The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2155-1

International Workshop on Cutting-Edge Plasma Physics

5 - 16 July 2010

Dust in fusion devices: experiment, theory, and modelling

S.I. Krasheninnikov
University of California at San Diego
USA

Dust in fusion devices: experiment, theory, and modeling

Sergei Krasheninnikov

University of California San Diego

With contributions from:
D. A. Mendis, R. D. Smirnov, and A. Yu. Pigarov

University of California at San Diego

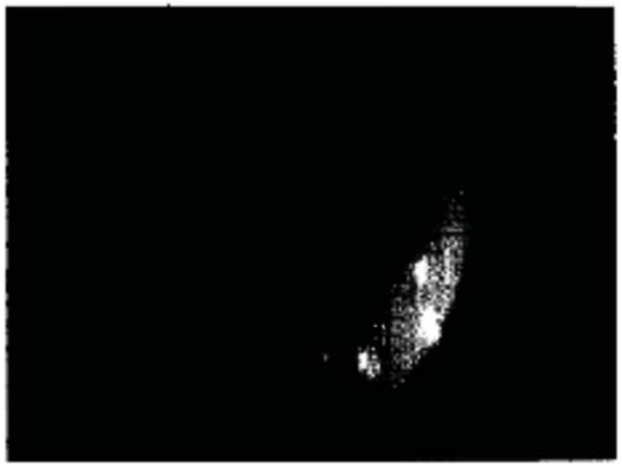
International Advanced Workshop on the Frontiers of Plasma Physics
ICTP, Italy, 5-16 July 2010

Outline

- Introduction
- Experimental observations
- Theoretical issues of dust in fusion
  - Dust generation
  - Basics of dust-plasma interactions
  - Dust-wall collisions
  - Main features of dust dynamics
  - Dust impact on plasma performance
  - Theoretical issues of dust diagnostics
- Discussions

Introduction

- It has been known for a long time that microscopic grains of solid matter (dust) exist in fusion devices
- Ohkawa (1977) speculated that dust can be a source of plasma contamination
- Goodall (1982) observed dust in DITE using a film camera

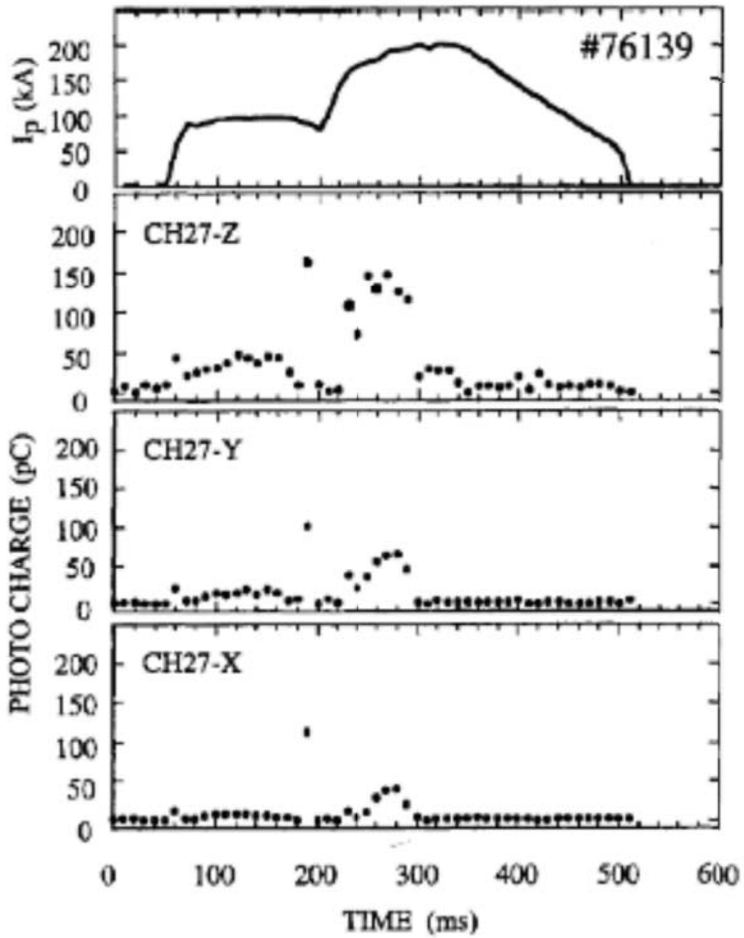


Introduction (con-d)

- Large spikes, occasionally detected by a Thomson laser scattering system on JIPPT-IIU tokamak, were interpreted as a reflection of laser light by dust (1997)
- However, Carbon dust particles (~2 μm), deliberately injected into JIPPT-IIU, have been detected with Thomson scattering only at low plasma density

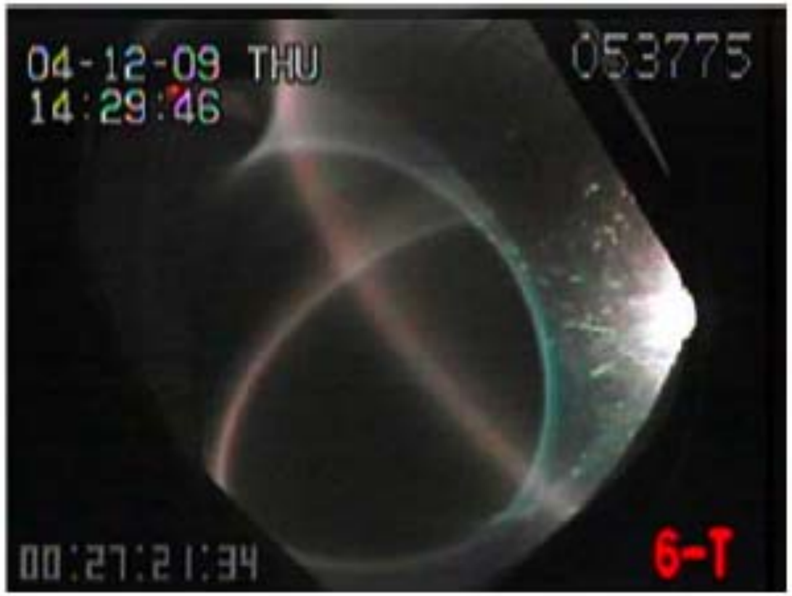
Introduction (con-d)

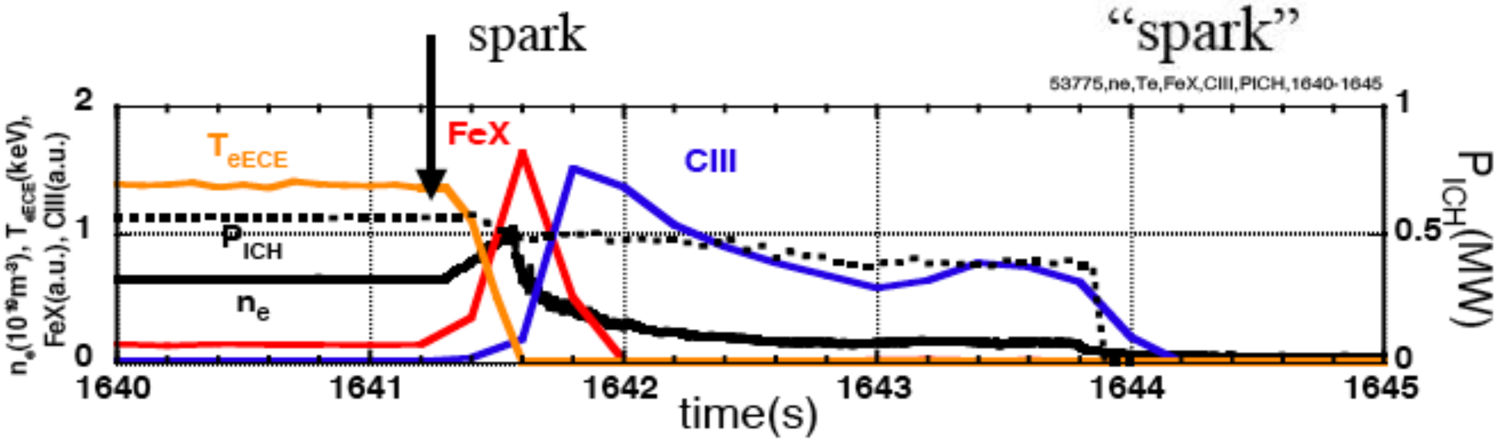
- The following conclusions were made:
  - *“We speculate that the dust particles spread to a much more extended region than expected …”*
- We will see later on that this is probably the case



Introduction (con-d)

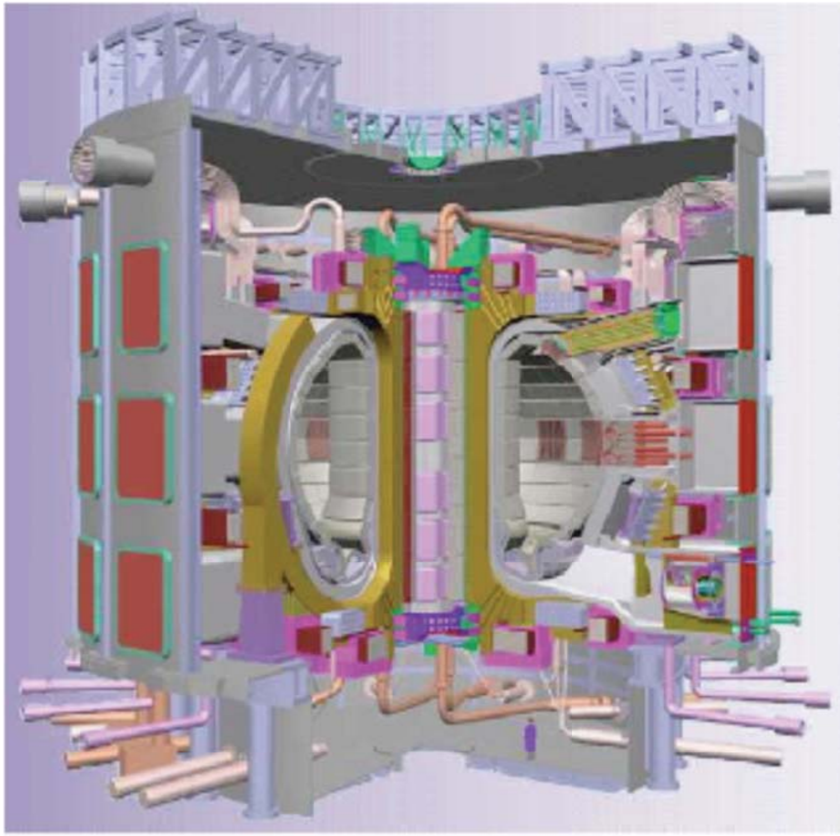
- Often long pulse/high power discharges in current devices are terminated by accidental massive invasion of dust (e.g. “sparks” in LHD)





Introduction (con-d)

- In the next step device (e.g. ITER) dust brings new features: it can pose safety problems related to its chemical activity, tritium retention, and radioactive content
- In particular, the presence of dust in the vacuum chamber of ITER is one of the main concerns of the ITER licensing process (J.-Ph. Girard, 2007)



Introduction (con-d)

- In ITER safety requirements severely limit the amount of dust on hot surfaces:

  11 kg of Be or 230 kg of W or 15 kg of C

- However, it is plausible that long pulse ITER discharges may be affected by “sparks” seen in current devices
- In order to address these issues we need to understand:
  - Dust generation mechanism(-s)
  - Dust dynamics and transport in fusion plasmas
  - Impact of dust on plasma performance

Experimental observations

- Majority of available experimental data on dust in fusion plasmas are obtained with
  - dust collection during the vents and analysis of this dust
  - laser scattering technique
  - dust imaging with fast cameras
- Although, some other diagnostics are available or under development (e.g. the electrostatic detectors (Skinner, 2004), capacitive diaphragm microbalance (Counsell, 2006))

