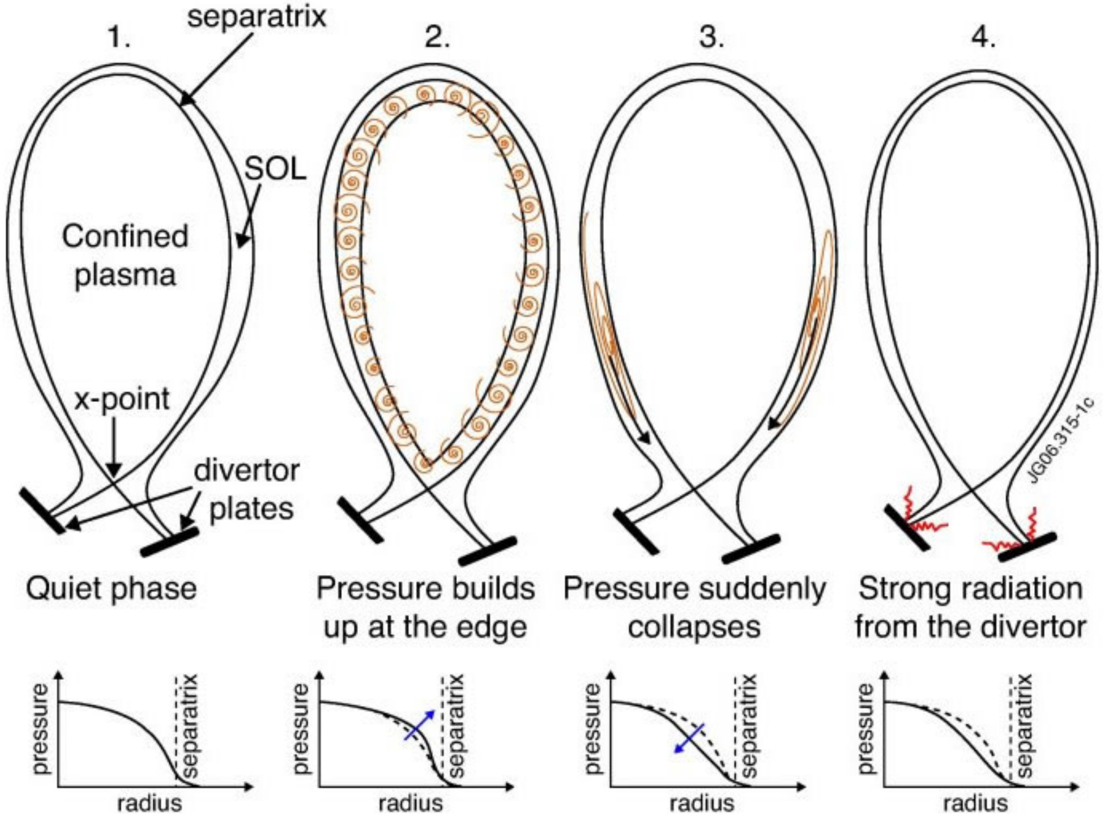
Federici et al, (2001);
Lorte et al, (2007);

Edge-localized mode (ELMs): transient heat ~ (7-10%) > 30 MW/m^2



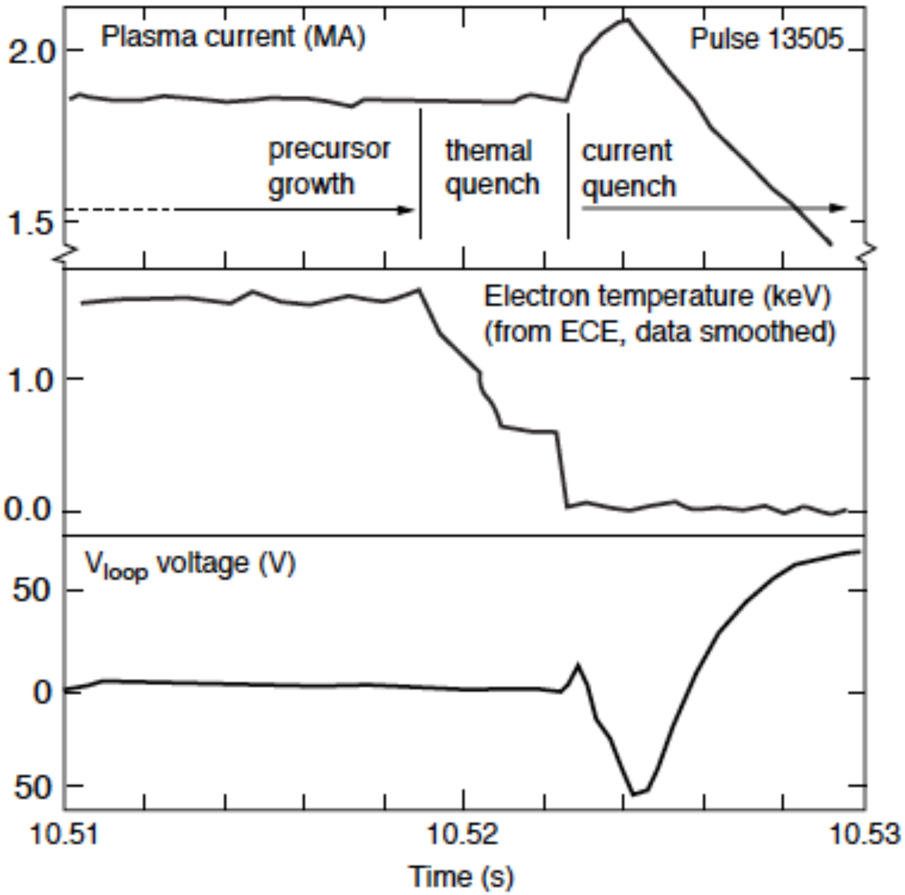


Dunne et al, NF (2015)



https://www.euro-fusion.org

Disruption: The biggest "threat" to ITER



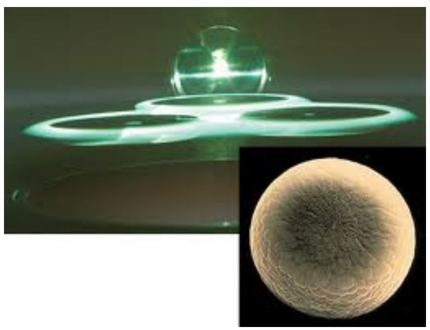
JET

- **Full plasma transient**
  - Global MHD instability, VDE
  - Frequency (~ 10%) x 15000 discharges
  - Precursors
  - Not fully predictable
- **Thermal quench**
  - Thermal plasma Heating/Melting
  - Runaway electrons
- **Current (Ip) quench (70% I_0)**
  - Runaway electrons
  - Electromagnetic forces J (eddy) x B (10-65 MN /60 MN) "halo"
  - I_p decay rate is critical for ITER:
    - the"goldilocks" rule: between 50 ms and 150 ms

