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Dust in Tokamak Plasmas

S. Krasheninnikov
University of California, San Diego, U.S.A.

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Dust in tokamak plasmas

Sergei Krasheninnikov

University of California, San Diego, USA

With contributions from:

A. Yu. Pigarov[1], T. K. Soboleva[2], W. P. West[3], and D. L. Rudakov[1,3]

[1]University of California, San Diego, USA
[2]UNAM, Mexico D.F., Mexico and Kurchatov Institute, Moscow, Russia
[3]General Atomics, USA

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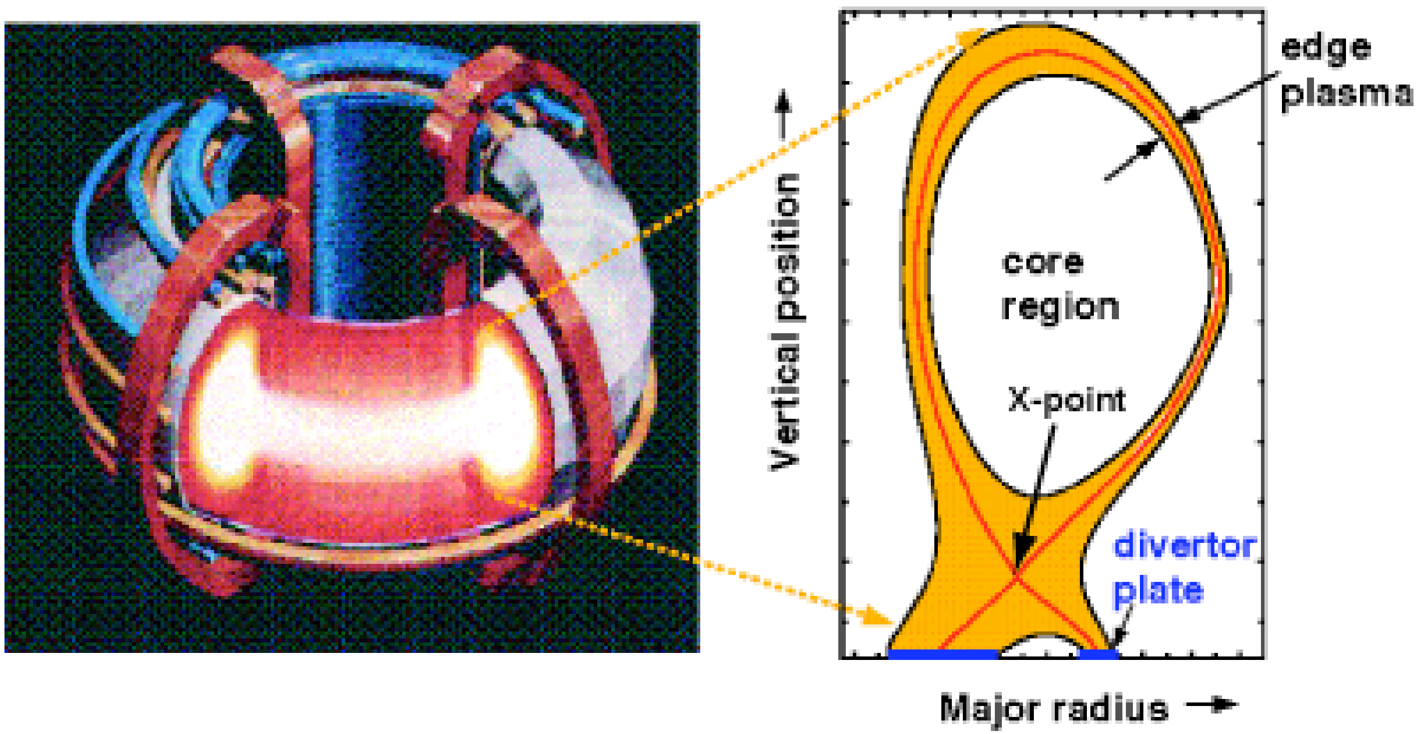
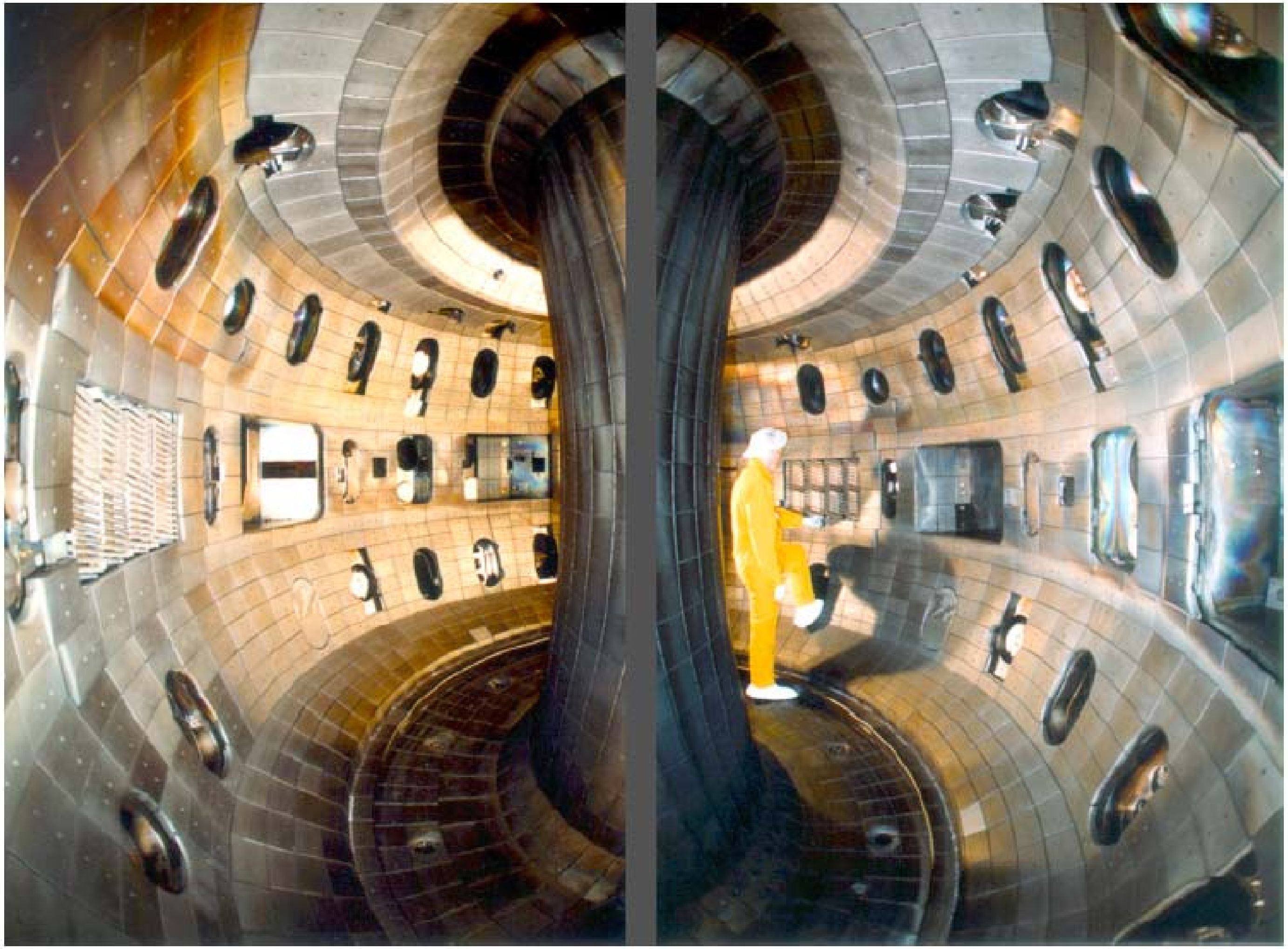
I. Introduction

- Significant amount of dust particles is observed in the chambers of magnetic fusion devices (in particular tokamaks)