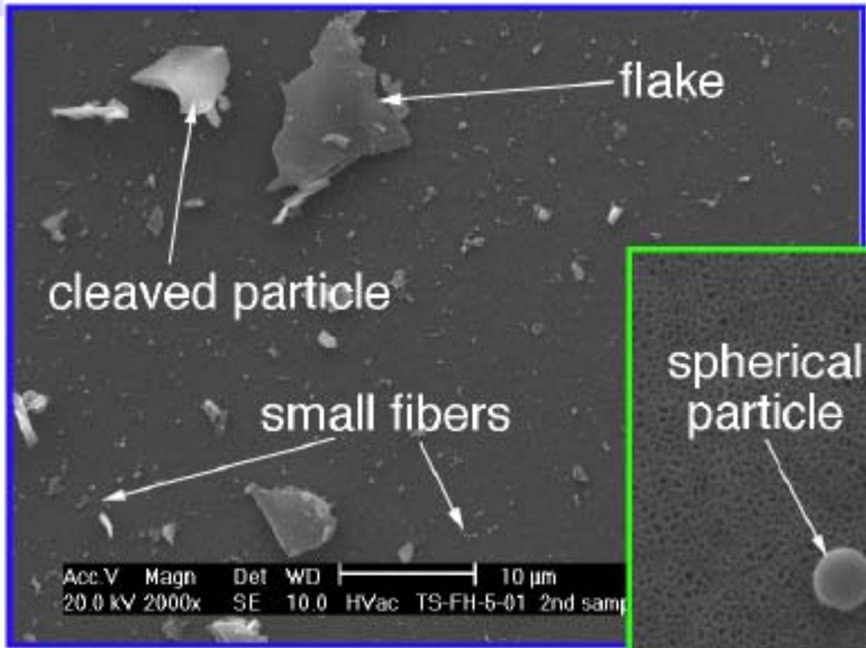
Experimental observations

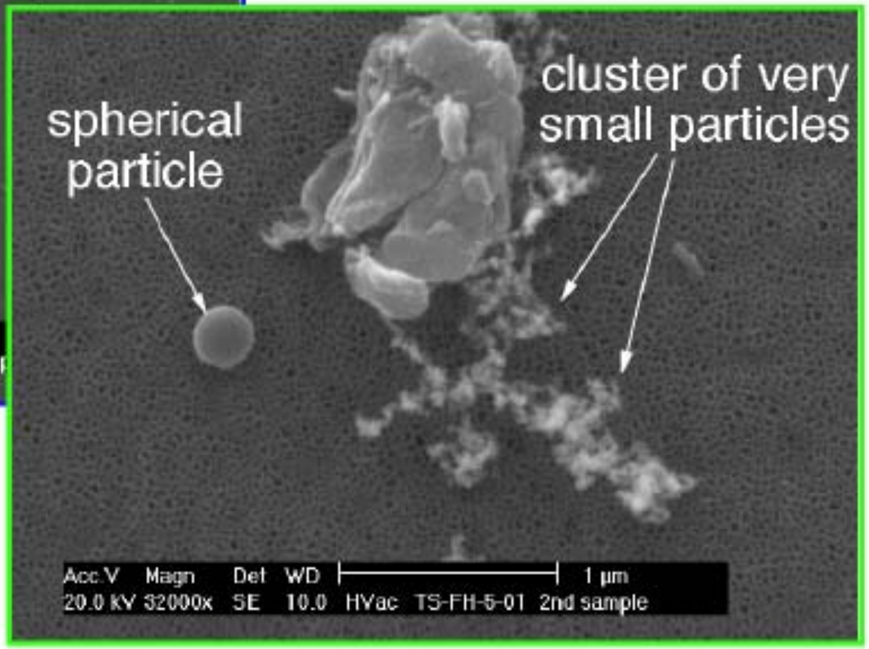
Dust collection

- Analysis of collected dust show that sizes of fusion dust vary in a very wide range from ~ 10 nm to ~ 0.1 mm
- Dust typically consists of the chamber wall's materials and has a variety of flake-like, irregular and, sometime, spherical shapes, which suggest different mechanisms of dust production
- Among the mechanisms considered are: flaking of deposited layers, condensation of impurities in cold plasma regions, sputtering of plasma contacting surfaces, and other surface damaging mechanisms such as brittle destruction, melting and unipolar arcs

Experimental observations

Dust collection (con-d)

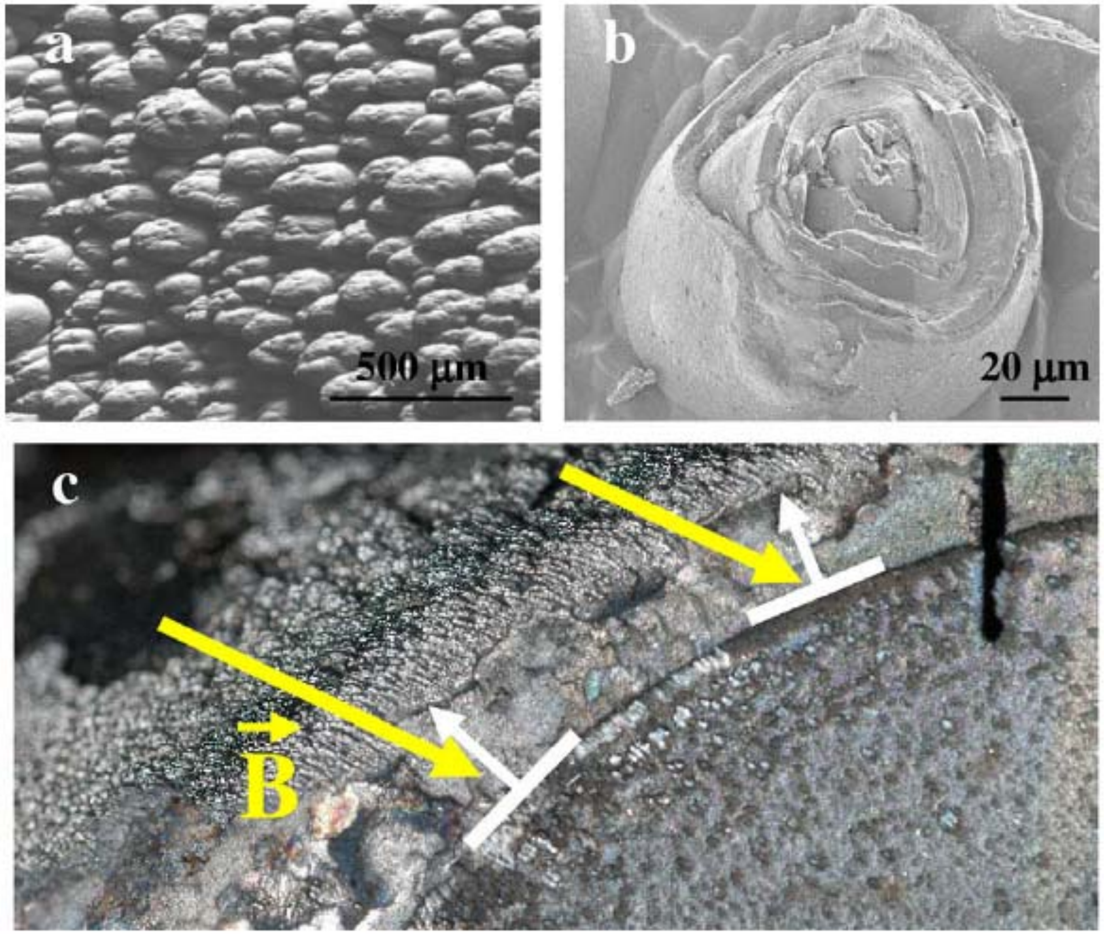




Dust collected in Tore Supra (Sharpe, 2005)

Experimental observations

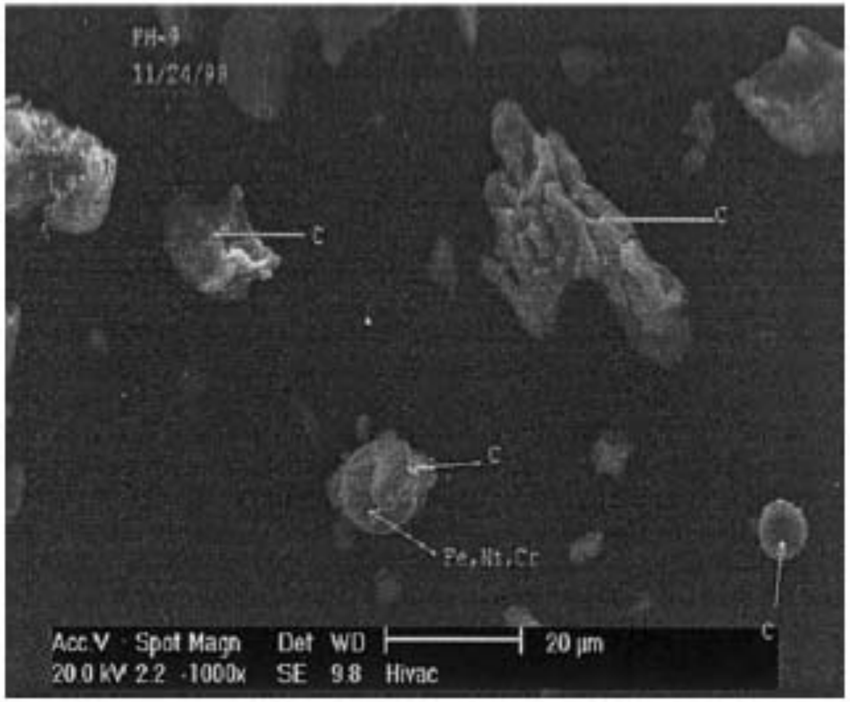
Dust collection (con-d)



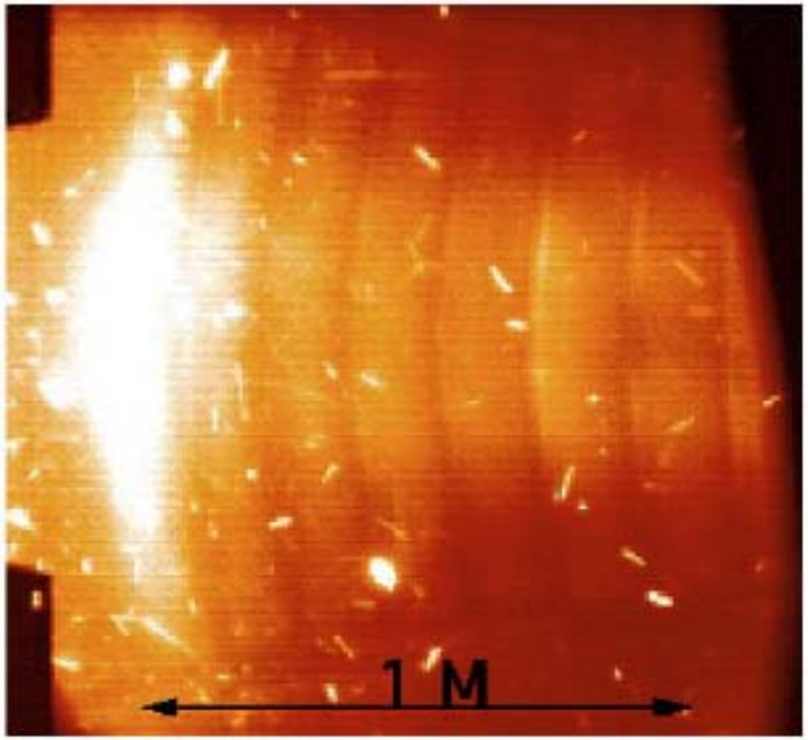
Carbon deposits in Tore Supra (Roubin, 2009)

Experimental observations

Dust collection (con-d)



Microphotograph of DIII-D dust with indicated composition (Carmak, 2000)



Dust Dust generation in NSTX during disruption (Roquemore, 2007)

Experimental observations

Dust collection (con-d)

Machine	Dust (g)	Density (g/m2)	Diameter (μm)	Surface area (m2/g)	Elemental composition
C-Mod [1, 2]		≤10	0.78 – 2.89	0.2 - 0.77	Mo, B
AUG [3]		≤1.5	3.33	≤3.7	Cu, Fe, Cr, Ni
DIII-D [1, 2]	90-120	≤1	0.46 – 1.0	2.44	C
JET [4, 5]		<4	4	4.7	C, Fe, Cr, Ni,T
JT60-U [6]	7.5	0.037	3.08	≤1.18	C, Si
LHD [3]	16.2	0.04	9.6		C, Fe, Cr, Mn
NSTX [6]	0.5	0.033	3.27		C, B
TS [2]	31	≤1.1	3.0	1.32	C, O, Fe, Cr, Ni