Smirnov, Wesley, et al, NF 39 (1999);

Extreme Heat → erosion → Dust generation near surfaces (physics + chemistry)

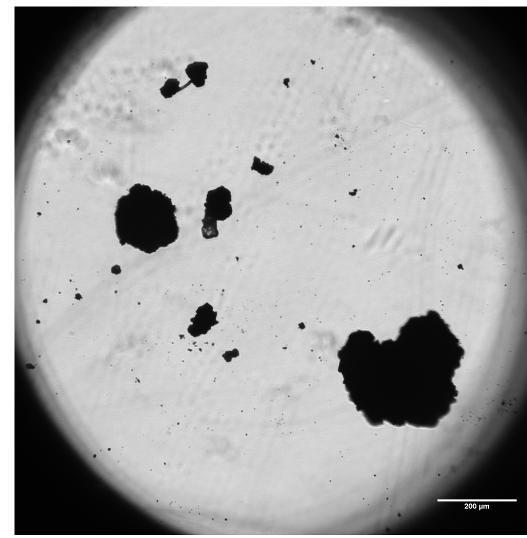
Coagulation



Selwyn (1989)
Merlino & Goree (2004)

Arc, q > 30 MW/m^2,
Liquid/molten surface

Redeposition



ITER estimate: 350 MJ, several 10s of kg/disruption

Dust is bad, because…

- **Safety**
  - Flammability
  - Explosion
  - Tritium retention/Radioactivity
  - 2T/C
- **Negative impact on fusion**
  - Plasma core cooling (a few percent of W is sufficient)
  - ELMs, Disruptions

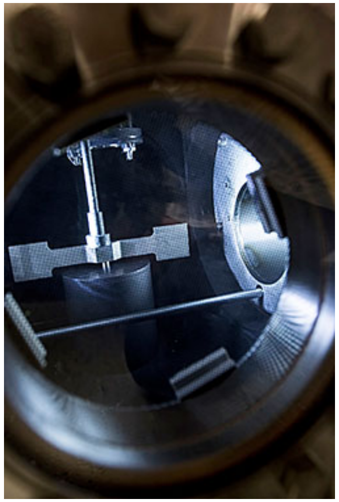
Problems arise from ITER and MF Reactors

PMI (Intense thermal & nonthermal heat flux)

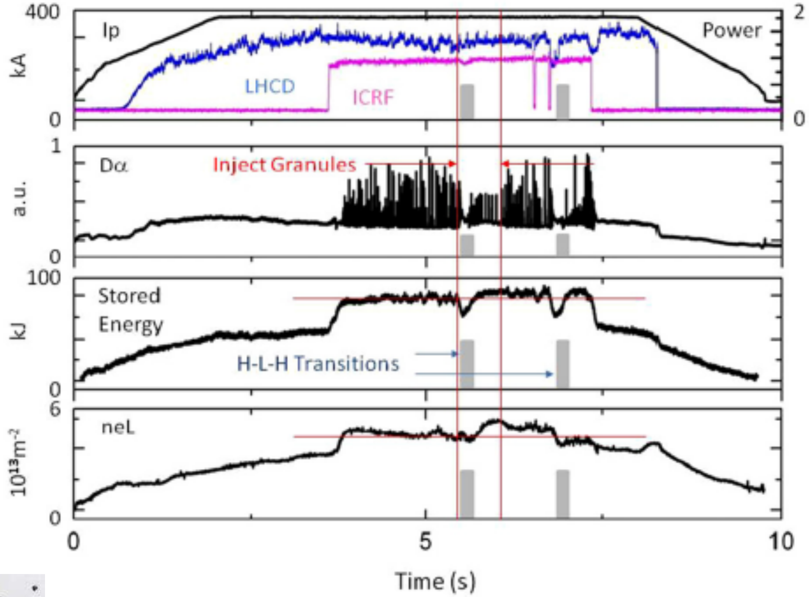
- SOL, Steady-state Divertor
- Dust production/impurity, safety → removal techniques
- ELMs
- Disruptions

Do controlled dust injections supply a solution?
(alternatives do exist)

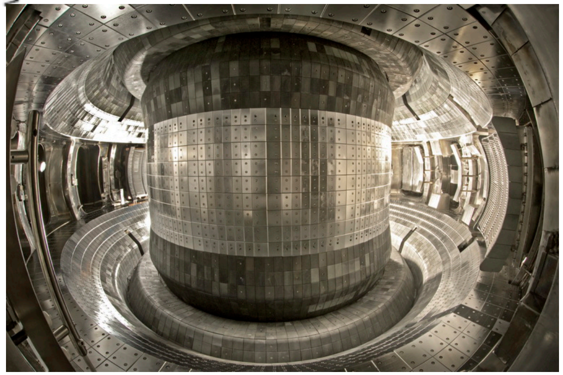
“Good” use of dust for ELM pacing



Mansfield et al (2013)



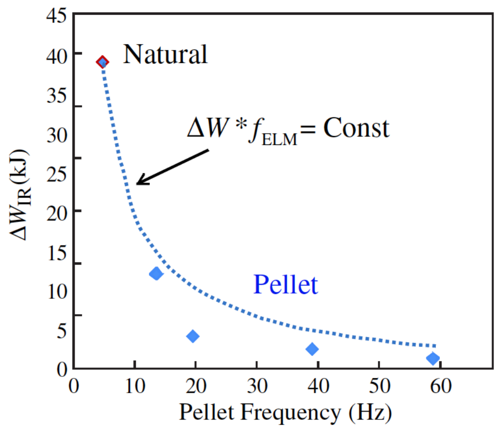
(Li)



EAST (China)

(SD)