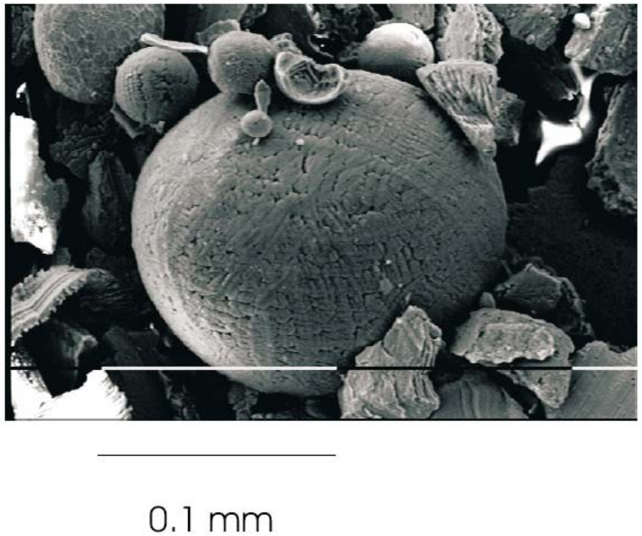
Tokamak magnetic fusion device

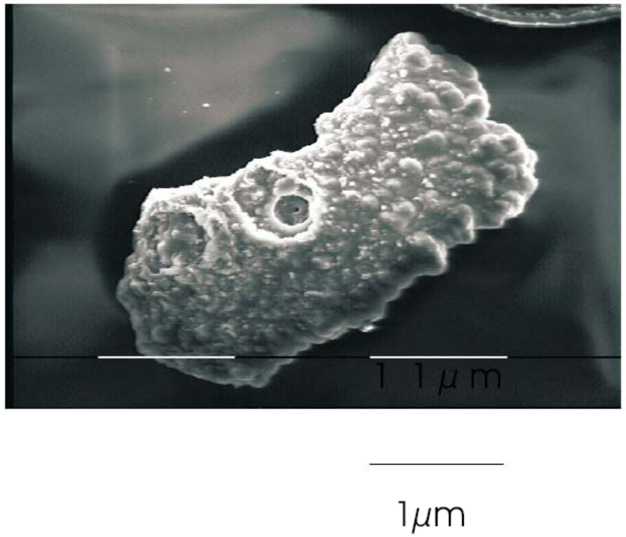
Simulated edge-plasma region

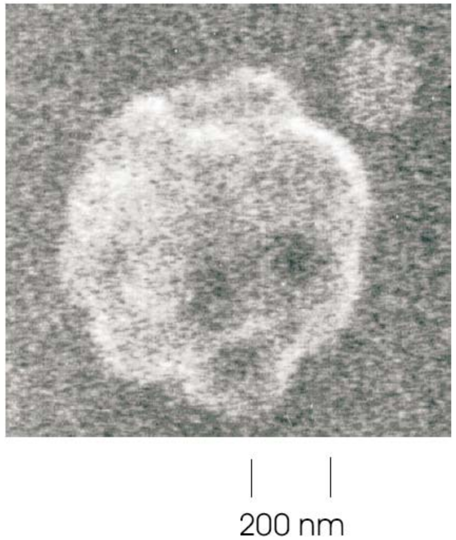




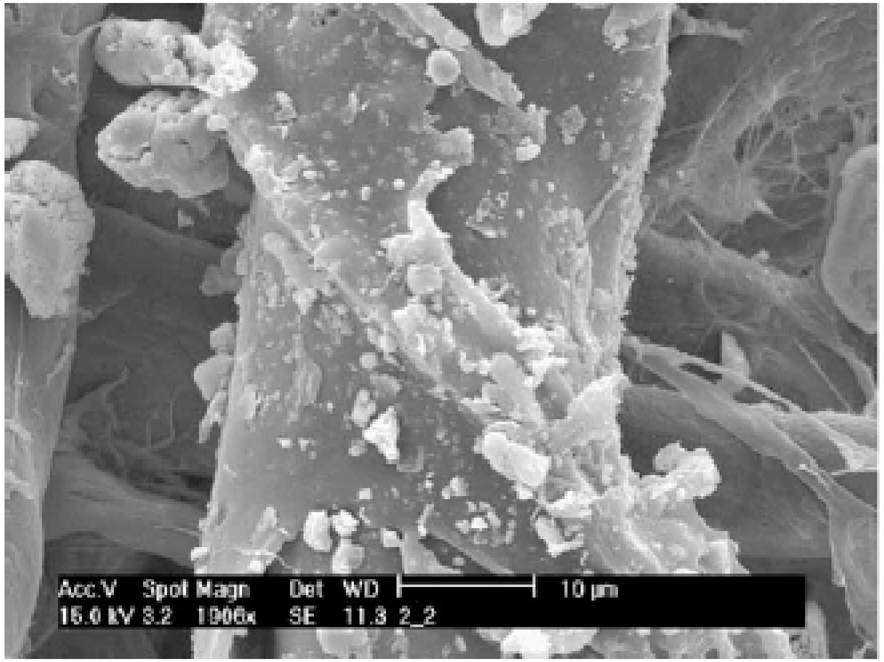
DIII-D tokamak

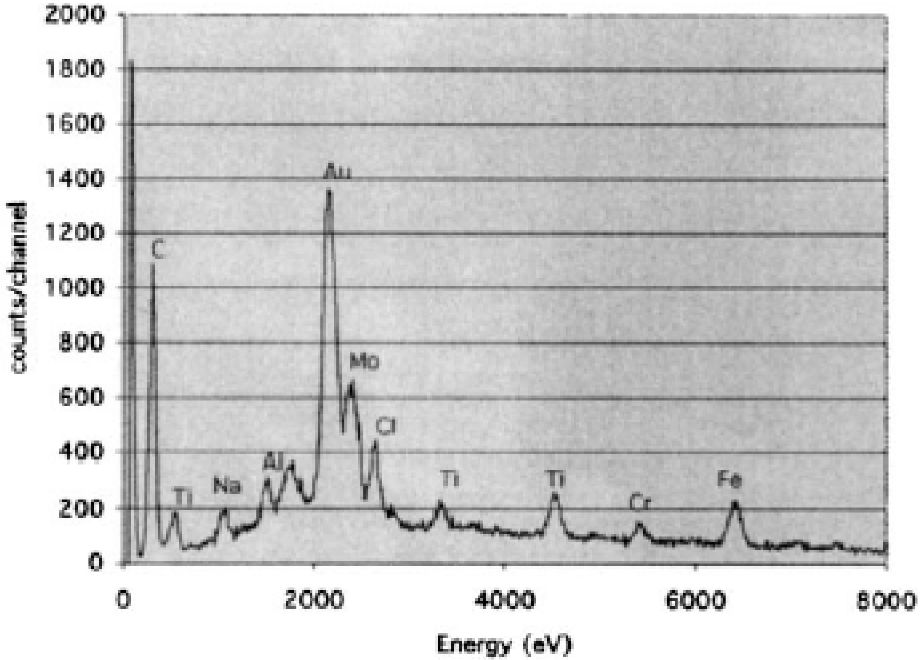




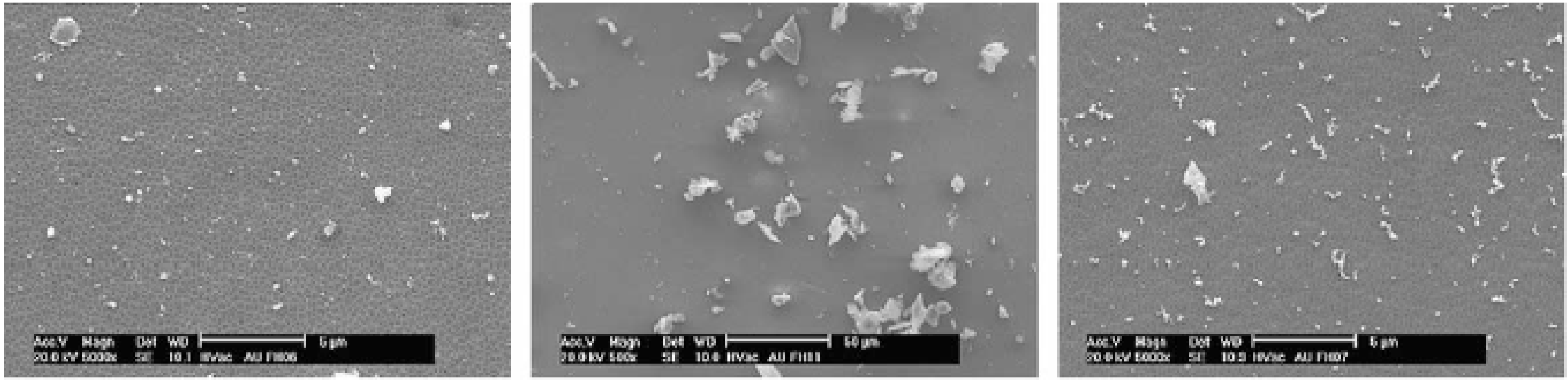


Winter, Plasma Phys. Contr. Fusion, 1998



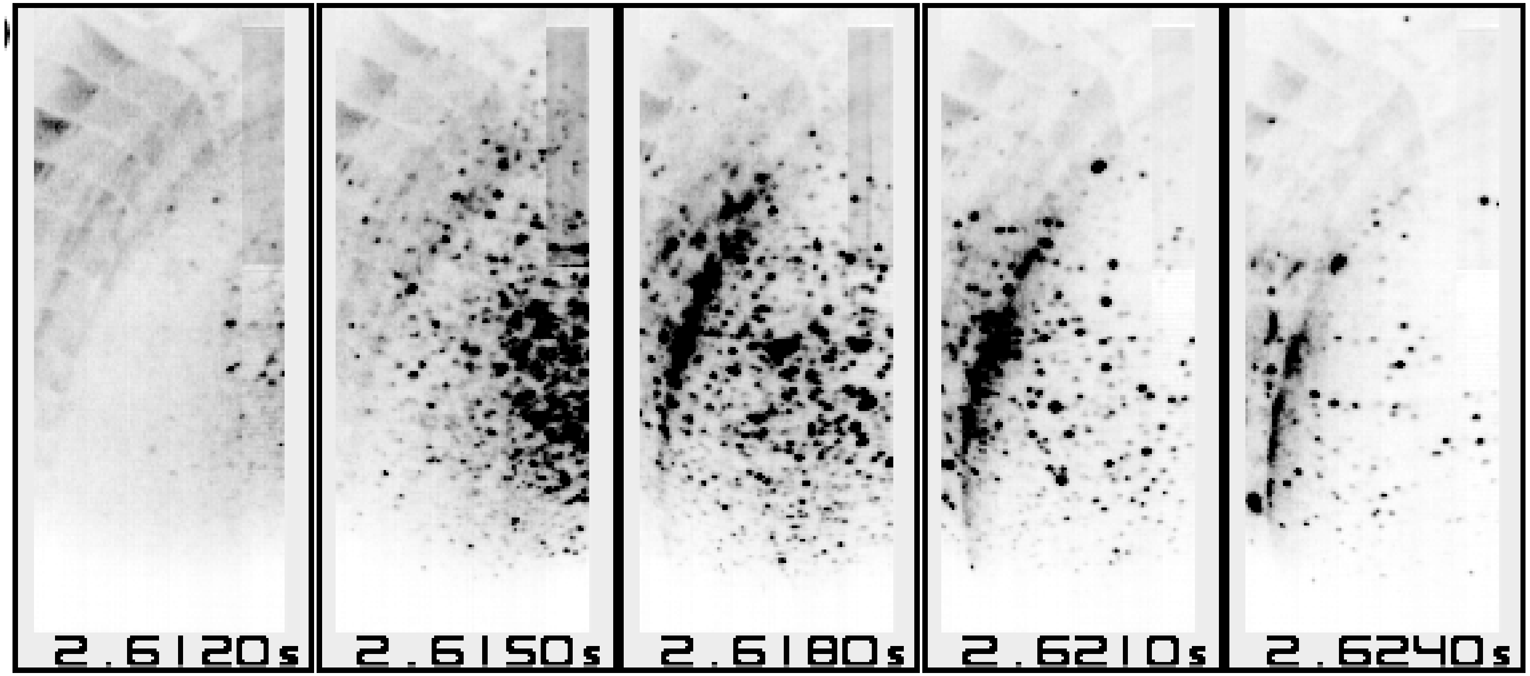


Carbon, steel and titanium particle collected from the LHD coil armor
(Sharpe et al., J. Nucl. Mater, 2003)