[1] Carmack 2000, [2] Sharpe 2001, [3] Sharpe 2003, [4] Federici 2001, [5] Bekris 2005, [6] Sharpe 2005

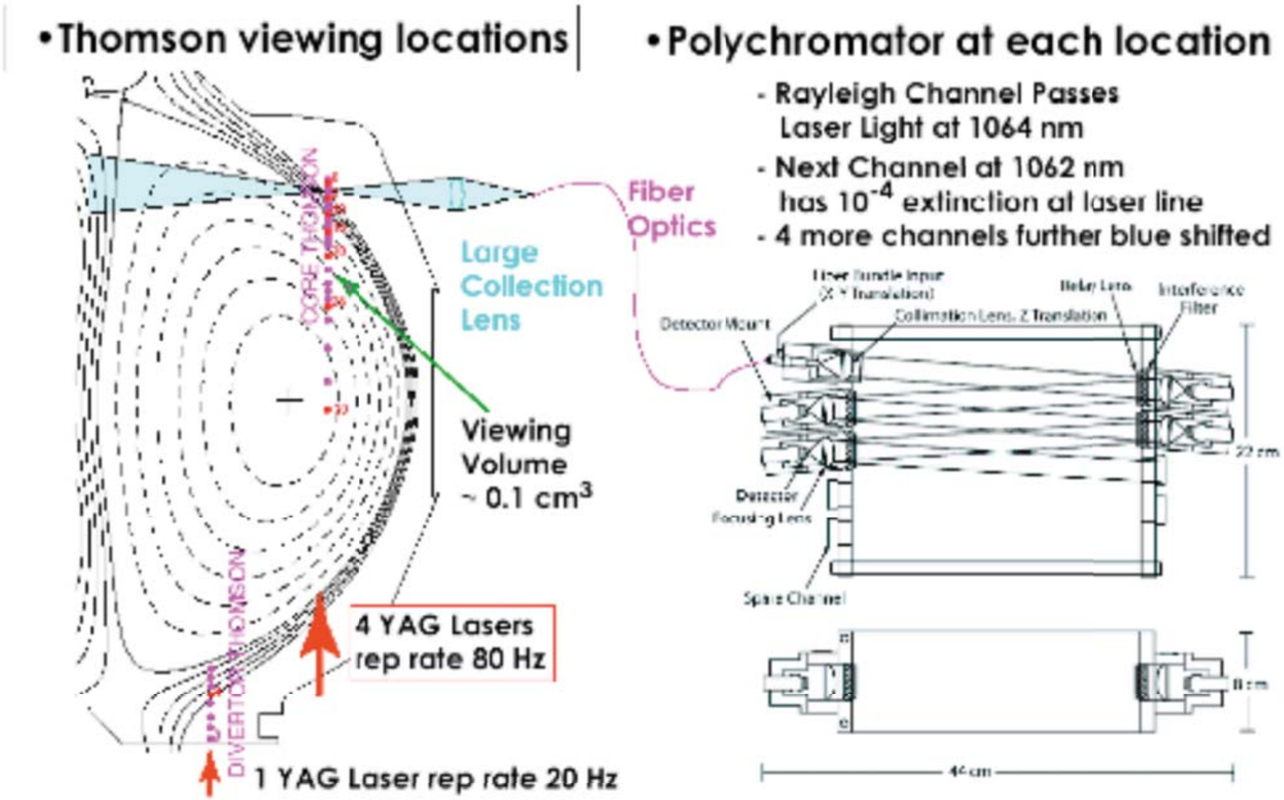
Parameters of dust collected from different devices

In DIII-D: dust surface area ~200 m^2 >> wall surface ~30 m^2!!!

Experimental observations

Laser scattering

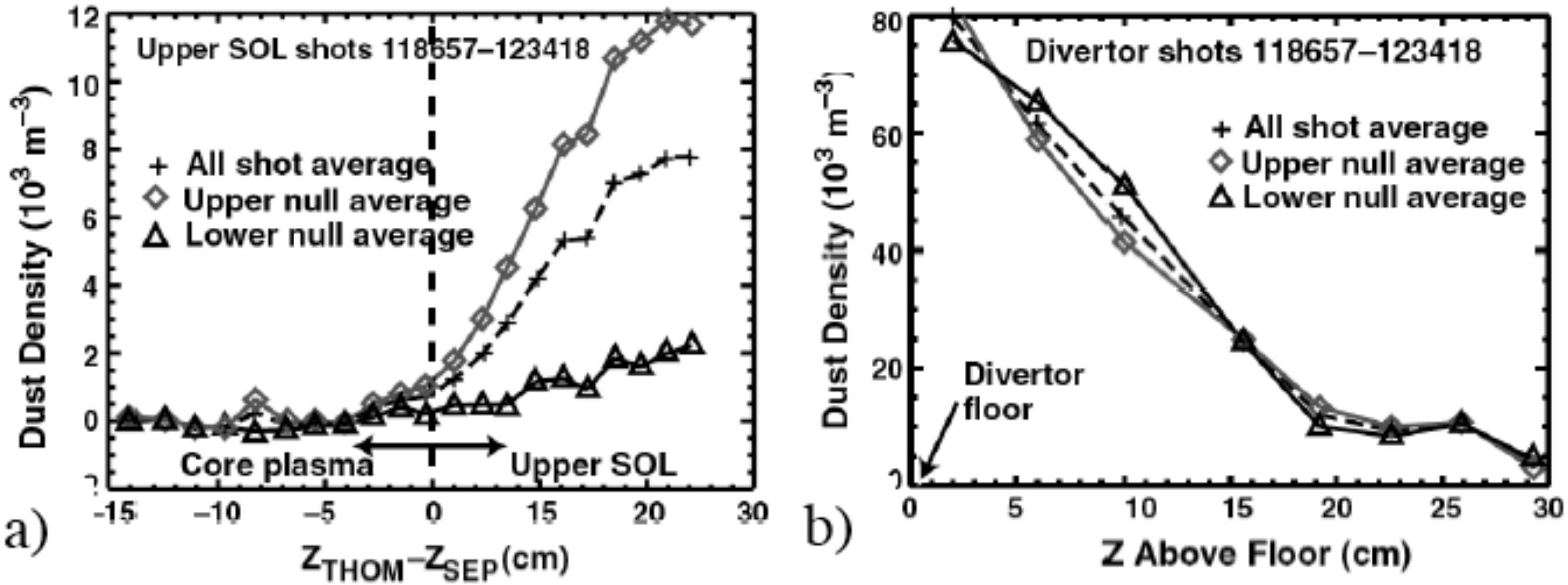
- Non-shifted detector channels of the Thomson scattering system can be used for the studies of dust statistics (West, 2006, 2007)



Experimental observations

Laser scattering (con-d)

- Dust density distribution was inferred from the upper scrape-off layer (SOL) and divertor Thomson data



averaged dust density in DIII-D plasma is below 0.1 cm^{-3}!

No dust-dust interactions!!!

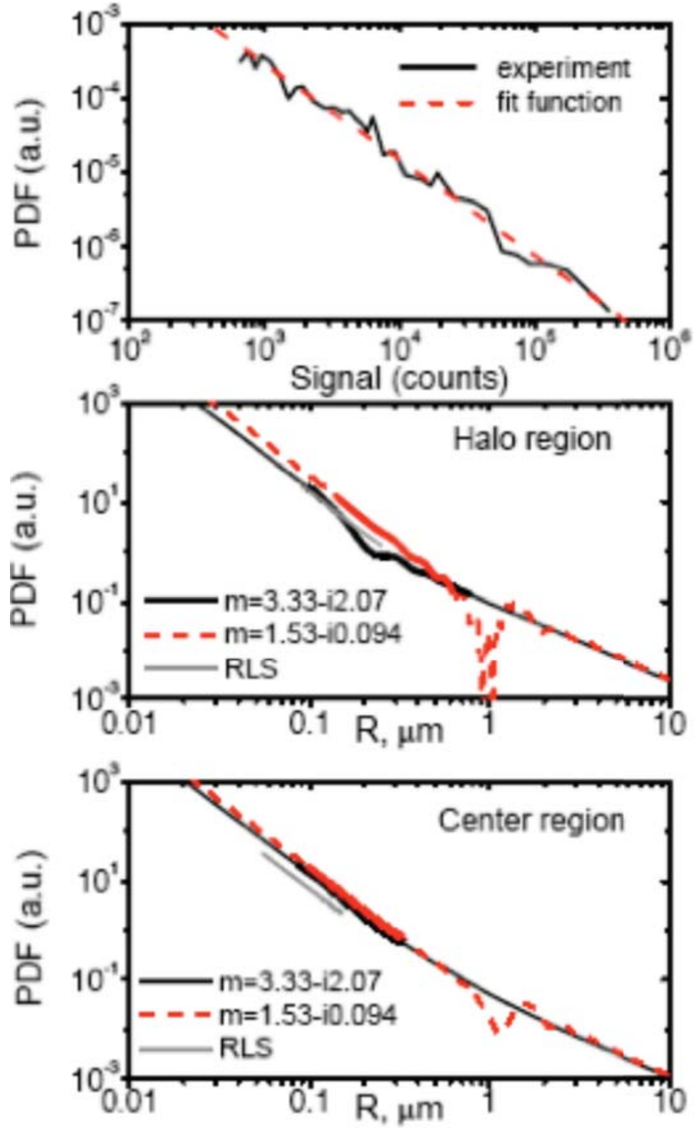
Experimental observations

Laser scattering (con-d)

- The dust probability distribution function over the radius, was constructed (West 2007, Smirnov 2007)
- $< R_d >= 0.17\ \mu m$
- PDF can be fitted with the power-law function $\sim (R_d)^{-\sigma}$ $\sigma = 2.7$ **<3!**

$\Rightarrow$

- Crucial role of large particles $R_d > 10\ \mu m$ (missed in the data) in plasma contamination



Experimental observations

Fast cameras

- Fast framing cameras are widely used now to monitor different events occurring in edge plasmas such as blobs, ELMs and dust
- Camera is the only tool allowing to estimate the speed of dust grains
- Cameras allow assessment of amount of dust in an individual shot
- Tracking of dust particle with a few fast cameras (already in progress!) and measurements of radiation spectrum can provide important information on both dust and plasma parameters

Experimental observations

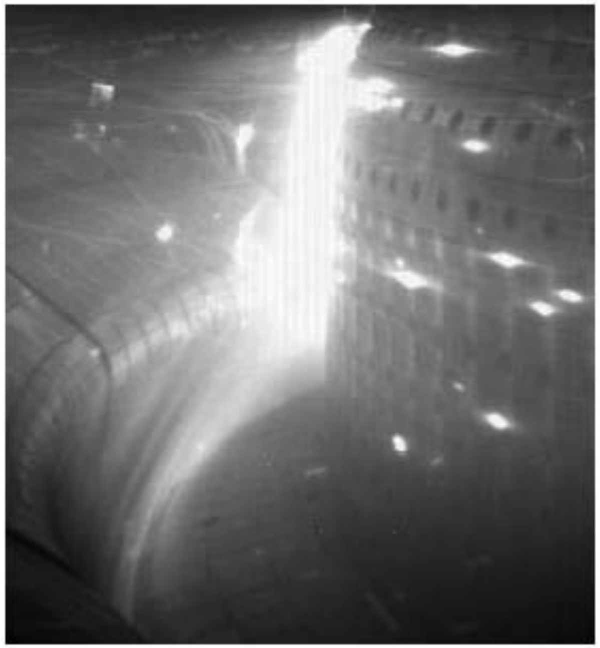
Fast cameras (con-d)

- Major findings with fast cameras:
  - In DIII-D fast camera typically observes between 10-100 dust grains per discharge in “normal operations”
  - Dust grains moving at velocities of up to ~500 m/s and collisions of with the walls and breakup of grains into pieces are observed
  - The preferential direction of dust motion is toroidal, however, in some cases the trajectories of dust grain are very surprising
  - Disruptions often generate significant amount of dust particles (up to 10^5), observable with fast camera
  - Increased dust levels are also observed following entry vents, but after a few days of plasma operations (about 100 discharges) dust level is reduced to the “normal operations” rates