Combs et al

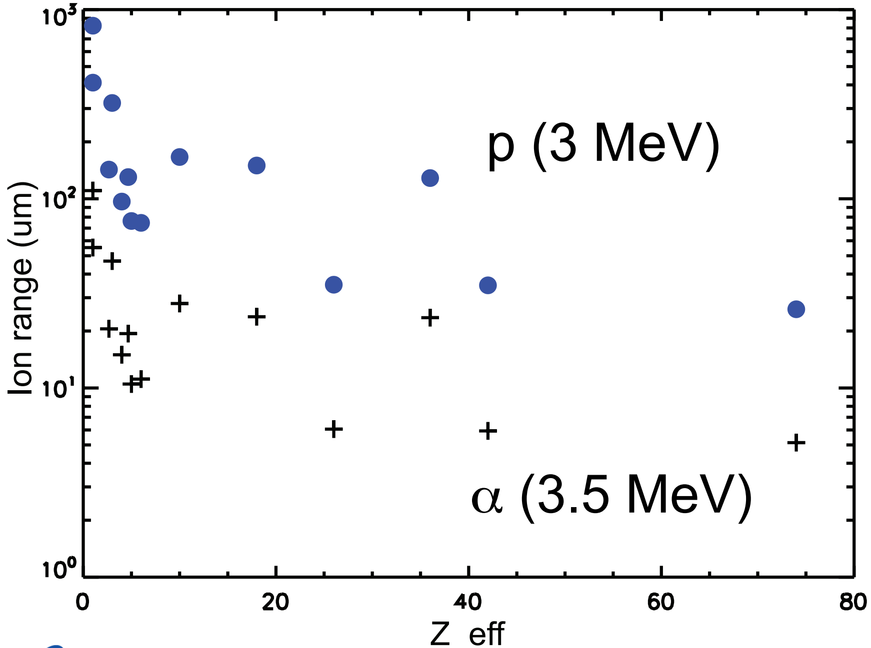


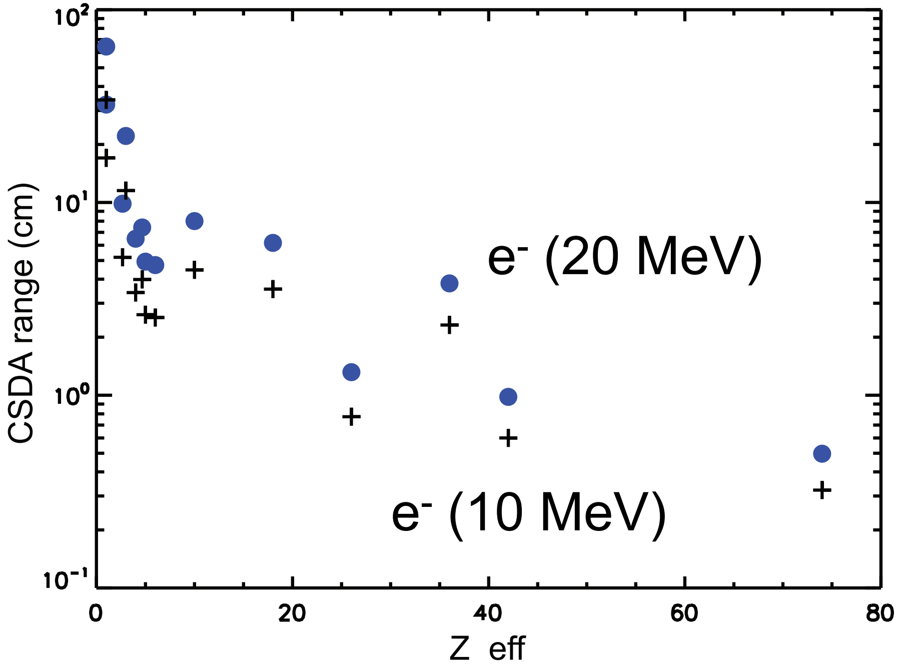
Baylor et al (2013)

DIII-D (USA)

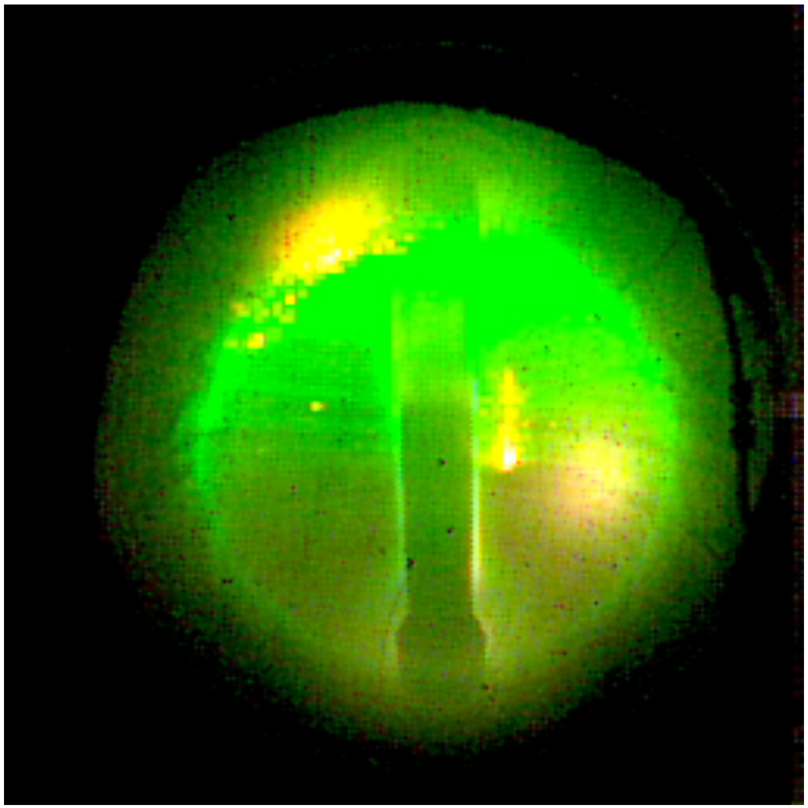
Stopping of energetic particles during disruption

- Energetic ion (p, α) stopping in dust
- Runaway Electrons (10-20 MeV, 10 MA, 20-200 MJ) stopping

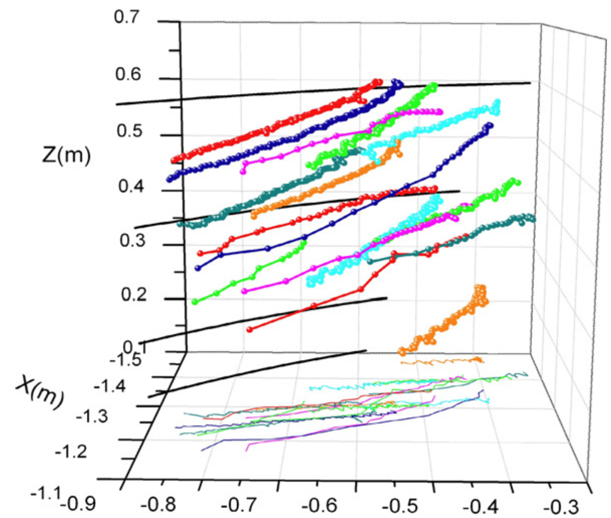


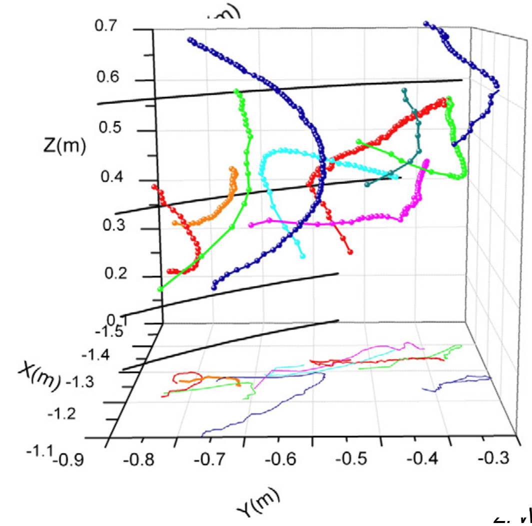


Dust transport (experiments)