(a) lower (b) middle (c) upper

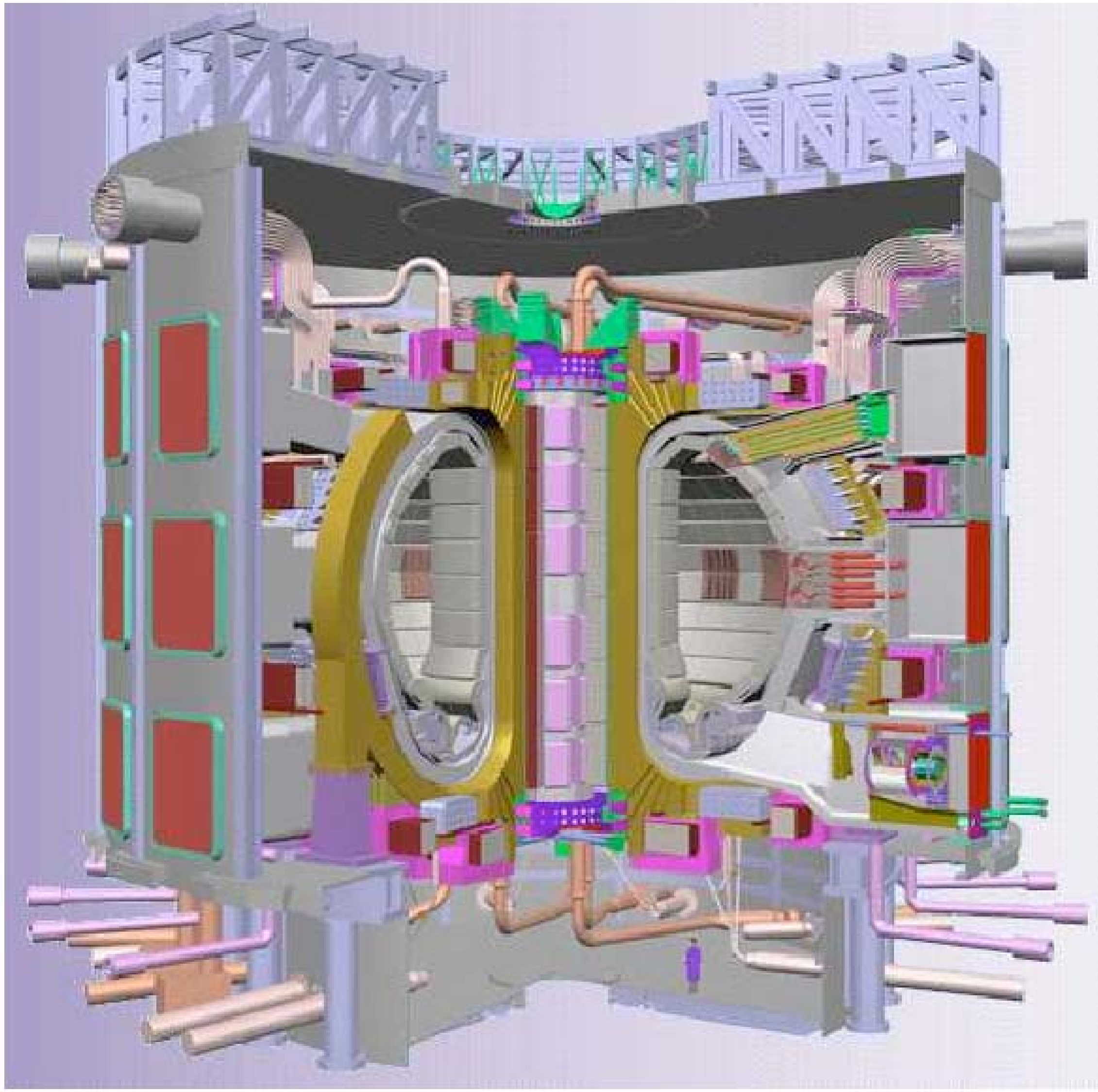
Dust particles collected from (a) lower, (b) middle, and (c) upper regions of Asdex-U (Sharpe et al., J. Nucl. Mater, 2003)



Flying debris after the disruption in the TFTR observed with fast camera

(Maqueda and Wurden, Nuclear Fusion, 1999)

- So far an impact of dust on the performance of current fusion devices is not clear
- But, in burning plasma experiments dust can contain toxic and radioactive materials and retain tritium