Experimental observations

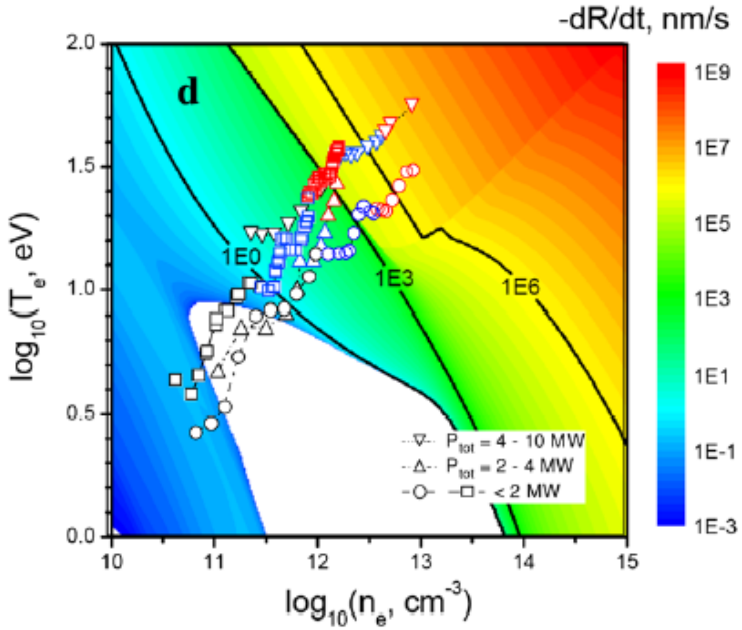
Fast cameras (con-d)

- Similar trends in dust trajectories and statistics as well as the “self-cleaning” of plasma from dust were shown on many fusion devices
- In C-Mod, ~20 run-hours were needed for recovery after the failure of LH launcher, (Lipschultz, 2005)



Theoretical issues of dust in fusion
Dust generation

- In fusion devices dust is generated
  - volumetrically through nucleation, deposition, and agglomeration processes (like in gas discharge plasmas)
  - at the surface through the processes of films peeling off, splashing off molten material, mechanical failures
- Volumetrically growing dust is almost stagnant, dust caused by mechanical failures comes into plasma with speed V_{in}~10 m/s
- Today we unable to predict dust generation rate from first principals
- Experiment suggests ~10% out of net erosion rate



(Smirnov 2007, Roubin 2009)

$$V_{in} \sim \sqrt{\sigma_{TS}/\rho_d} \sim 10\ \mathrm{m/s}$$

σ_{TS} – tensile stress

ρ_d – grain mass density

Theoretical issues of dust in fusion
Basics of dust-plasma interactions

- Unlike dusty-plasma experiments, in fusion plasmas the shape, size, and constituency of natural dust grains are not defined *a priori*
- Therefore, the analysis of dust-plasma interactions in fusion plasmas is, in most cases, approximate
- Moreover, we are dealing with hot, $T_e \sim T_i \sim 10\text{-}100$ eV, and dense, $n_e \sim 10^{12\text{-}14}$ cm^{-3}, plasma, which heats grain to the temperatures $T_d \sim$few 1000 K
- As a result, secondary and thermionic emissions, thermal radiation, and ablation become important ingredients of plasma-dust interactions

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- If vapor does not affect electron- and ion- grain interactions, we can approximate dust as a spherical particle with effective radius R_d and use "standard" models for dust-plasma interactions (e.g. see reviews Tsytovich 1997, Shukla 2002, Fortov 2005 and the references therein) accounting, however, for electron emissions, radiation, and ablation processes
- Plasma-dust interactions in fusion devices is somewhat complicated by the presence of ~few T magnetic field
- However, usually we are dealing with relatively small grains $R_d \sim 1\ \mu m << \rho_i \sim 10^{-2}$ cm, so that an impact of magnetic field on plasma-dust interactions is mild and can be neglected

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- Due to dust-plasma interactions dust grain is always charged to maintain ambipolarity of electron and ion fluxes to the grain
- If electron emission is unimportant, then dust is negatively charged and the charge number Z_d of the grain can be found from

$$\frac{e^2 Z_d}{R_d} = \Lambda T$$

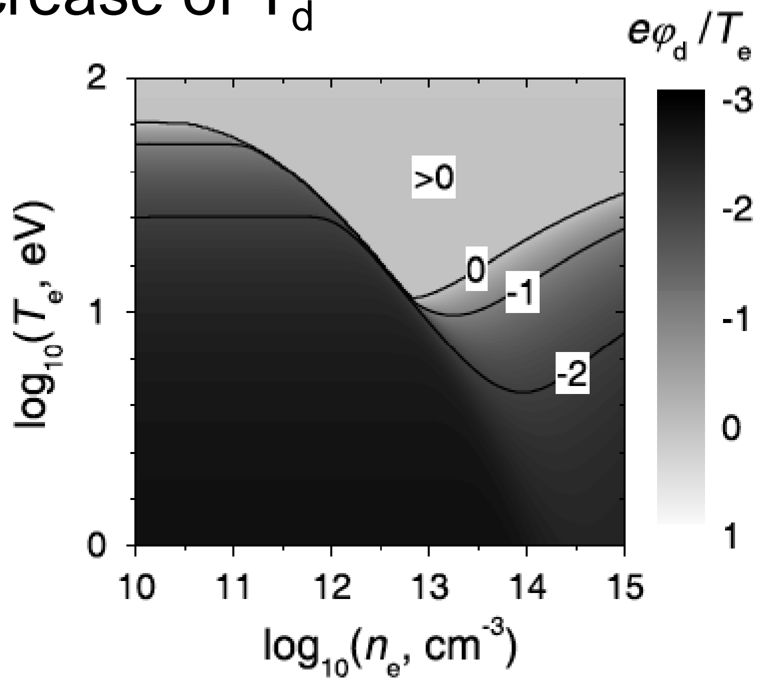
where $\Lambda \sim 3$ weakly depends on plasma parameters

- For $T \sim 10$ eV and $R_d \sim 1$ μm we have $Z_d \sim 10^4$

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- However, in hot and dense plasma T_d increases, which also increases thermionic emission
- It reduces grain electrostatic potential $\phi_d = eZ_d/R_d$ and allows more plasma electrons come to the grain
- This increases the heat flux to the grain and, consequently, leads to further increase of T_d

- As a result, thermal bifurcation can occur (Nedospasov 1983), which is accompanied by the bifurcation of Z_d
- Self-consistent treatment of grain charging and energy balance confirms these bifurcations (Smirnov 2007)



Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- Analysis of the forces acting on dust grain in fusion plasmas shows (Krasheninnikov 2004) that plasma-grain friction force and electric force (mainly in the sheath) usually dominate

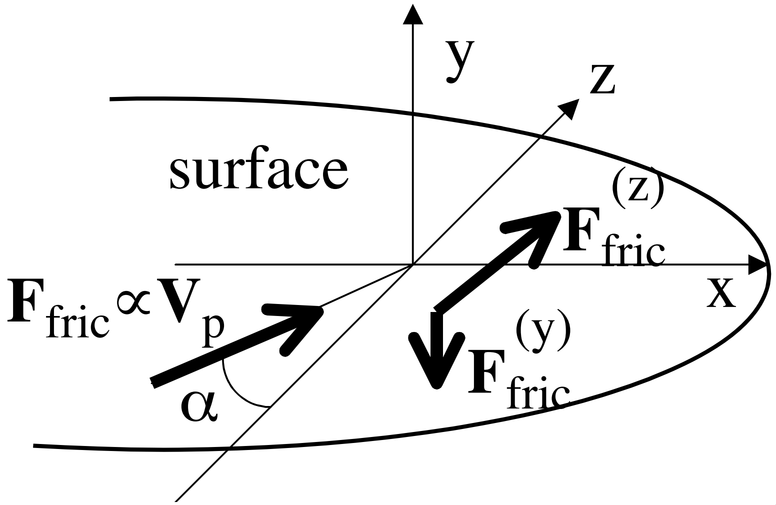
$$\vec{F}_{fric} = \xi_F \pi R_d^2 M_i n_e V_{Ti} \left(\vec{V}_p - \vec{V}_d \right)$$

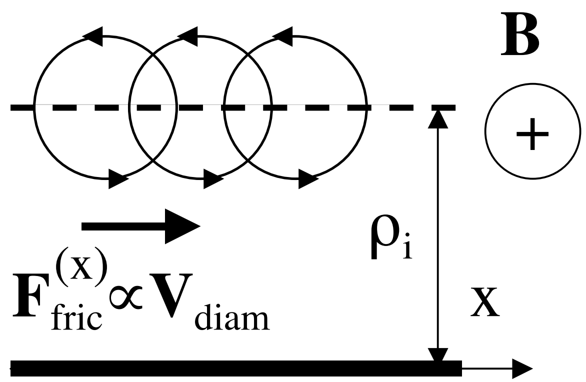
$$\vec{F}_E = -eZ_d \vec{E}$$

$\xi_F \sim 10$ is the numerical factor, which depends on plasma parameters

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- Friction forces in magnetized sheath are due to plasma flow along the magnetic field and **E×B** and diamagnetic flows across **B**





- In the sheath M~1 and $F^{(z)}_{fric} \approx F^{(x)}_{fric} \approx F_{sh} \equiv \xi_F \pi R_d^2 nT$
- Outside sheath $y \gtrsim \rho_i \sim 10^{-2}\,\mathrm{cm}$ both F_E and $F^{(x)}_{fric}$ are small
- But, $F^{(z)}_{fric}$ and $F^{(y)}_{fric}$ are large in recycling region $y \lesssim \ell_{rec} \sim 1\,\mathrm{cm}$

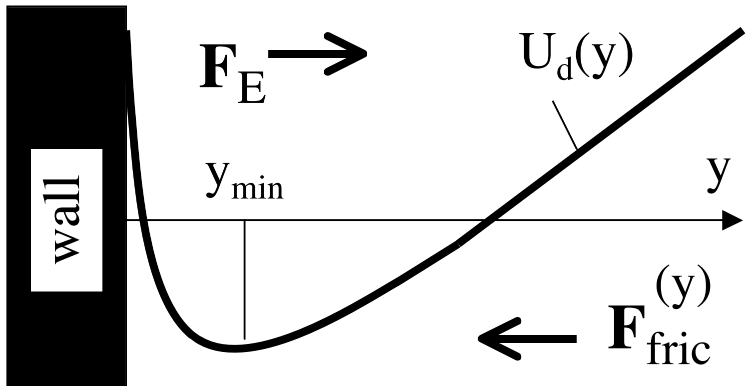
Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- In recycling region the motion of negatively charged grain in the direction perpendicular to the surface is described by effective potential $U_d(y)$

$$U_d(y) =$$

$$= \alpha \xi_F n T \pi R_d^2 y + \Lambda \frac{R_d T}{e} \varphi(y)$$

$$y_{min} \sim \rho_i \sim 10^{-2} \text{cm}$$



- In order to reach the surface or escape from potential well grain should have speed

$$V_d > V_{sh} \equiv \left(\frac{3}{2\pi} \frac{\Lambda_{sh} \Lambda T^2}{e^2 \rho_d R_d^2} \right)^{1/2} \sim 5 \text{ m/s}$$

$$V_d > V_{esc} \equiv \left(\xi_F \frac{3}{4} \frac{\alpha n_e T \ell_{rec}}{\rho_d R_d} \right)^{1/2} \sim 10 \text{ m/s}$$

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

- However, the components of friction force in z- and x-directions are not balanced and grain in recycling region is continuously accelerated in these directions!
- Other forces which can be important in fusion plasmas are:

Gravity force $$\mathbf{F}_g = \frac{4\pi}{3} R_d^3 \rho_d \mathbf{g}$$

Magnetic force $$\mathbf{F}_M = -\pi R_d^3 \varepsilon_M \frac{B_{sat} B_{tor}}{4\pi R} \frac{\mathbf{R}}{R}$$

"Rocket" force $$F_{roc} = \xi_{roc} M_v V_v \Gamma_v$$

Lorentz force, $e\mathbf{B}\times\mathbf{V}_d/c$, can only be important for nano-scale grains