NSTX

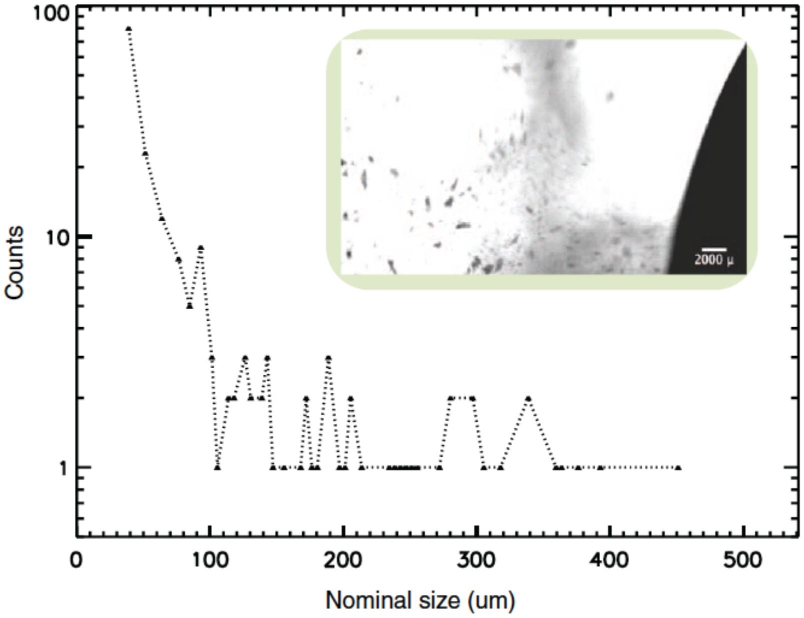




Nichols et al, JNM (2011)