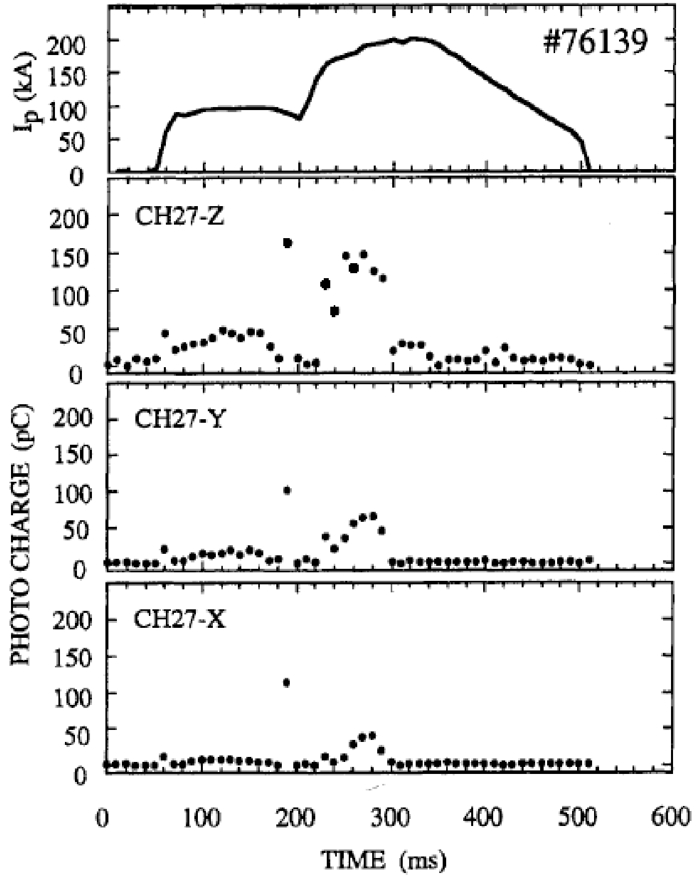


II. Active experiments with dust in tokamaks

II.a Active experiments with dust in JIPPT-IIU tokamak

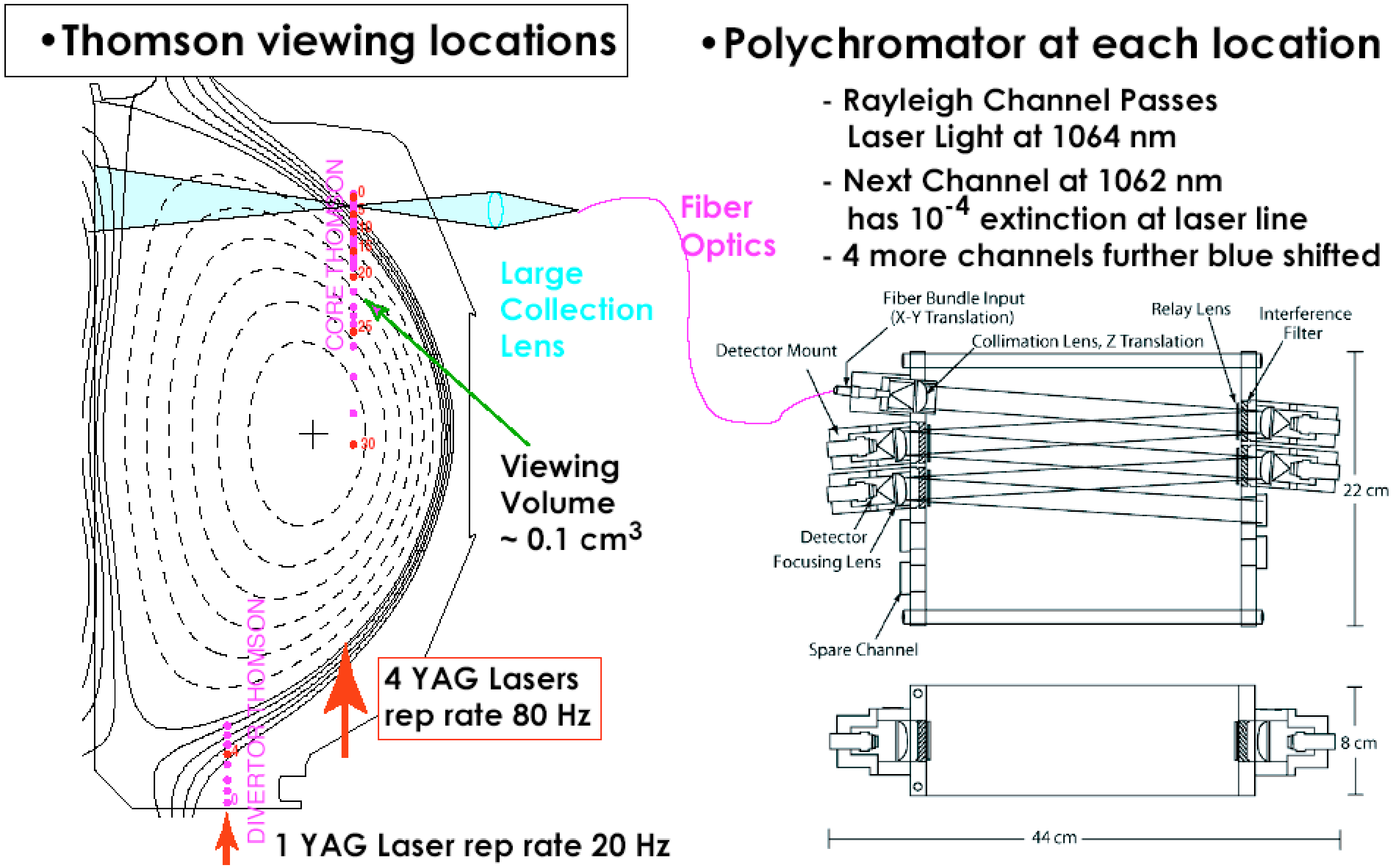
- Carbon dust particles (~2 μm), deliberately injected into JIPPT-IIU, have been detected with Thomson scattering only at low plasma density
- "*We speculate that the dust particles spread to a much more extended region than expected …*"

(Narihara et al., Nuclear Fusion, 1997)



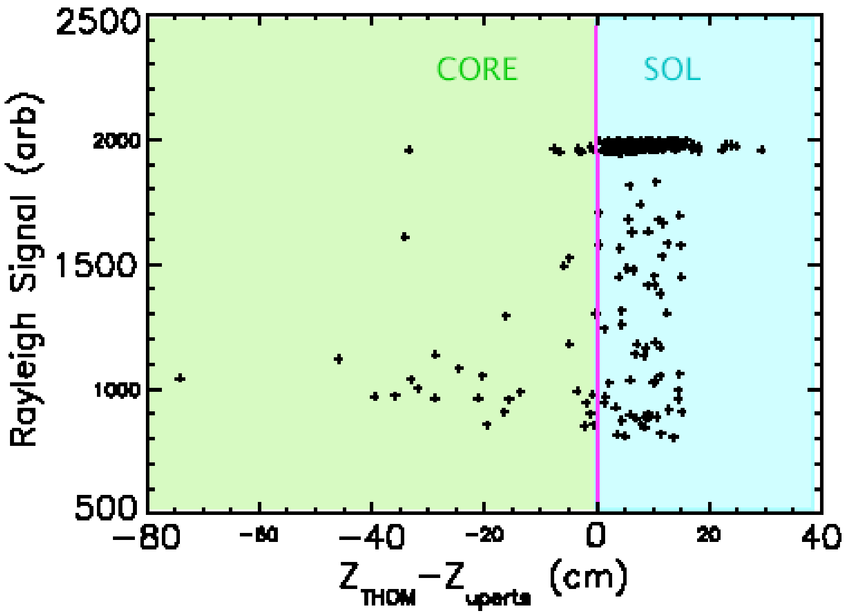
II.b Active experiments with dust in DIII-D tokamak

- Natural dust particles were also detected with Thomson scattering (Rayleigh channel) in D-IIID tokamak (West et al., WS in Napa, 2005)