Theoretical issues of dust in fusion
Basics of dust-plasma interactions (con-d)

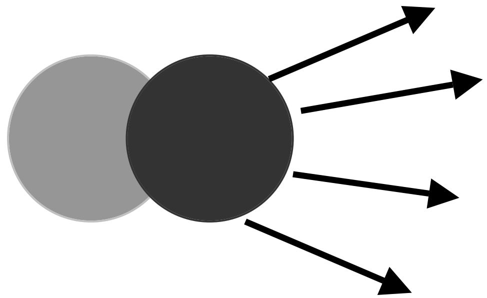
- In modern tokamaks for e_M~1 the magnetic force is larger than the gravity force. But both of them can only exceed friction force with M~1 plasma flow either in the case of large size grains or in rather thin or no plasma (e.g. between the shots) cases
- Estimation of asymmetry factor ξ_{roc} for homogeneous dust gives

$$\xi_{roc} = \left(1 + 2\frac{\kappa T_d^2}{R_d q_d E_{ev}}\right)^{-1} << 1$$

due to a small temperature variation within grain caused by high heat conductivity of grain material, κ, and small grain size

Theoretical issues of dust in fusion Basics of dust-plasma interactions (con-d)

- As a result, friction force due to M~1 plasma flow is always larger than "rocket" force
- However, compound grain ξ_{roc}~1 and "rocket" force can dominate in hot and dense plasma



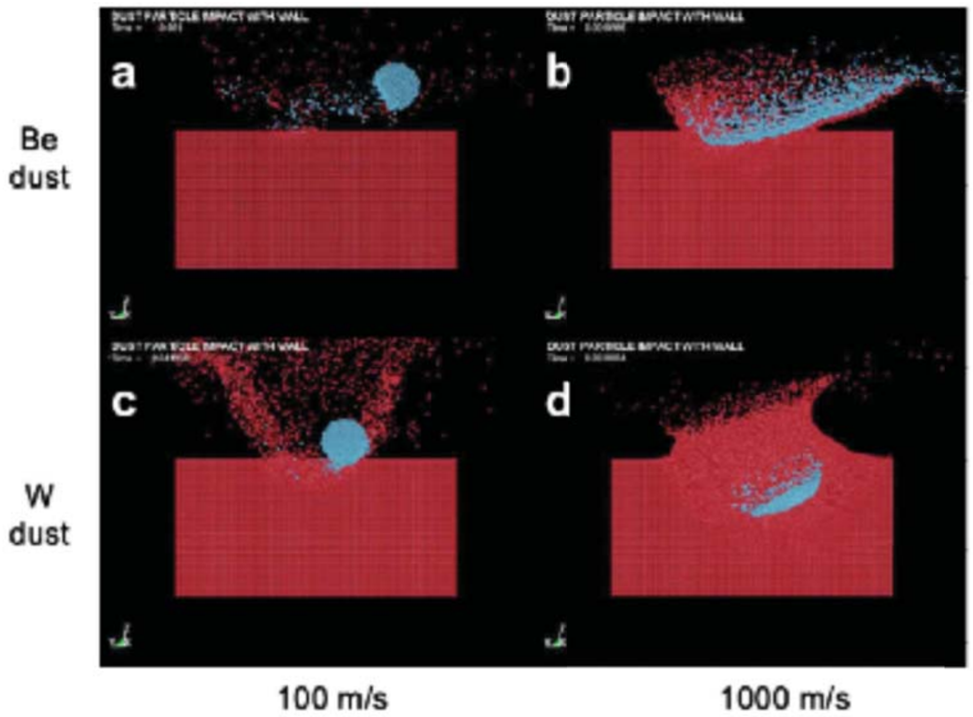
- This estimates suggest that "strange" spiral motion of the grains, occasionally observed with fast cameras, is, probably, caused by the impact of "rocket" force on compound grains

Theoretical issues of dust in fusion
Dust-wall collisions

- Dust-wall collisions have two profound effects: i) they cause wall erosion and may even (under some conditions) produce dust avalanche, and ii) they slow down the grains and may also result in grain destruction
- There is very limited number of experimental measurements on dust-wall interactions and practically nothing for the parameter range and materials interesting for ITER, e.g. tungsten, carbon, and beryllium
- Therefore, the simulations with code LS-DYNA were used to estimate the restitution coefficients ε (the ratio of velocities after and before collision)

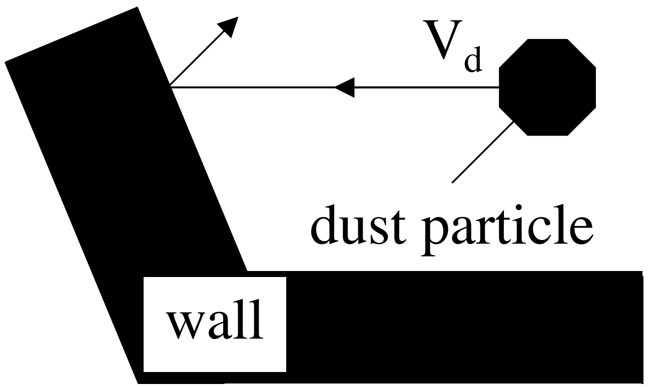
Theoretical issues of dust in fusion
Dust-wall collisions (con-d)

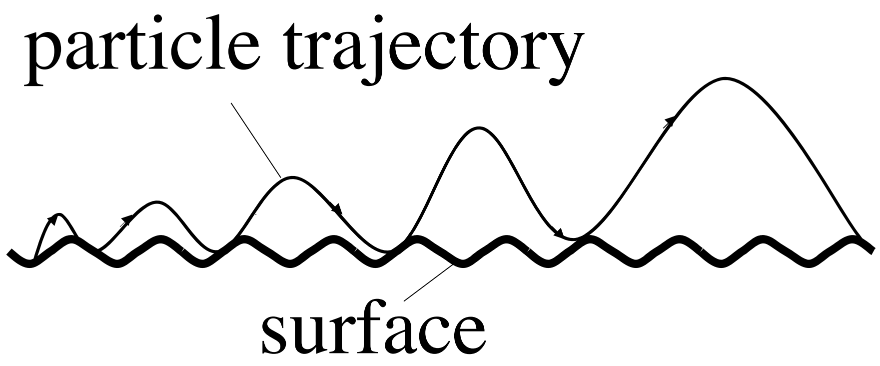
- It was found that for beryllium dust in beryllium wall $\varepsilon_{\perp}$~0.3 and $\varepsilon_{\parallel}$ is close to unity (for the velocity range up to few 100 m/s)
- At low speeds ~100 m/s neither beryllium nor tungsten dust cause significant damage to beryllium wall
- At high speed ~1 km/s beryllium dust is completely destroyed and tungsten dust causes significant damage to the wall



Theoretical issues of dust in fusion
Main features of dust dynamics

- As we found, in order to escape from potential well through recycling region dust should have perpendicular velocity >10 m/s
- Dust can gain such velocity due to an interplay of continuous acceleration by friction force along the wall (mainly in toroidal direction) and wall corrugation, which couple dust motion along and perpendicular to the wall

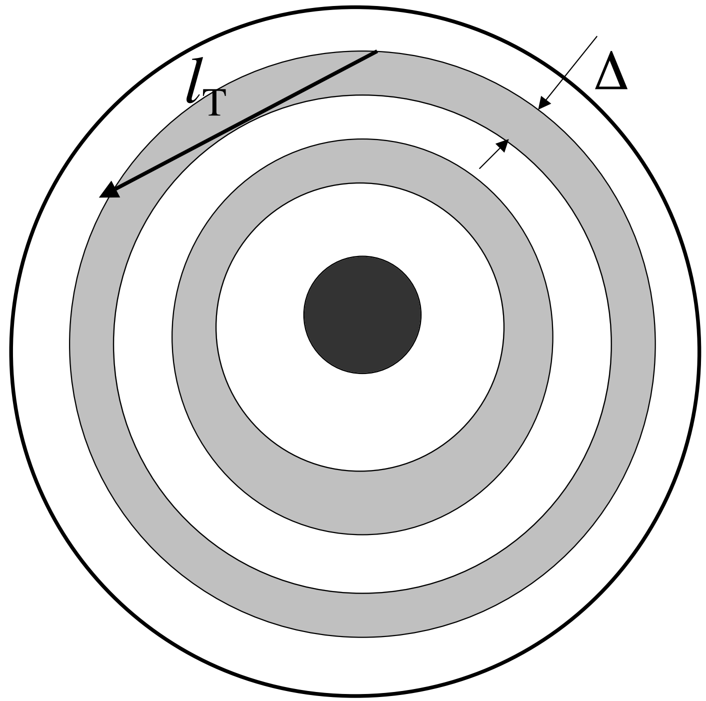




Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

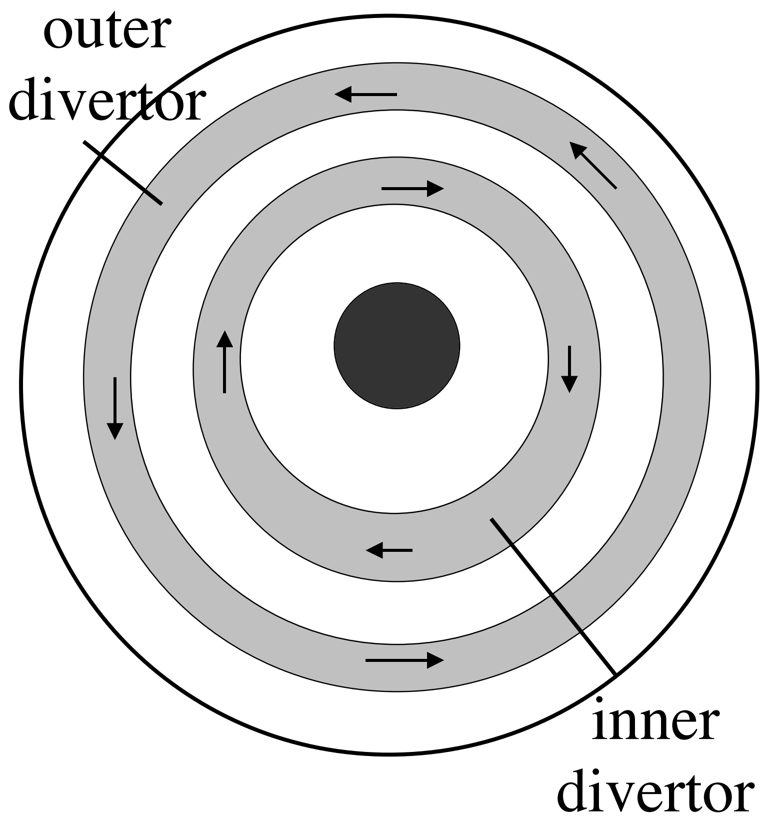
- However, due to effect of toroidal geometry, grain only can be dragged along the target in high recycling region the distance $\ell_T \sim \sqrt{2\Delta R} \sim 30\mathrm{cm}$ and then with total speed ~ few 100 m/s go to side-wall

- Therefore, in high recycling region grains with low initial speed stay near divertor targets for a long time moving in toroidal direction