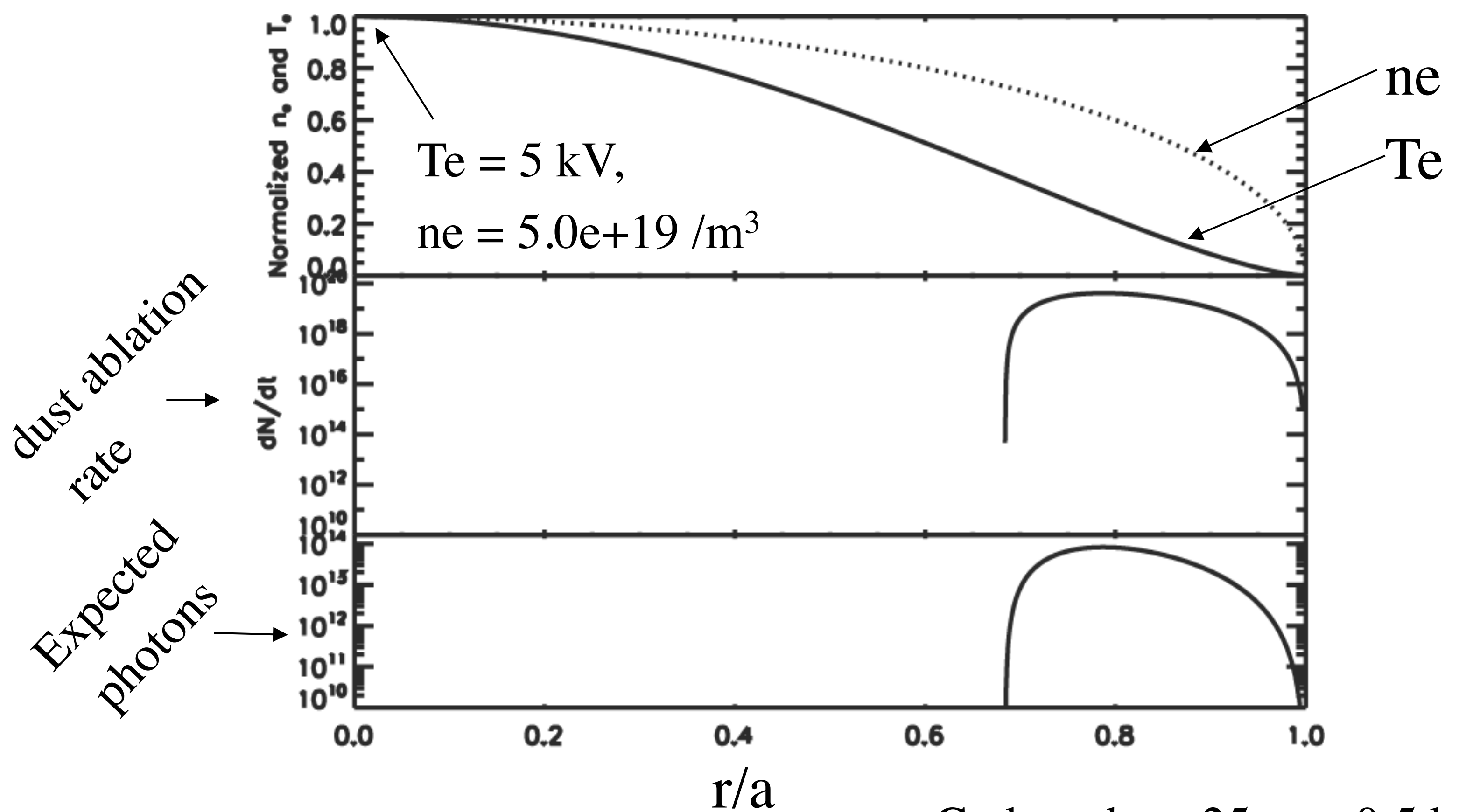
Dust plasma for disruption mitigation

ORNL/ITER



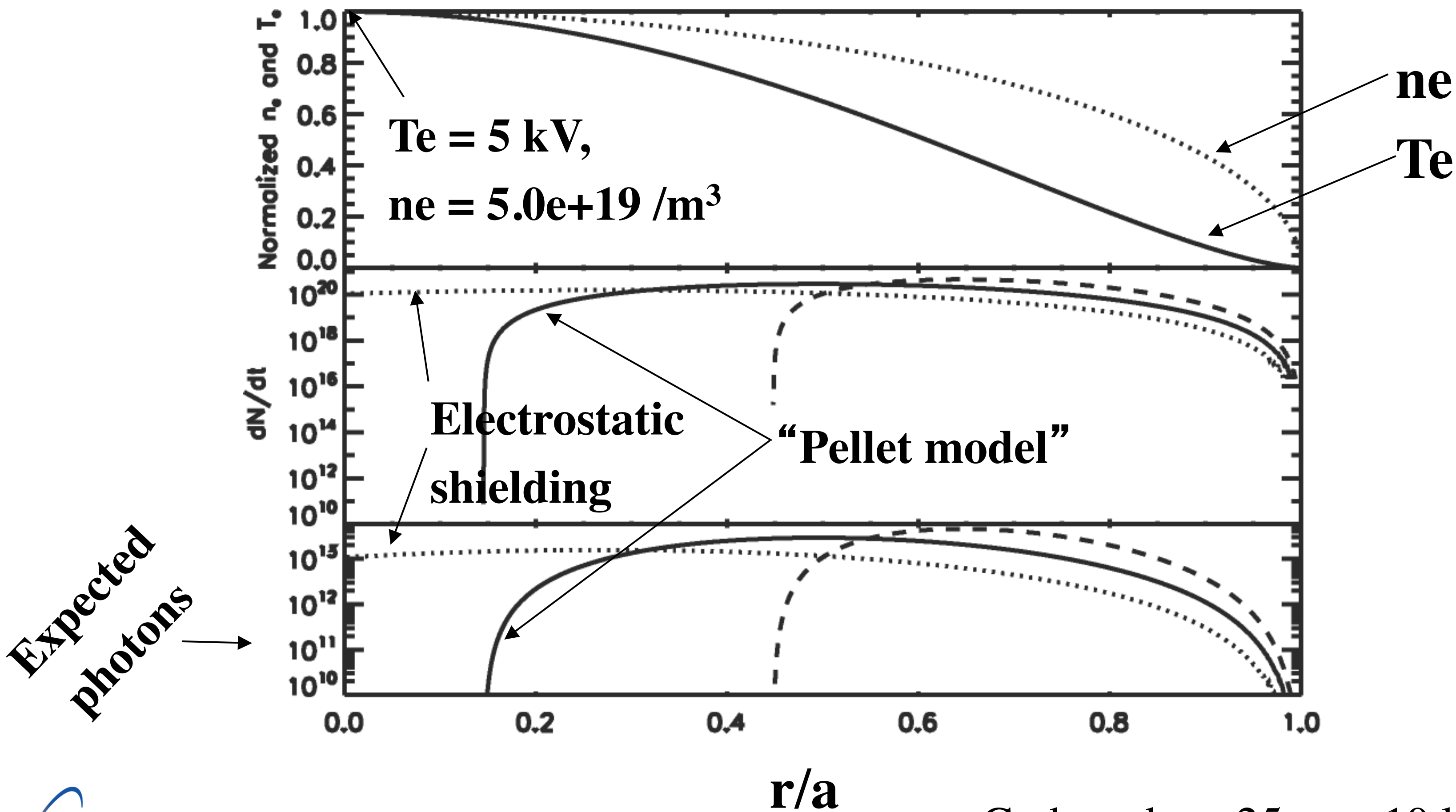
“The largest dusty plasma ever in a laboratory”

Insufficient dust injection speed



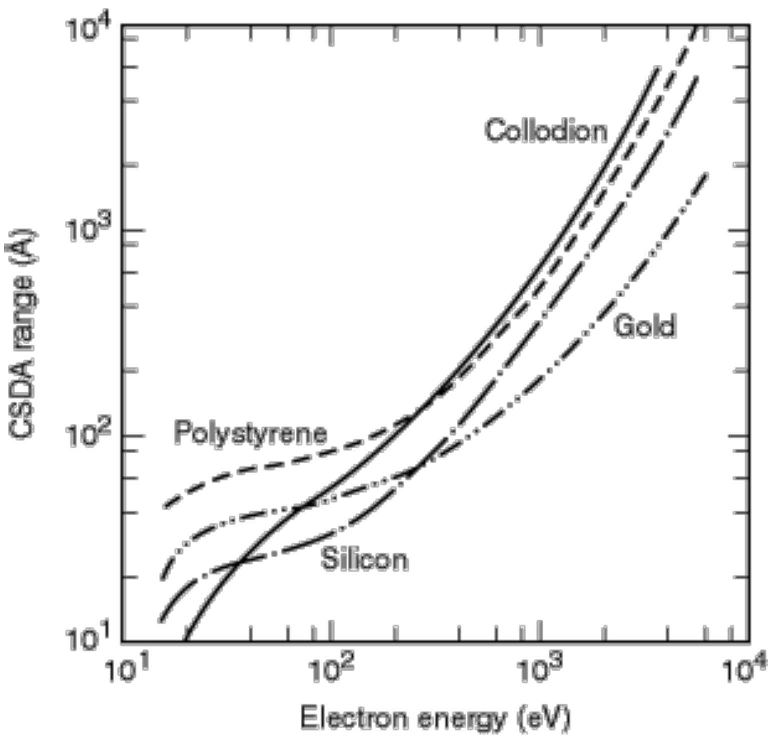
Carbon dust, 25 μm, 0.5 km/s

Uncertainties in dust ablation/transport models



Carbon dust, 25 μm, 10 km/s

Dust ablation models

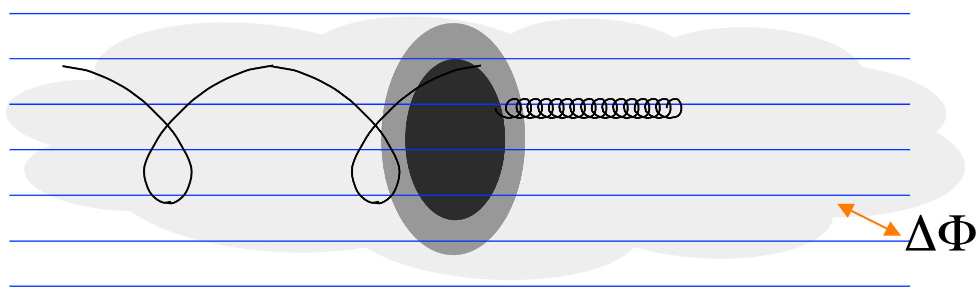


http://xdb.lbl.gov/Section3/Sec_3-2.html

- **Ablation model**
  - The value of f_s.