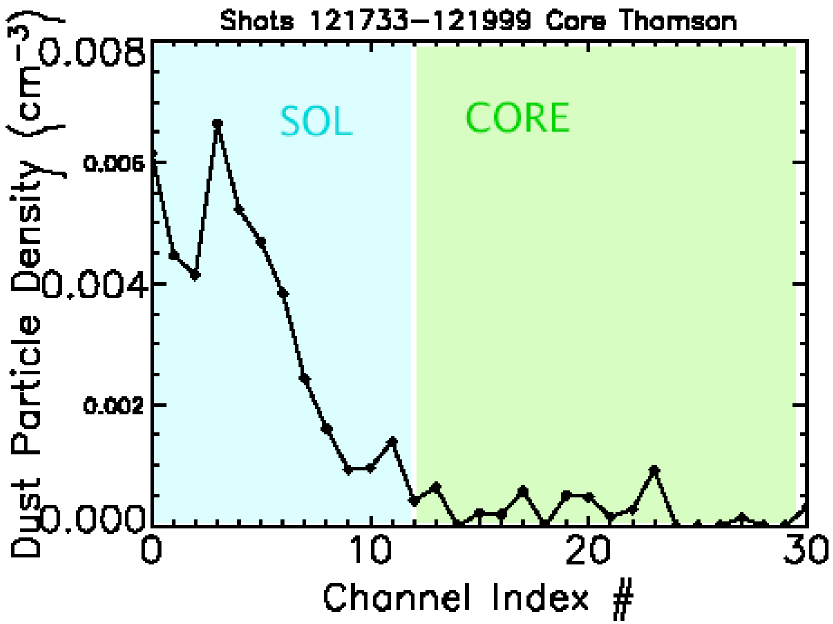


- Dust density distribution was inferred from scrape-off layer (SOL) and divertor Thomson data

Dust Frequent in SOL but
Rare in the Core

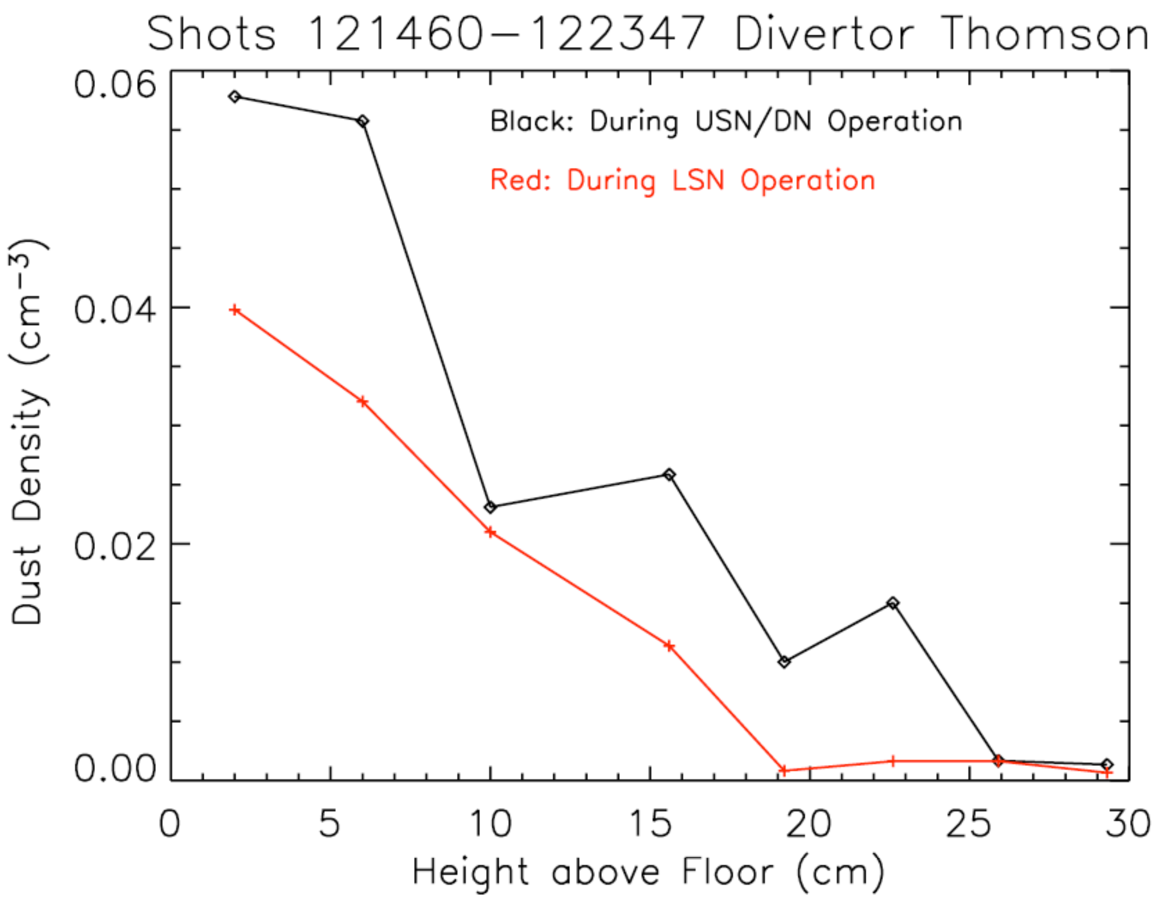


Particle Density vs
Thomson Channel Index

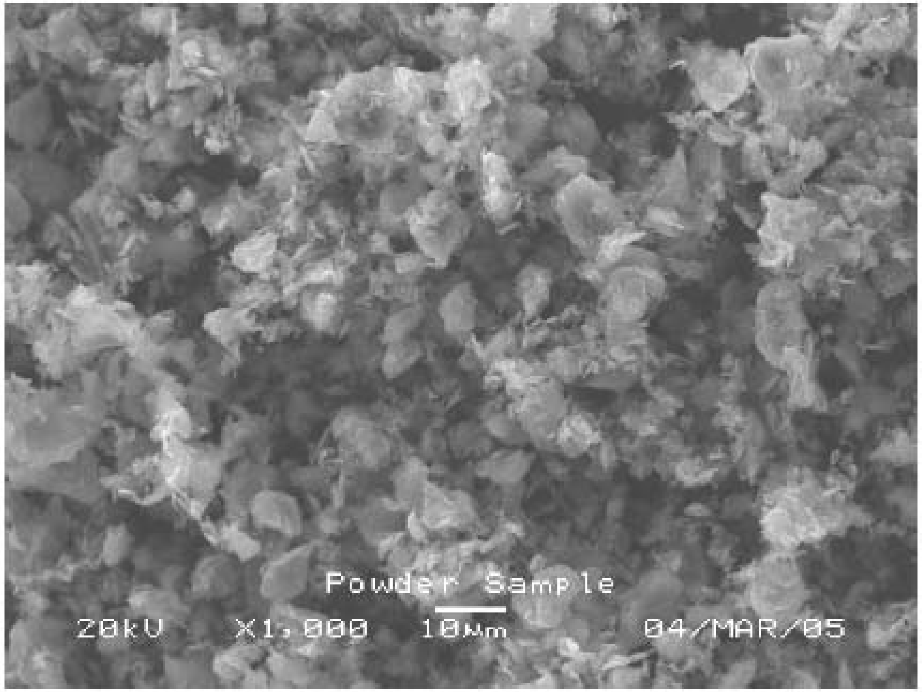


Time Averaged Dust density =
 # events/(viewing volume x # laser pulses)

- Dust density about factor 10 higher in lower divertor compared to upper scrape-off layer