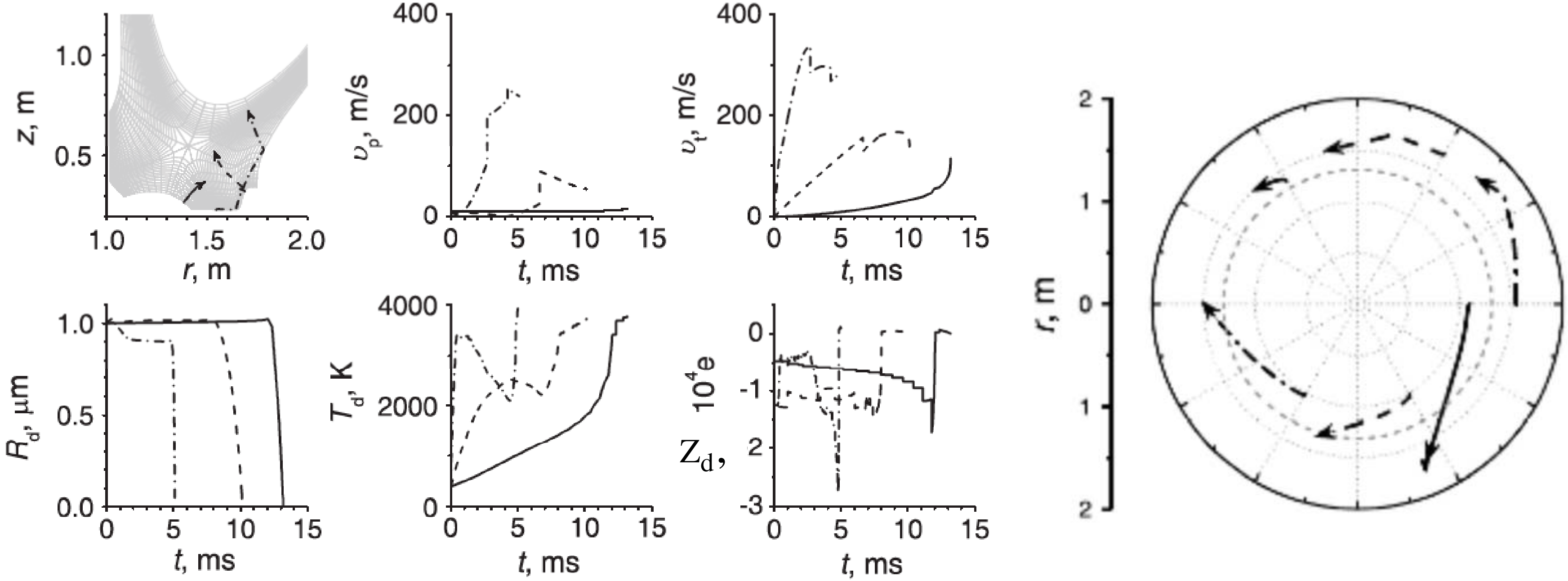
Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

- Moreover, due to helical structure of magnetic field, toroidal components of plasma flow in high recyling regions in inner and outer divertors are opposite, which causes opposite toroidal motion of dust grains in inner and outer divertors (Krasheninnikov 2005)
- This explains fast camera data from MAST (recall MAST movie!)

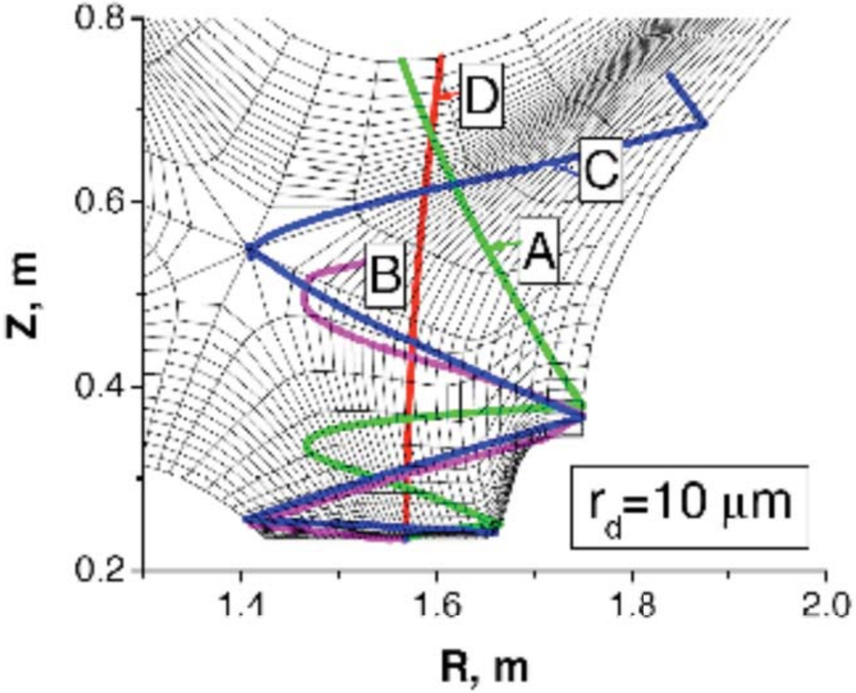


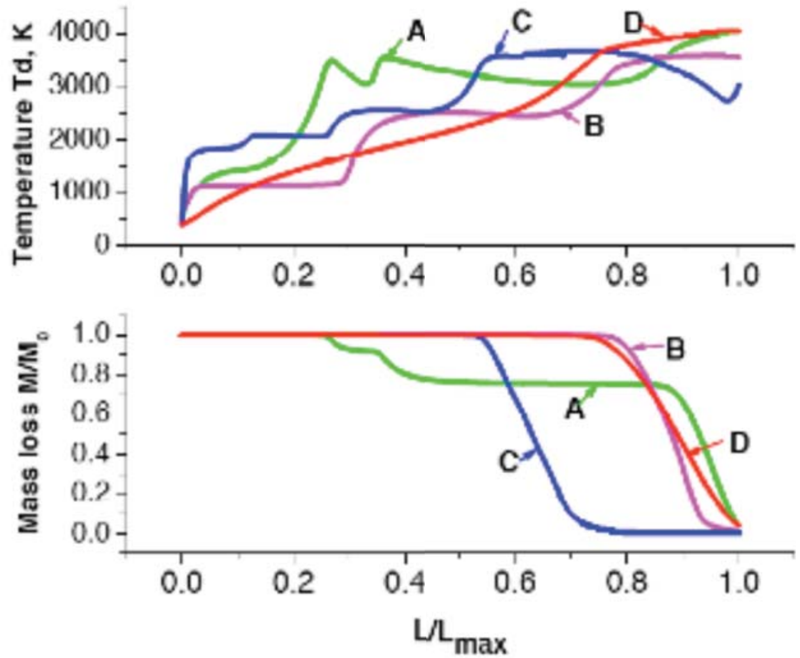
Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

- Dynamics of the grains in realistic toroidal geometry and relevant plasma parameters can only be studies with numerical codes (e.g. DUSTT)
- DUSTT code accounts for grain charging, energy and mass balances, and calculate forces acting on a grain
- Main analytic conclusions are confirmed by DUSTT



Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

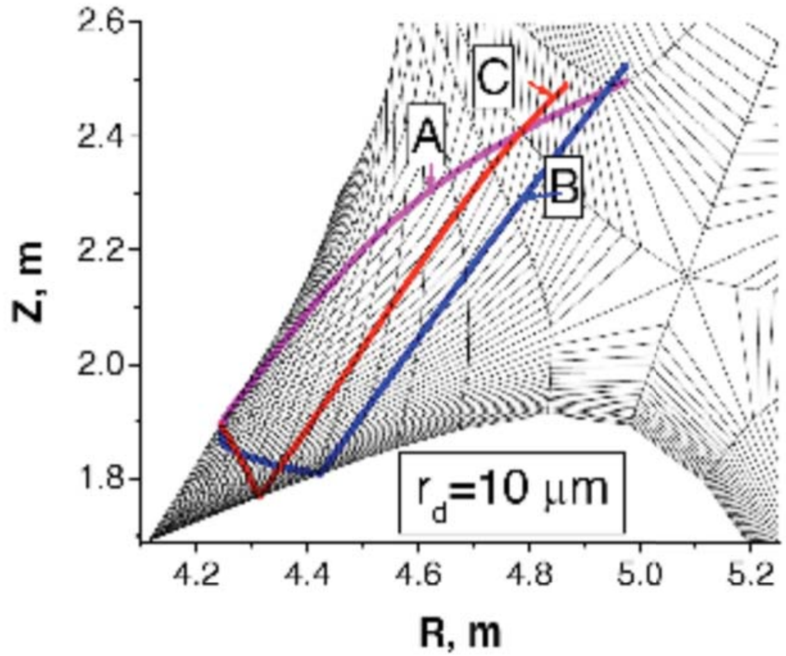


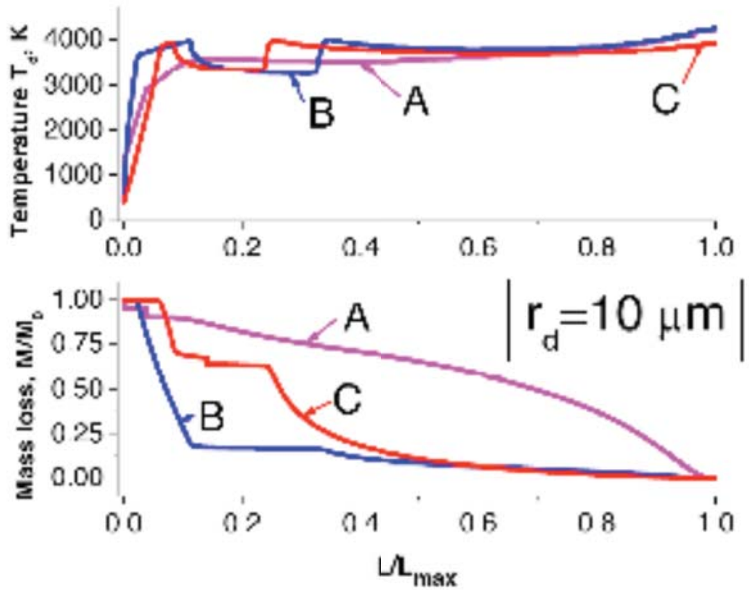


In DIII-D grains can penetrate through separatrix

$V_d(t=0)$=0.1 (A), 1 (B), 10 (C), and 100 (D) m/s

Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

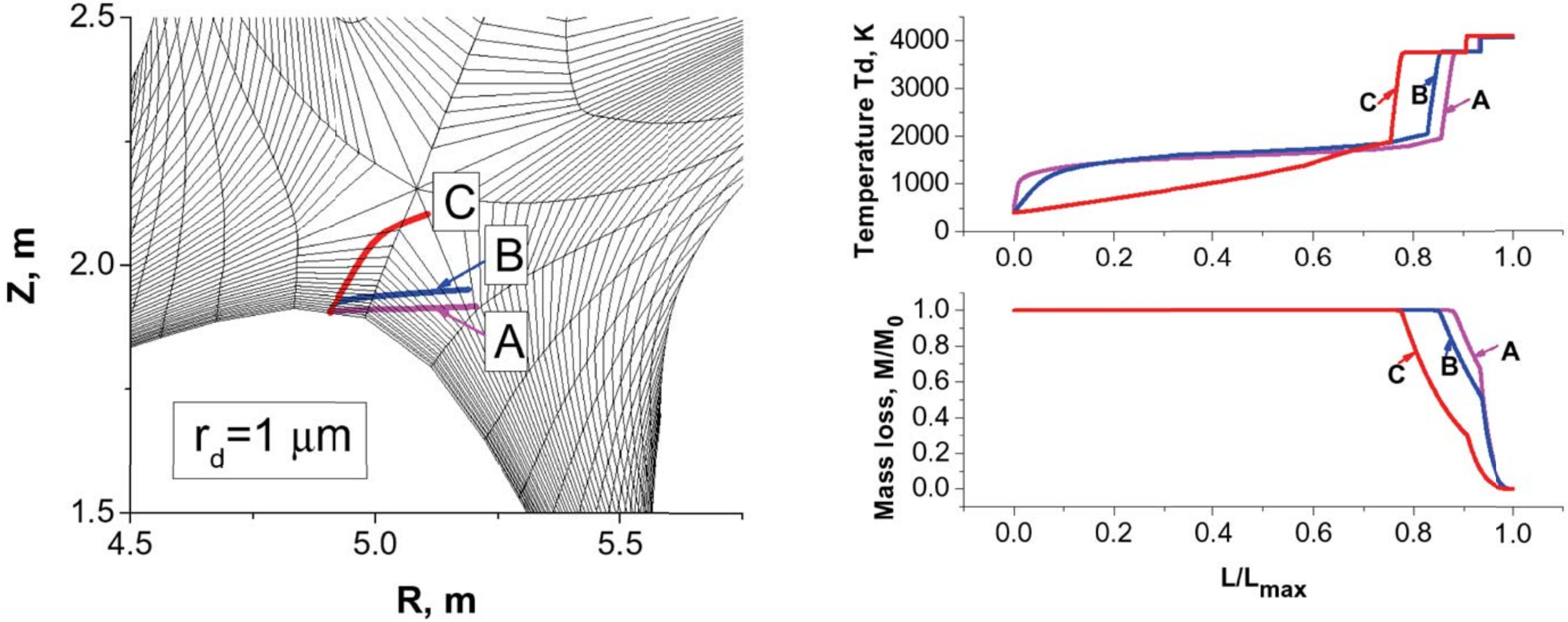




In ITER grains can penetrate to separatrix

$V_d(t=0)$=1 (A), 10 (B), and 100 (C) m/s

Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

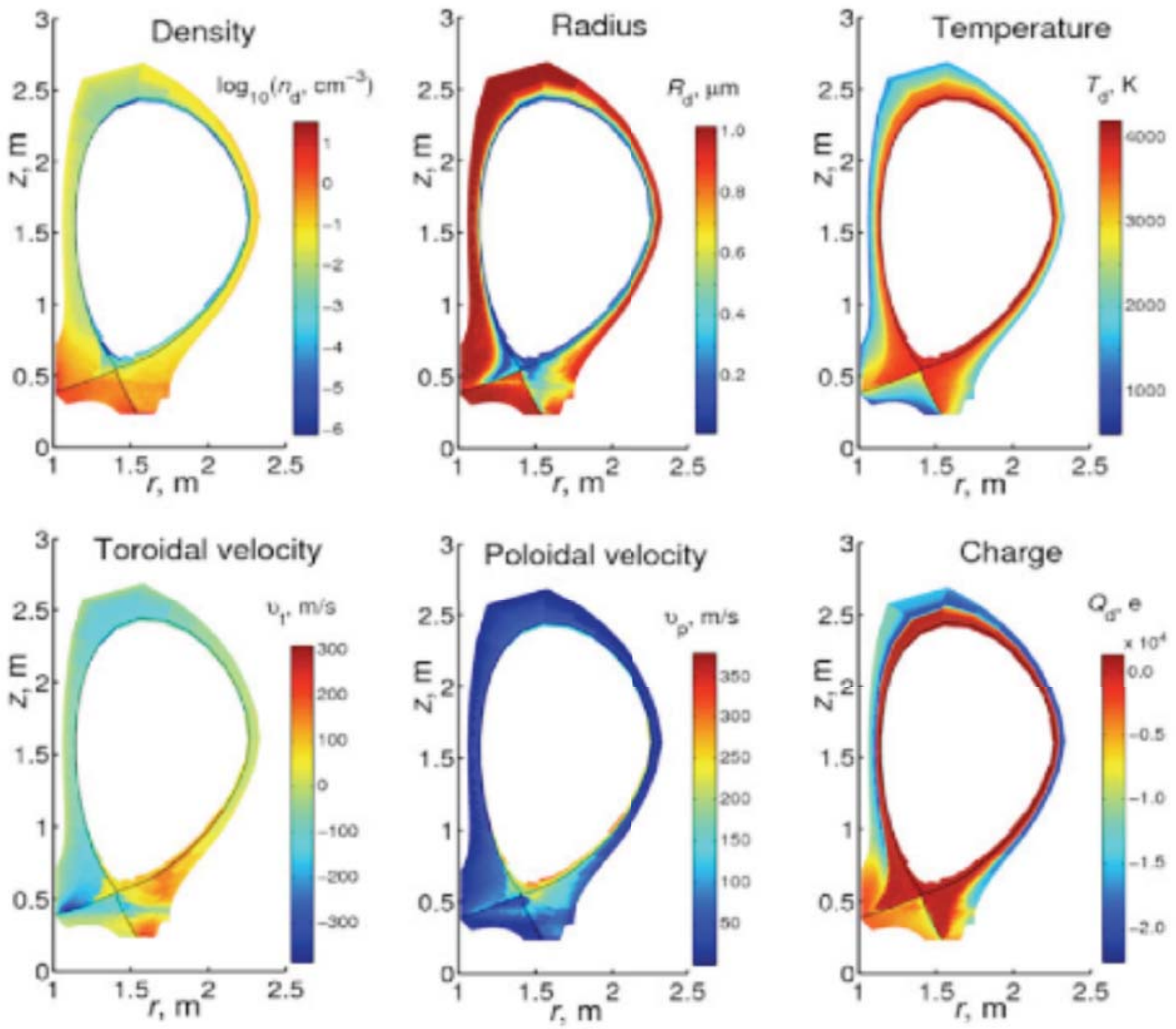


Grains launched from private region can easier reach separatrix

$V_d(t=0)$=1 (A), 10 (B), and 100 (C) m/s

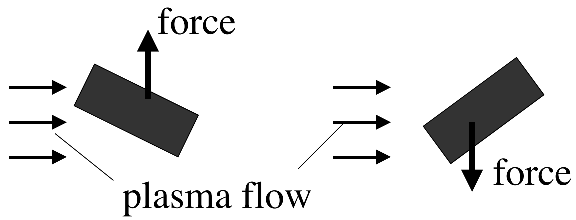
Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

- DUSTT code can also operate in statistical mode



Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

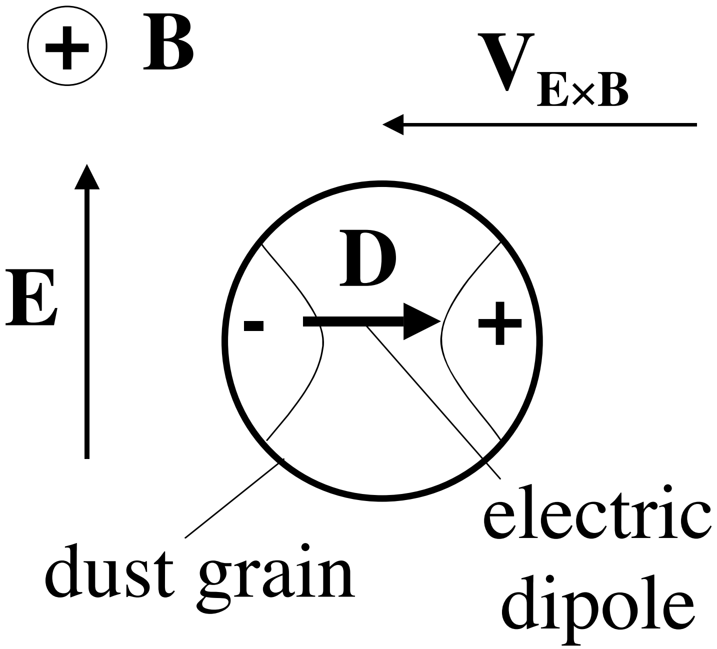
- Internal dynamics (e.g. spinning) of the grain may be responsible for the grain break up, which is occasionally seem with cameras, or in the dithering of grain trajectory (Roquemore 2009) caused by the change of orientation of the irregular grain (Krasheninnikov & Mendis 2010)



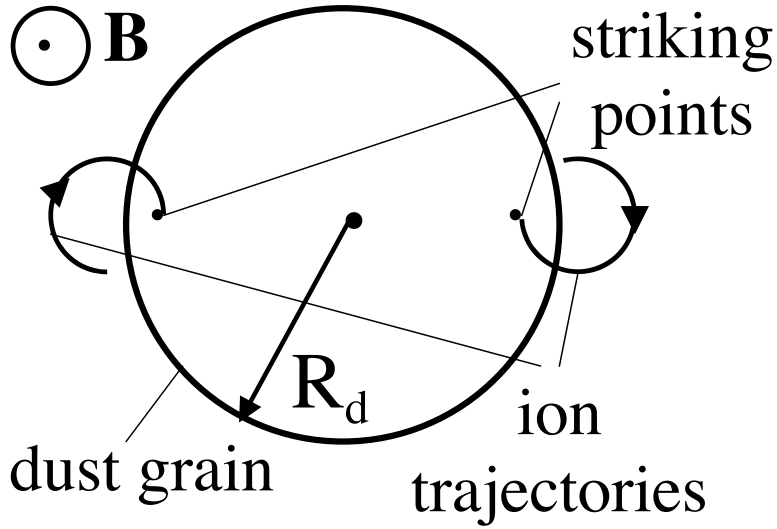
- The spinning of dust particles was observed in different environments from laboratory to astrophysical plasmas
- In dusty plasma experiments spinning can be associated with: (i) plasma flow shear (Sato 2005); (ii) irregular dust shape & plasma flow (Tsytovich 2003); (iii) synergy of sheath electric field, plasma flow, and dust electric dipole induced by plasma flow (Hutchinson 2004)

Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

- In the presence of a strong magnetic field, new mechanisms of dust spinning become available (Krasheninnikov & Shukla 2006, Krasheninnikov 2007)



can be driven by plasma turbulence!



also **j×B** force contributes!

Theoretical issues of dust in fusion
Main features of dust dynamics (con-d)

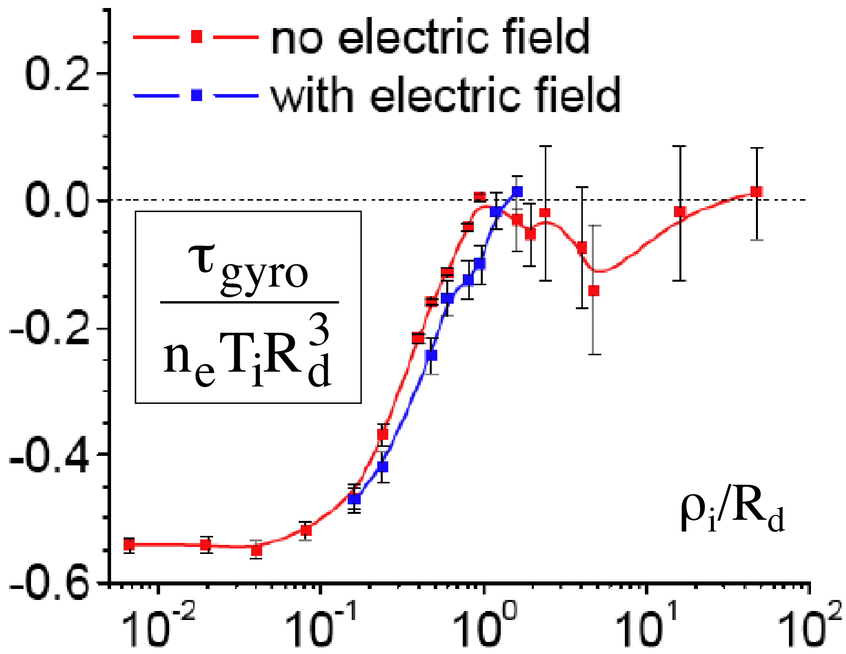
- Corresponding torques and the limitations for dust angular velocity Ω:

$$\tau_{gyro}(R_d << \rho_s) \sim nTR_d^3(R_d/\rho_s)$$

$$\Omega_{ss}^{(gyro)} \sim \omega_{Bi}$$

$$\tau_{\vec{E}\times\vec{B}} \sim \pi\langle E\rangle^2 R_d^2 \rho_s$$

$$\Omega_{ss}^{(\vec{E}\times\vec{B})} < \omega_{Bi}$$



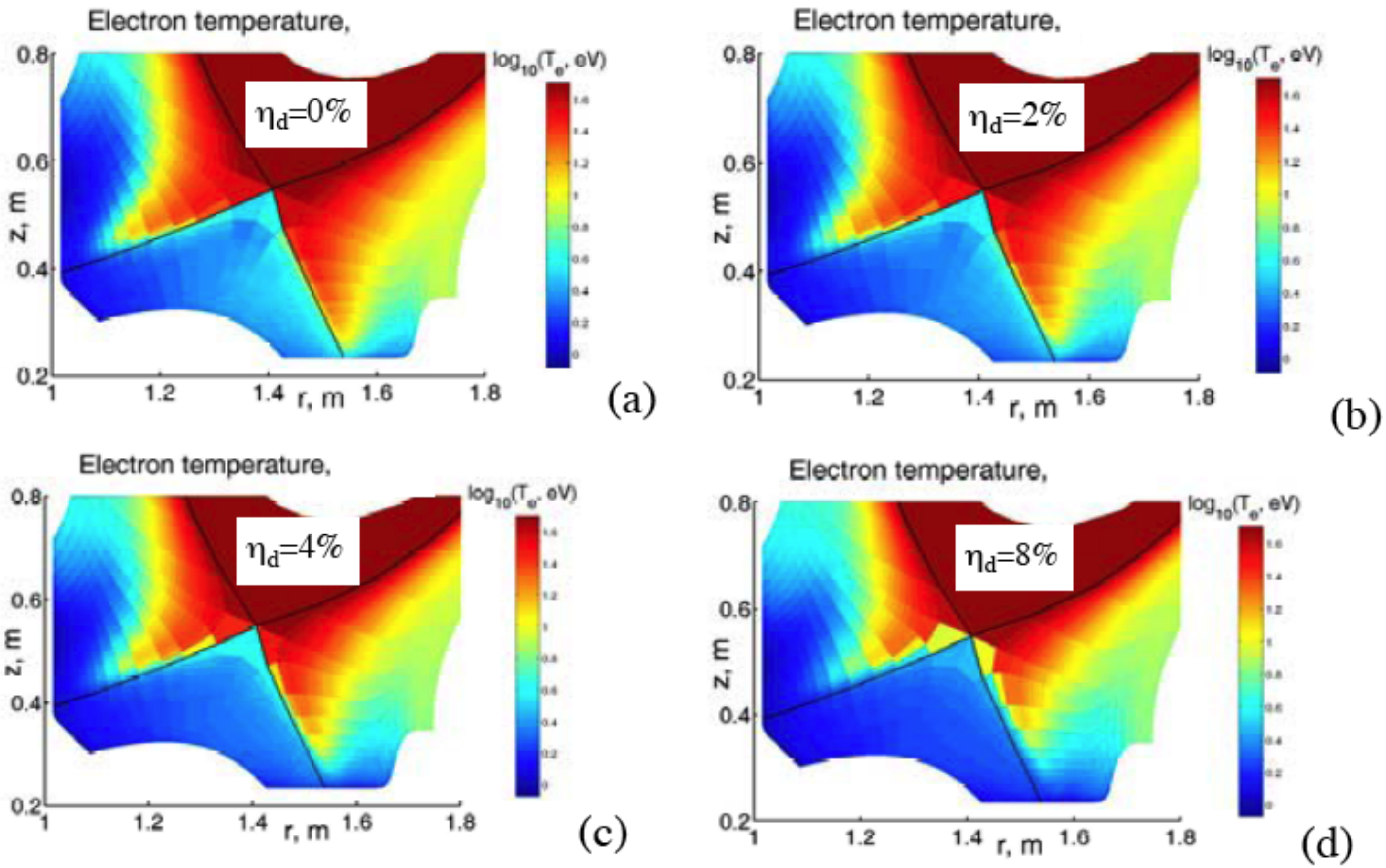
Numerical simulation of “gyro” mechanism with DiMag PIC code supports analytics (Smirnov 2007)

Theoretical issues of dust in fusion
Dust impact on plasma performance

- Self-consistent modeling of dust on edge plasma performance was simulated with UEDGE-DUSTT package (Krasheninnikov 2006)

significant effects already for conversion efficiency

$\eta_d = 2\%$



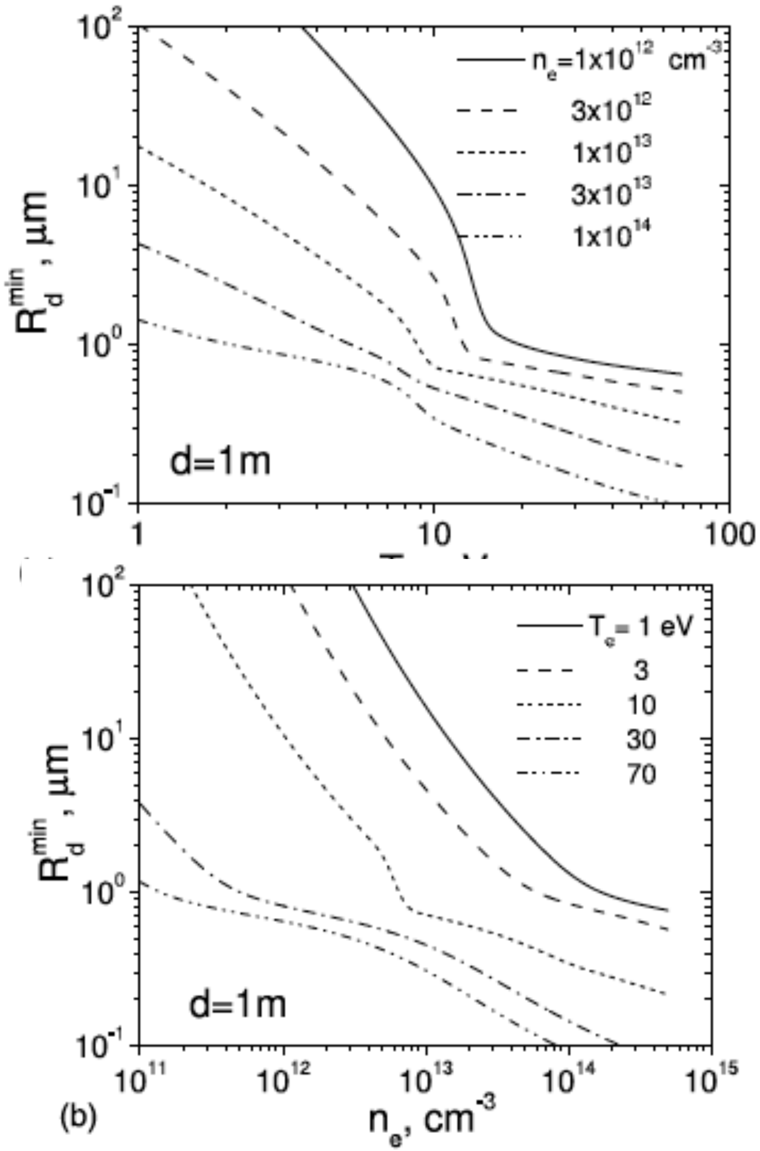
Theoretical issues of dust in fusion Theoretical issues of dust diagnostics

- Theoretical interpretation of experimental data (e.g. from laser scattering and imaging) can provide additional and important information on dust properties (e.g. dust size, temperature, density of dust material, etc.)
- Laser scattering:
  - Laser too powerful and can evaporate grain
  - Rayleigh theory should be replaced with Mie one because laser wave length is comparable with R_d
- Improvements in data interpretations resulted in doubling of averaged grain size measured with Thomson (Smirnov 2007)

Theoretical issues of dust in fusion
Theoretical issues of dust diagnostics

- Fast imaging:
  - What size of grains which can be visible with cameras?
  - What do we see: grain thermal radiation or plume radiation?
- Theoretical analysis shows (Smirnov 2009) that:
  - plume radiation dominates in hot plasma close to separatrix and grain radiation in far SOL
  - at distance d=1 m carbon grain is visible for

$$R_d > R_d^{min}(n,T)$$



Theoretical issues of dust in fusion Discussions

- In last few years substantial progress was achieved in understanding the physics of dust in fusion devices
- Significant amount of new experimental data on dust dynamics and statistics in tokamak plasma was obtained and analyzed with theoretical models
- New codes capable of modeling of dust charging, dynamics, energy and mass balances for tokamak geometry and fusion plasma parameters were developed in rather short time (thanks to “dusty” guys for developing basic theory!).
- Many of theoretical predictions and estimates of dust behavior in fusion devices in ball park are confirmed by experiments (e.g. grain speed, directions of grain motion in inner and outer divertors, grain densities in the SOL and divertor, etc.)
- Theory became an important ingredient of the interpretation of experimental data (e.g. grain distribution over effective radius, observations of dust with fast cameras, etc.)

Theoretical issues of dust in fusion Discussions (con-d)

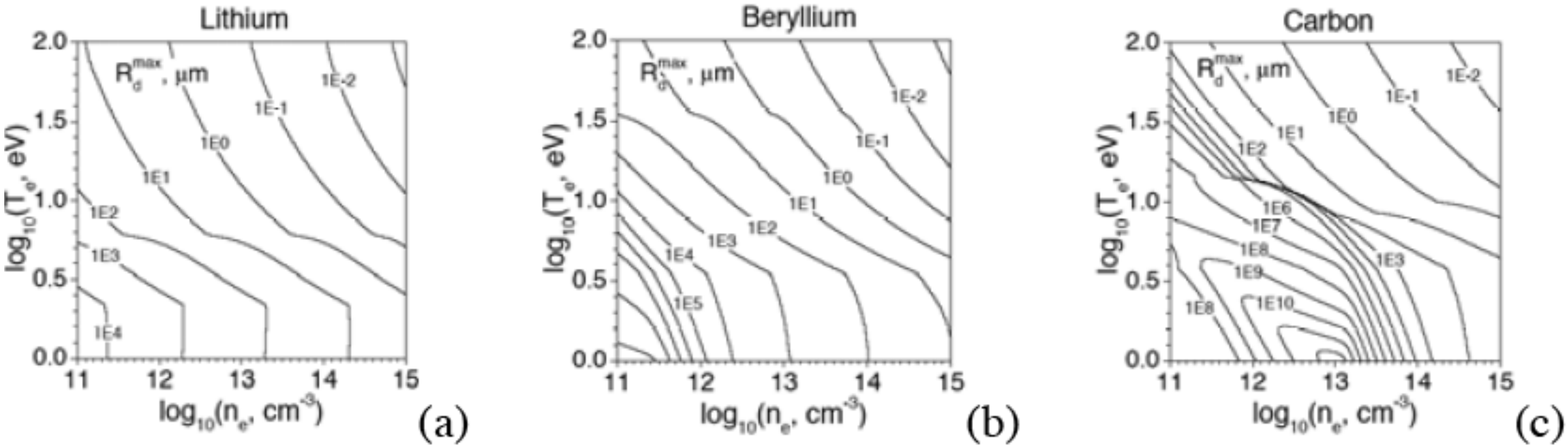
- However, still there substantial gaps in our understanding of the physics of dust in fusion plasmas
- Today we unable to predict dust generation rate from first principals (experiment suggests ~10% out of net erosion rate)
  - Largely this is due to more global issue associated with lack of tractable models of plasma-wall interactions, which would account for the change of both morphology and constituency of the plasma facing surfaces
- Description of plasma-grain interactions is solely based on the models build under assumptions of perfectly spherical grains and no magnetic field effects
  - But, synergy of internal dynamics of non-spherical and plasma-grain interactions can sygnificantly alter grain dynamics

Theoretical issues of dust in fusion Discussions (con-d)

- Models, used to study dust grain-plasma interactions in fusion plasmas, neglect the effects of vapor, which is always present in rather hot and dense edge plasmas
  - However, when the vapor density and/or the amount of ionized alter the grain-plasma interactions
  - Somewhat similar processes occur during pellet injection in fusion impurity atoms become large enough they can plasma (e.g. see Milora 1995 and the references therein)

Theoretical issues of dust in fusion Discussions (con-d)

- Recently it was shown (Krasheninnikov 2009) that vapor effects can only be ignored for relatively small grains $R_d < R_d^{max}(n,T)$



What to do with larger grains!?

Theoretical issues of dust in fusion Discussions (con-d)

- Analyzing an impact of dust on edge plasma parameters we are using statistical approach for the contribution of each grain into plasma pollution assuming that toroidal symmetry of plasma parameters still holds
- Meanwhile:
  - dust injection into plasma is rather rare event
  - ablation of rather large grains can significantly break toroidal symmetry due to strong impact on plasma parameters in the vicinity of the grain
- Neither applicability limits of our approach nor alternative way to proceed with self-consistent dust-edge plasma interactions are known yet

Conclusions

We still have a lot of things to do!

Conclusions (con-d)

Acknowledgements

We acknowledge the discussions of different issues related to the physics of dust in fusion plasmas with N. Ashikawa, B. D. Bray, G. F. Counsell, B. Lipschultz, A. M. Litnovsky, R. Maqueda, S. Masuzaki, N. Ohno, C. S. Pitcher, R. A. Pitts, T. D. Rognlien, A. L. Roquemore, M. Rosenberg, V. A. Rozhanskij, D. L. Rudakov, P. K. Shukla, C. H. Skinner, T. K. Soboleva, S. Takamura, J. L. Terry, J. H. Yu, W. P. West. This work is performed in part under auspices of USDOE by the grant DE-FG02-04ER54739 at UCSD