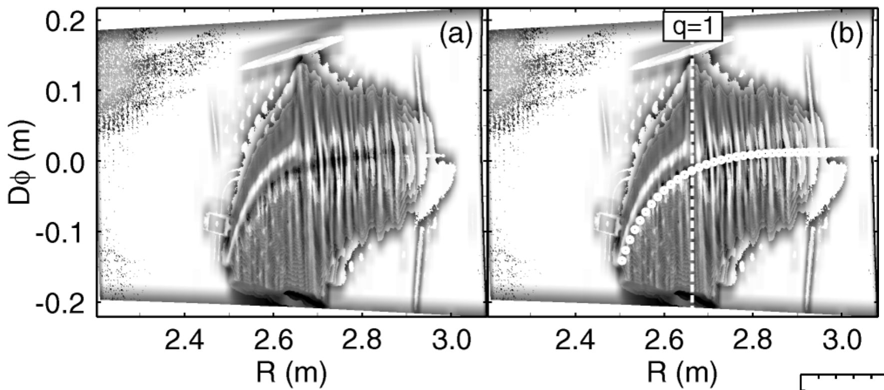
$$\frac{dN}{dt} = \frac{4\pi r_d^2 q_\infty f_S}{\Delta E}$$

- **Shielding mechanisms/size dependent)**
  - Gas/plasma dynamic (NGPS)
  - Magnetic shielding
  - Electrostatic shielding ($\Delta\Phi$ = 1-2 k_BTe/e)

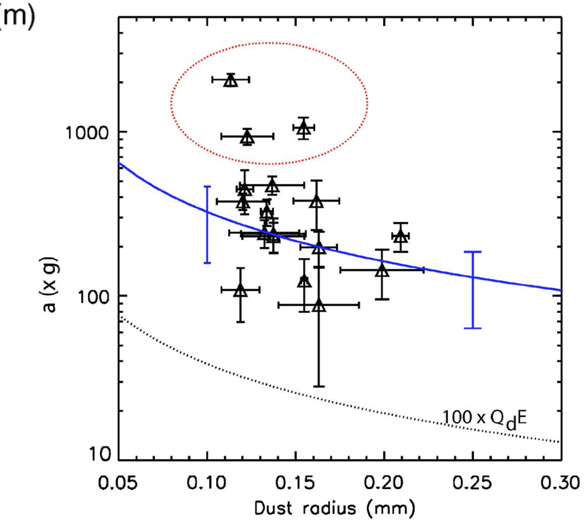


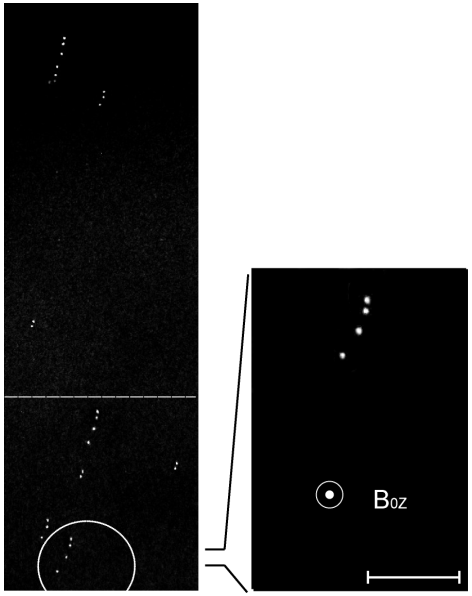
Dust transport, straight trajectories?

- **Unbalance heat & particle fluxes → Rocket effect.**



Waller et al, PRL (2003)



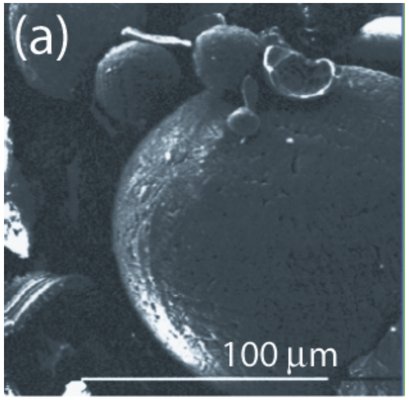


Dust transport in MF plasmas, a "dusty" problem

- **Ablation physics**
  - Mass not conserved
  - Rocket effect

$$\frac{dm_d}{dt}\mathbf{u}_d + m_d\frac{d\mathbf{u}_d}{dt} = \sum_j \mathbf{F}_j$$

- **Warm ions, high dust temp.**
  - Charge, motion, energy balance
- **Large gradient**
  - Radiation zone within closed fluxes
  - SOL ~ 1 cm thick, heat flux 30 MW/m^2, x10 in ITER
- **Irregular dust geometry, shape, composition**
  - Point/Sphere approximations break down (Tensor force, fine grid/long computation time)
  - Additional degrees of freedom (rotation, spin)



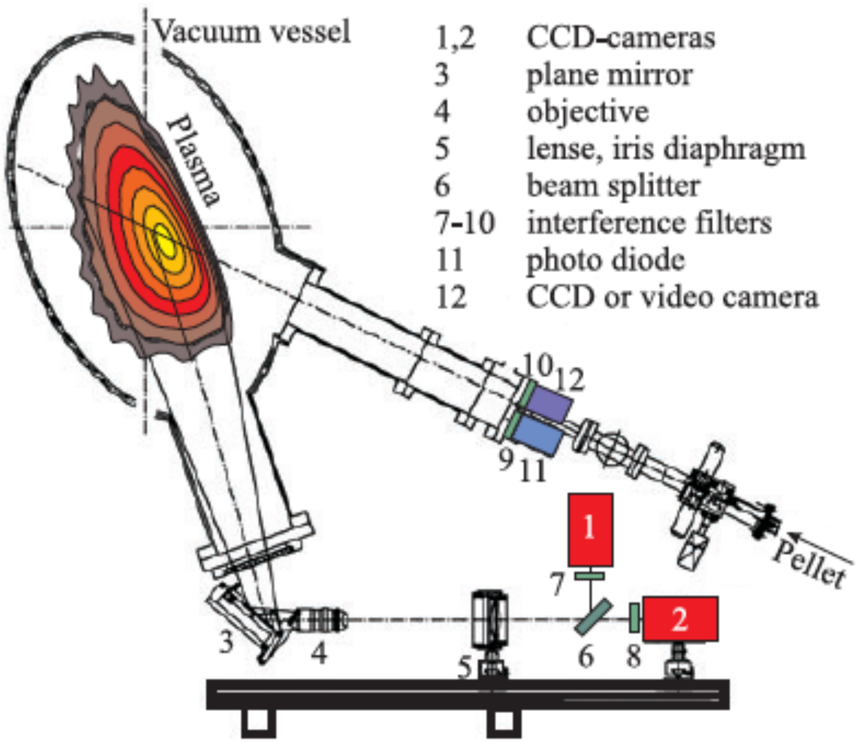
Winter, PoP (2000)