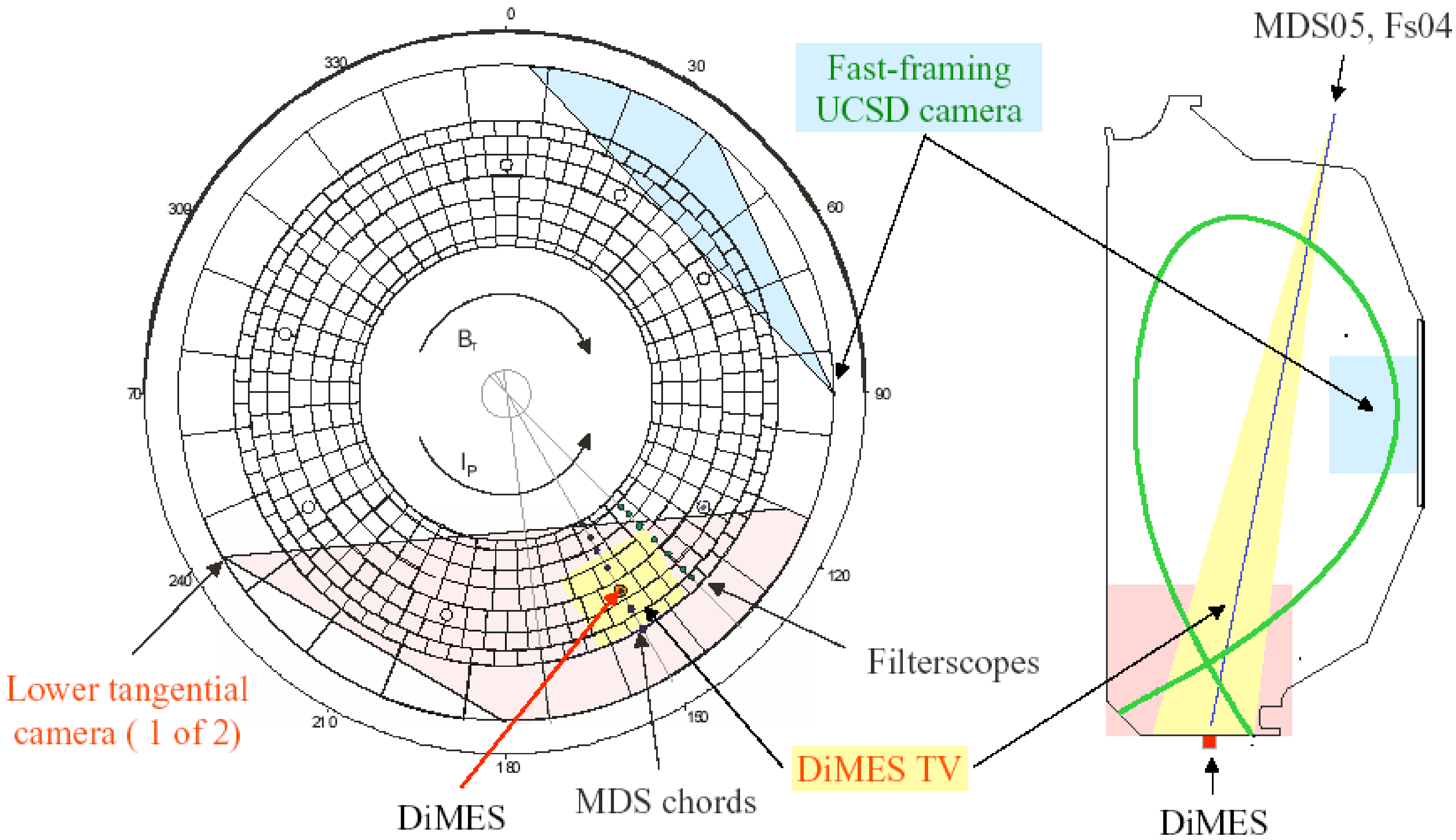


- Dust was also deliberately introduces into D-IIID plasma with the DiMES (removable holder) (Rudakov et al., WS in Napa, 2005)



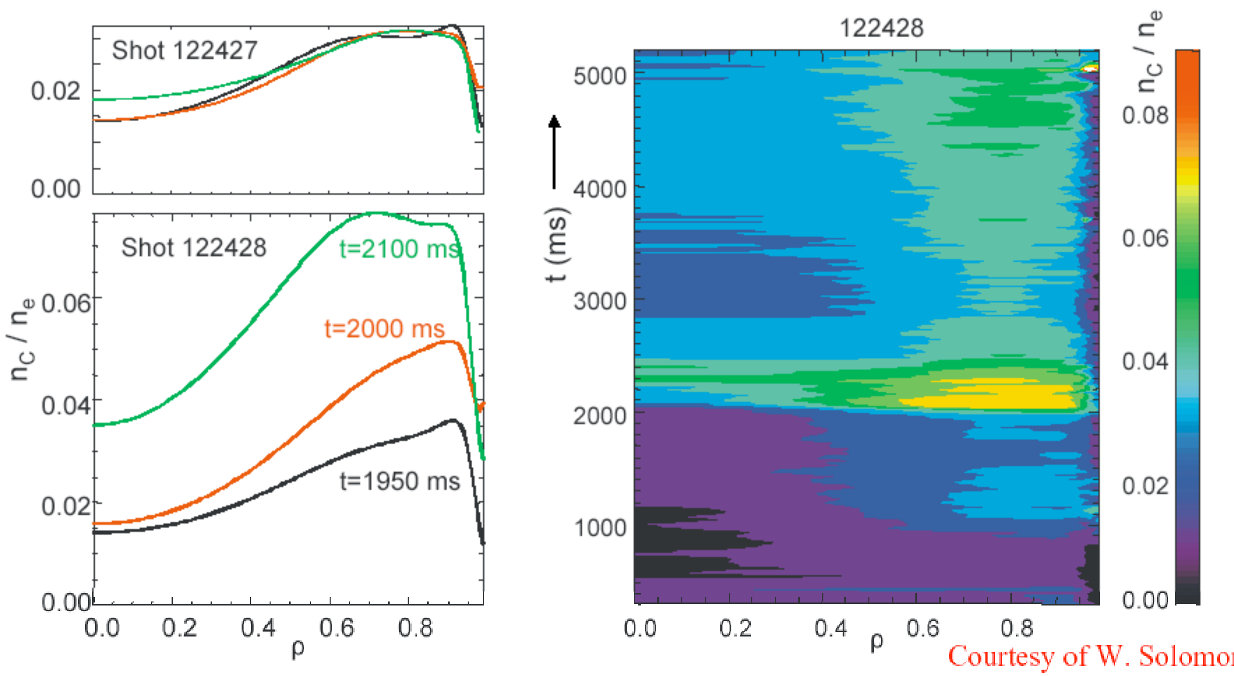
- About 25 mg of carbon 5-10 µm flakes were used in this experiment

- Diagnostic setup for the DiMES dust experiment



DiMES TV and one of tangential cameras were equipped with IR filters

- Spectroscopic data show huge increment in thermal continuum (×50), CI radiation, as well as in core carbon content (×3) after outer strike point passes over DiMES around 2000 ms



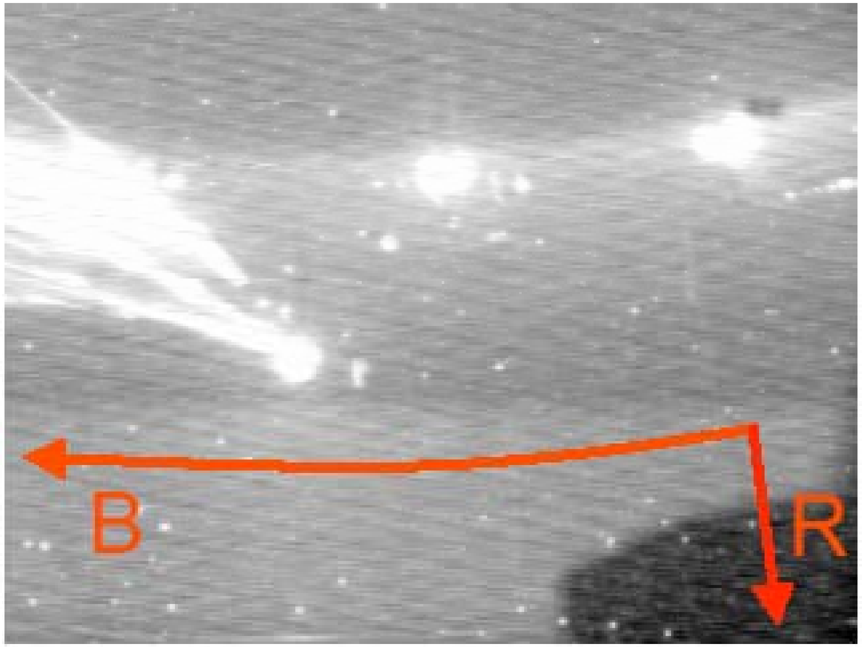
Courtesy of W. Solomon

- About 1-2% of the dust carbon made it into the core

- Dust particles move preferentially in the direction about 15 to 45 inward from the toroidal direction

- Dust velocity, calculated from the tracks, is about 10-100 m/s, which is in agreement with the estimates from (Krasheninnikov et al., PoP 2004)