Outline

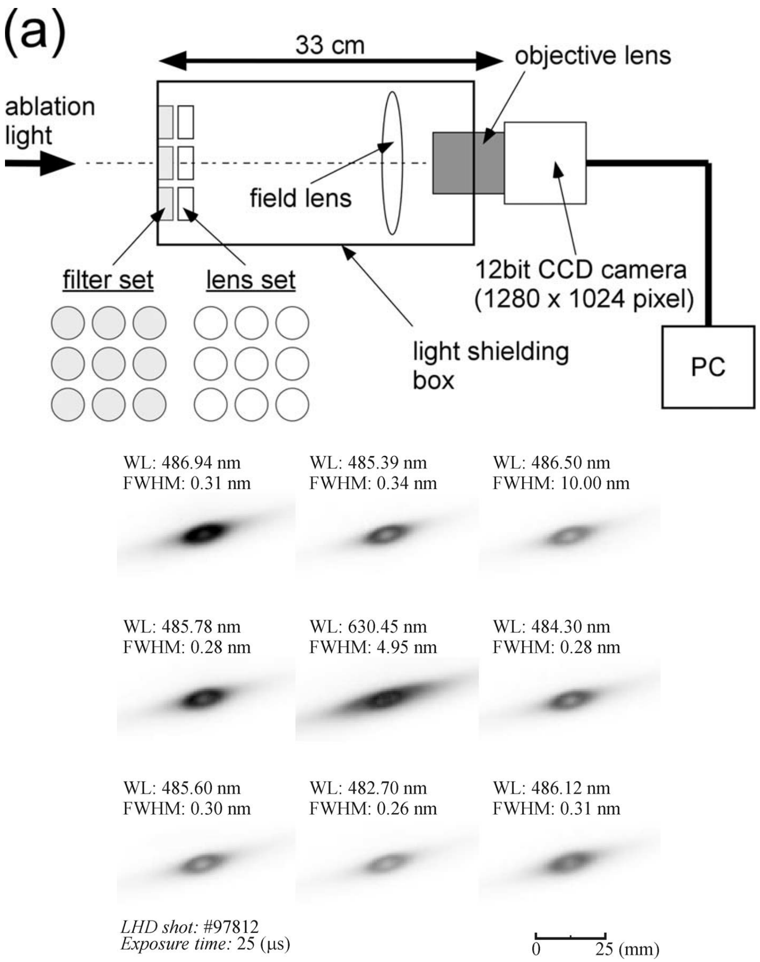
- **Motivations** (ITER → Material issues)
  - Heat: steady-state & transients (ELMs)
  - Disruptions
- **Dust in magnetic fusion plasmas**
  - Good, Bad & "Dusty"
  - Dusty plasmas for disruption mitigation
- **Experimental opportunities and challenges**
  - Technological advances & new facilities
  - Simulations of fusion plasma environment –
    - Magnetic field, Te ~ Ti, hot dust, hot surfaces

Dust ablation measurement through emissions

- **Emission rate – ablation rate**

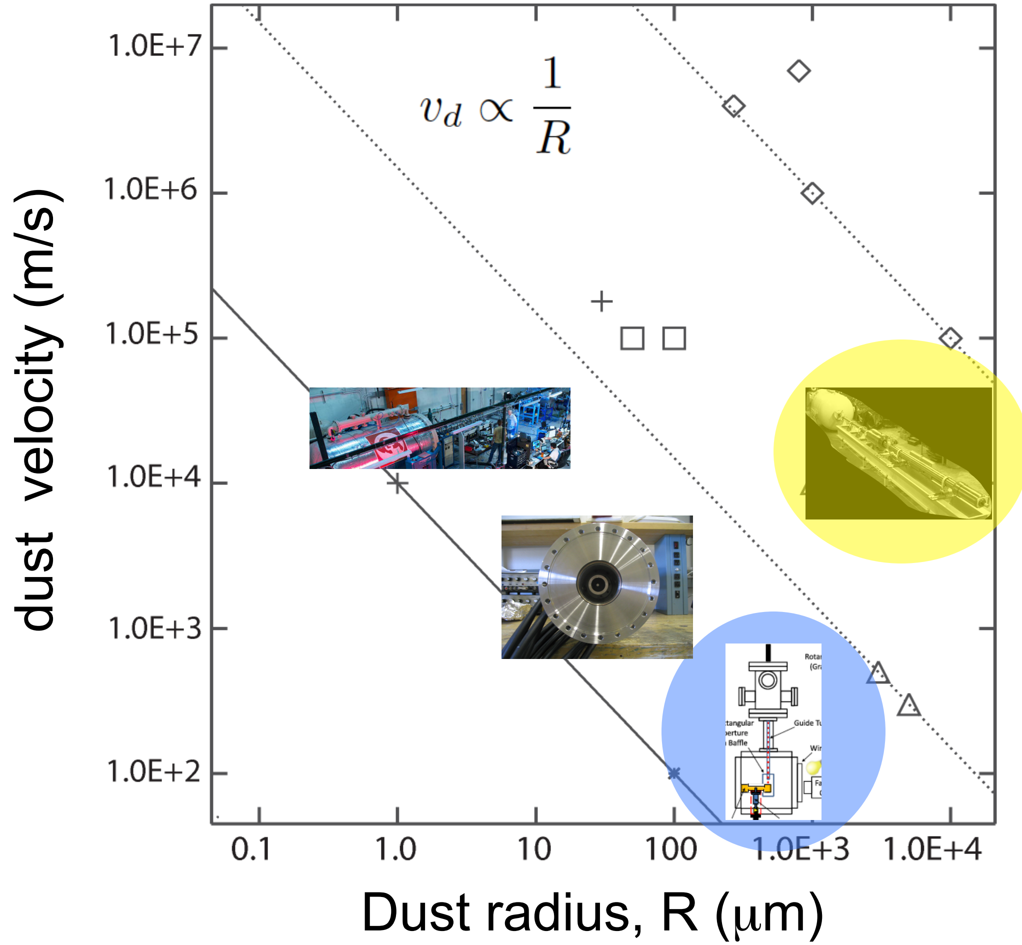


Ledl et al, NF 44 (2004)



Sharov et al, IEEE Trans. plasma Sci. 39 (2011)

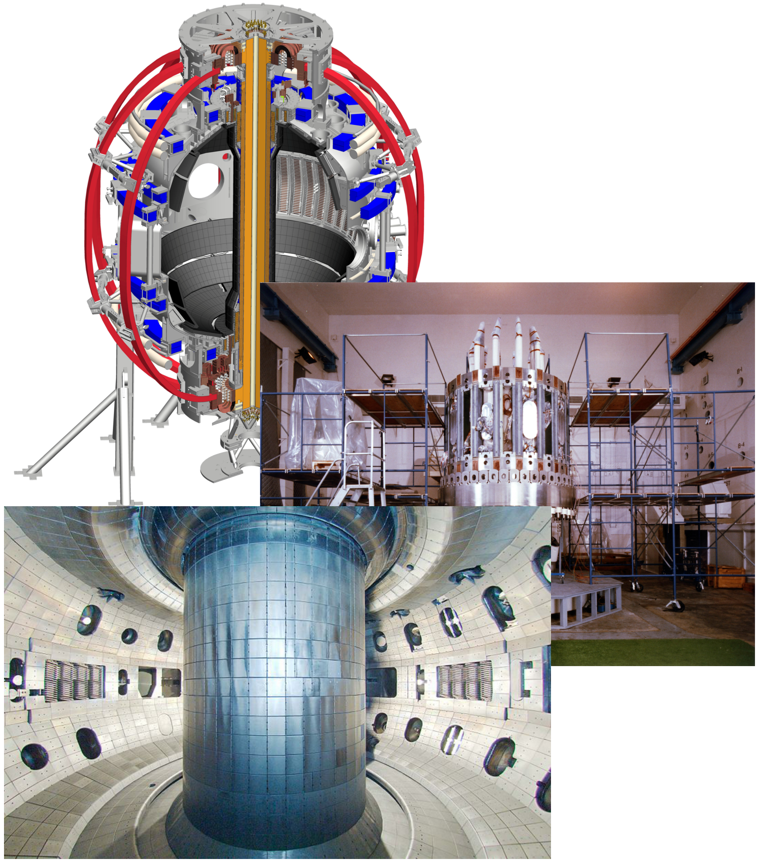
Dust/condensed matter injection technologies

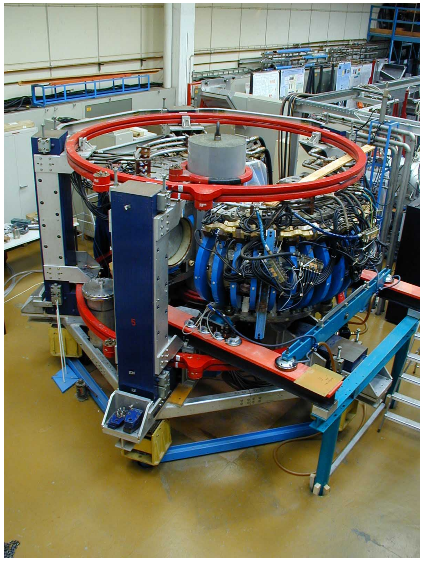


Performances:

- Velocity
- Mass control;
- Frequency control;
- Material flexibility;

New Experimental Facilities (US) → transport/burn-up



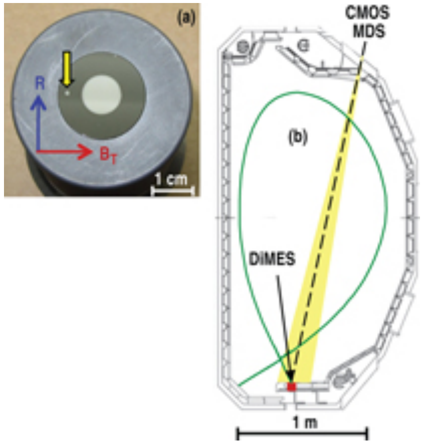


HIDRA

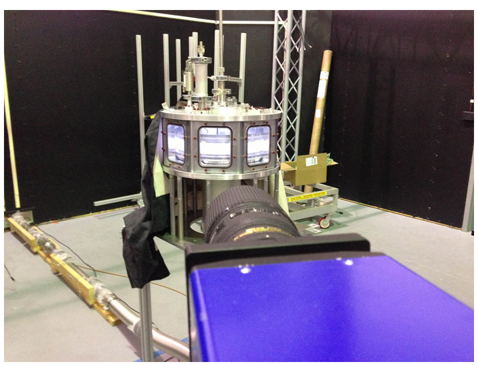
Initially: **0.3 T, n=5e18, T=5eV, 30 minutes**

Physics of warm/hot dust

- **Dust charging, growth**
  - Hot surfaces, Hot dust
  - Te ~ Ti (ion cyclotron heating)
  - High density (> 10^{16} m^3)
- **Dust transport on/near surfaces**
  - removal methods

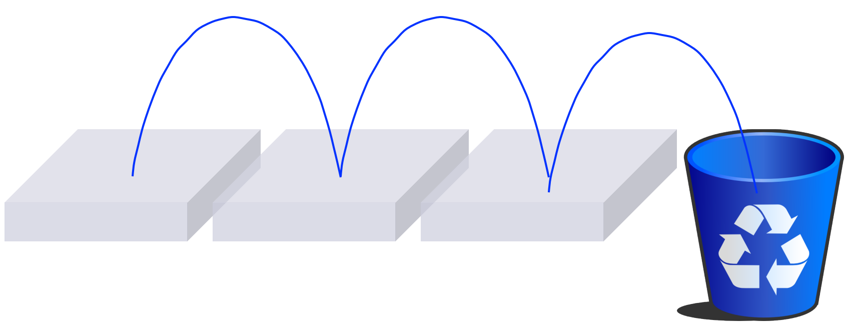


DiMES/MiMES
Rudakov et al (2014)



MDPX

3 T, n=5e16,
T=3 eV, SS



tritium

Summary

- **PMI poses new and important problems in the ITER era**
  - (an unconventional plasma/interdisciplinary problem)
- **Better understanding of dust physics**
  - Dust transport is a central issue
- **Experiments are needed to bridge the knowledge gap,**
  - ‘control dust’ inventory and
  - ELMs/Disruptions applications;
- **Experimental facilities like MDPX can address the dust challenges**
  - Charging, growth
  - Removal methods