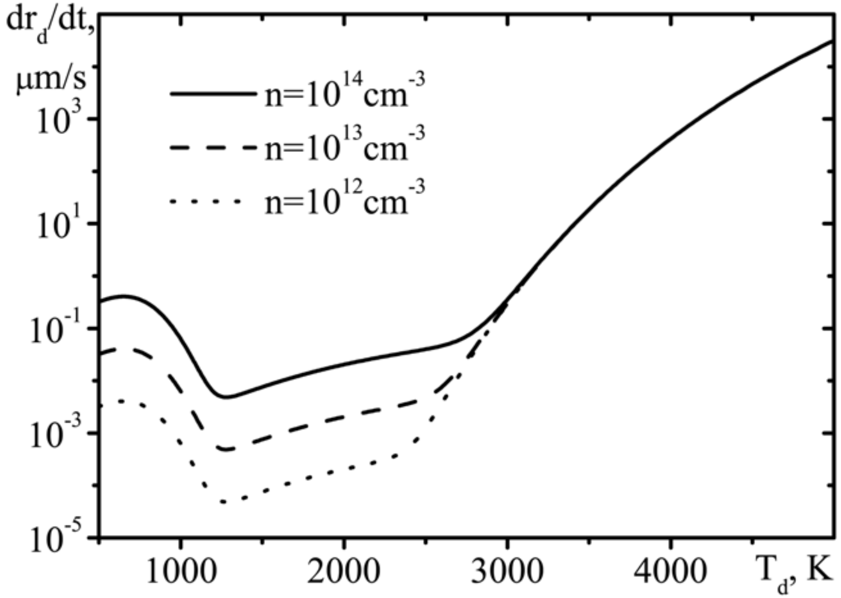
Frame #146, 2430 ms



- More about the Workshop “Dust in Fusion Plasmas” (Napa, April 5, 2005) can be found on the website <http://maemail.ucsd.edu/~dust/>

III. Modeling of dust dynamics and transport in tokamak plasmas

III.a Estimates of energy and particle balance



For $T_i \approx T_e = T \sim 10$ eV from power balance we find dust temperature T_d and estimate the erosion rate:

- In fusion edge plasmas dust particle of ~1 μm scale can live > 0.1 s (Krasheninnikov, PoP 2004; Martin, 31[st] EPS, 2004)
- Therefore, dynamics of dust motion is important!

III.b Dust in magnetized sheath, effects of surface corrugation

- Dust charge Z_d is determined by the ambipolarity of plasma flux

$$e^2 Z_d / r_d = \Lambda T, \qquad \text{where} \quad \Lambda \sim 3$$

- The forces acting on dust particle $\quad M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}$

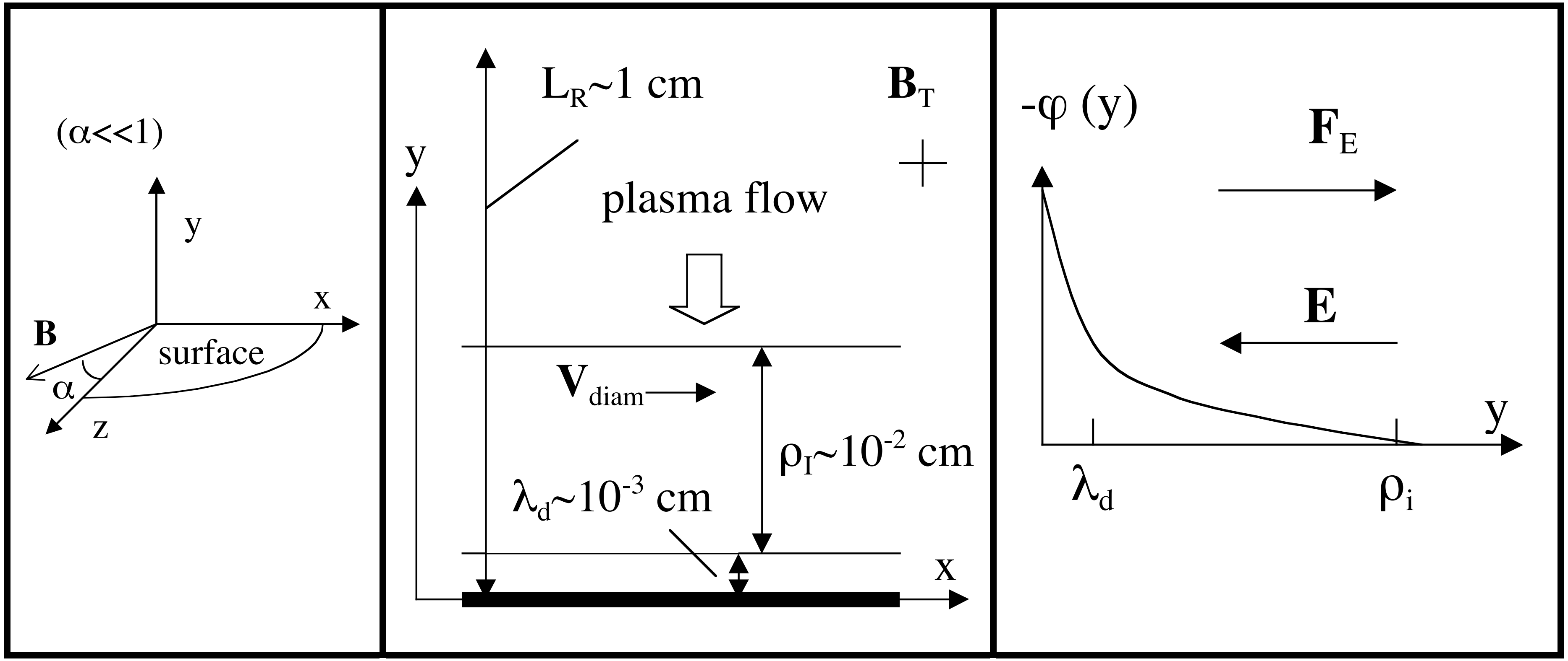
$$\mathbf{F}_E = -eZ_d\mathbf{E} \quad (\text{electric}), \qquad \mathbf{F}_{fric} = \varsigma_F \pi r_d^2 M_i n V_i \left(\mathbf{V}_p - \mathbf{V}_d\right) \quad (\text{friction}),$$

$$F_{roc} = \zeta_{roc} M_v V_v \Gamma_v \quad (\text{rocket}), \qquad \mathbf{F}_g = M_d\,\mathbf{g} \quad (\text{gravity}),$$

$$\mathbf{F}_M = -\pi r_d^3 \varepsilon_M \frac{B_{sat} B_{tor}}{4\pi R} \frac{\mathbf{R}}{R} \quad (\text{magnetic})$$

- Electric and friction forces dominate in tokamak edge plasmas

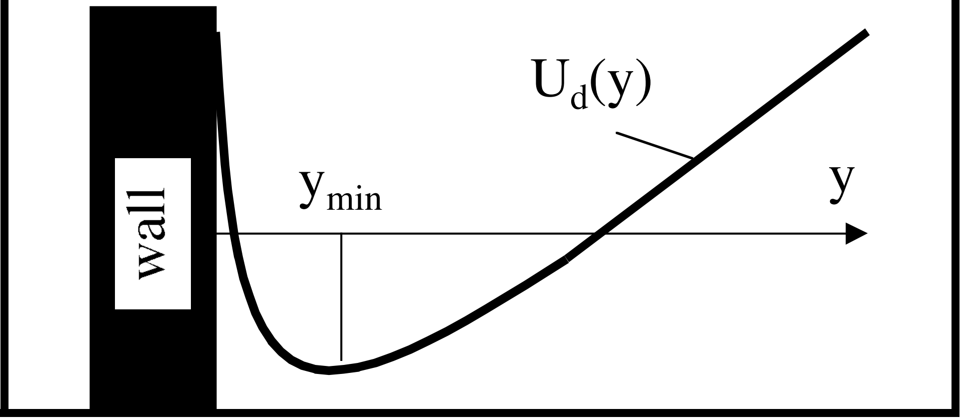
- In fusion devices the vicinity of the wall including both recycling and sheath regions are very important for dust dynamics



- Dust motion in direction ⊥ to the surface is described by the potential

$$U_d(y) = \alpha \varsigma_F n_{sh} T \pi r_d^2 y + \Lambda \frac{r_d T}{e} \varphi(y)$$

$$y_{min} \sim \rho_i$$



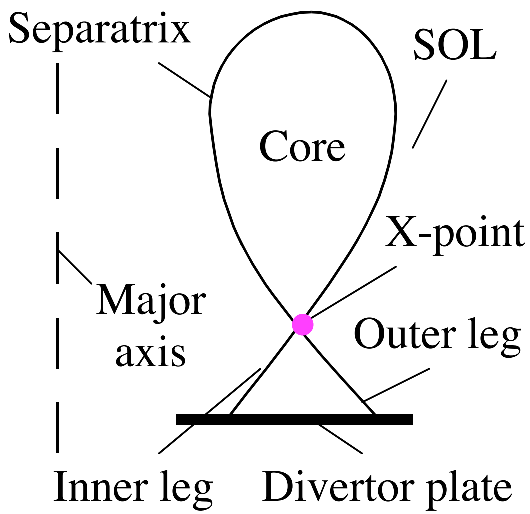
- Small oscillations of dust particle in the vicinity of y_{min} can be described by the following equations

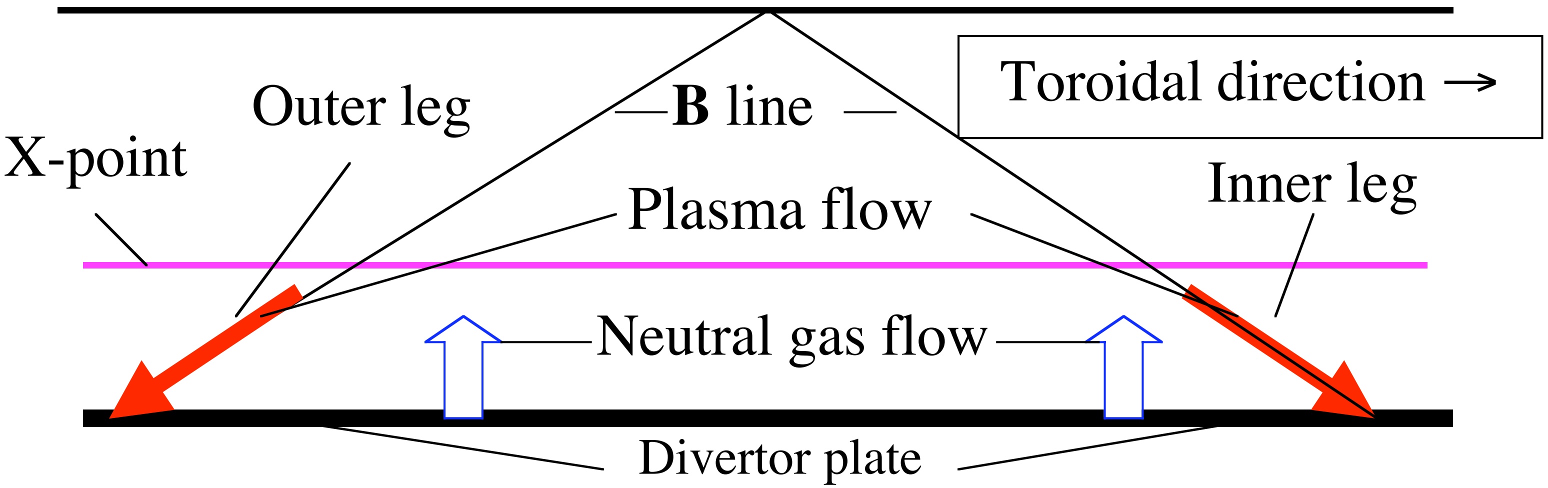
$$\frac{d^2 y_d}{dt^2} = -\Omega_d^2 (y_d - y_{min}) - \nu_V \frac{dy_d}{dt}, \qquad \Omega_d^2 = \frac{1}{M_d} \left. \frac{d^2 U_d}{dy^2} \right|_{y=y_{min}},$$

$$\nu_V = \varsigma_F M_i n_{sh} V_i \pi r_d^2, \quad \Omega_d \sim 10^4 \ s^{-1} >> \nu_V \sim 1 \ s^{-1}$$

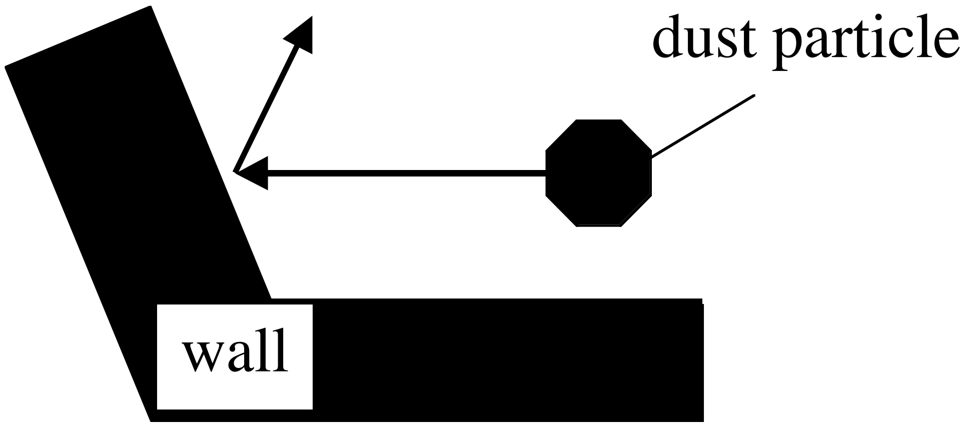
- Opposite toroidal components of plasma velocity in divertor recycling regions at inner and outer divertor legs push dust in **different toroidal directions**

(Krasheninnikov, PPCF **47** (2005) A339)

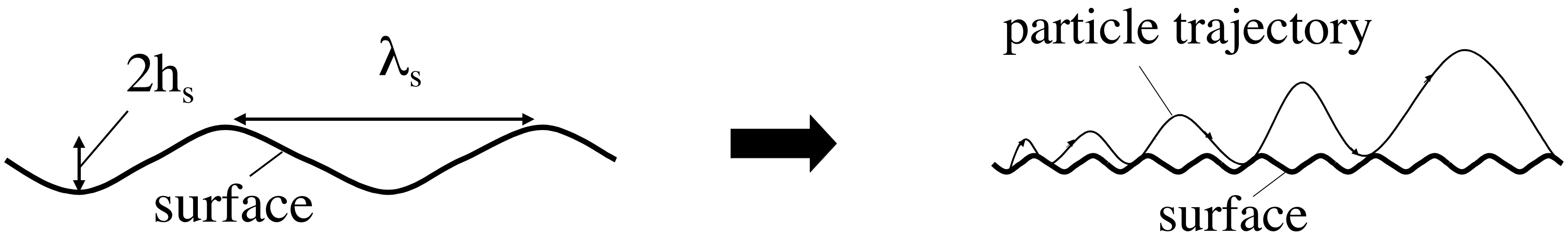




- Large unbalanced toroidal friction force causes continuous acceleration of dust particle along the surface and after being dragged for $\sim 1\,\mathrm{cm}$ micron scale dust particle gains speed $\sim 3\times 10^{3}\ \mathrm{cm/s}$
- Surface imperfections (corners, steps) can cause particle to leave sheath region and "fly" through plasma on large distance

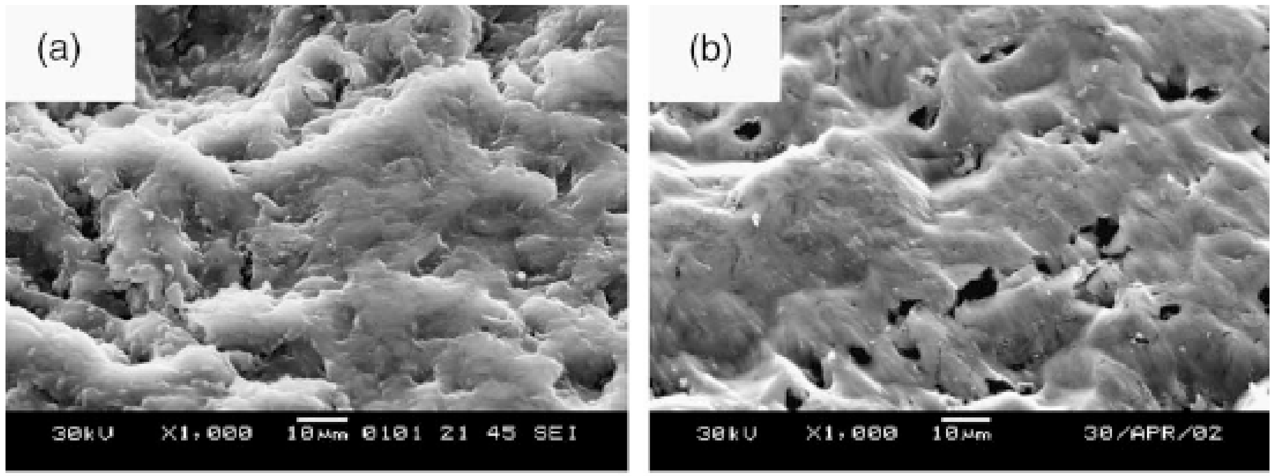


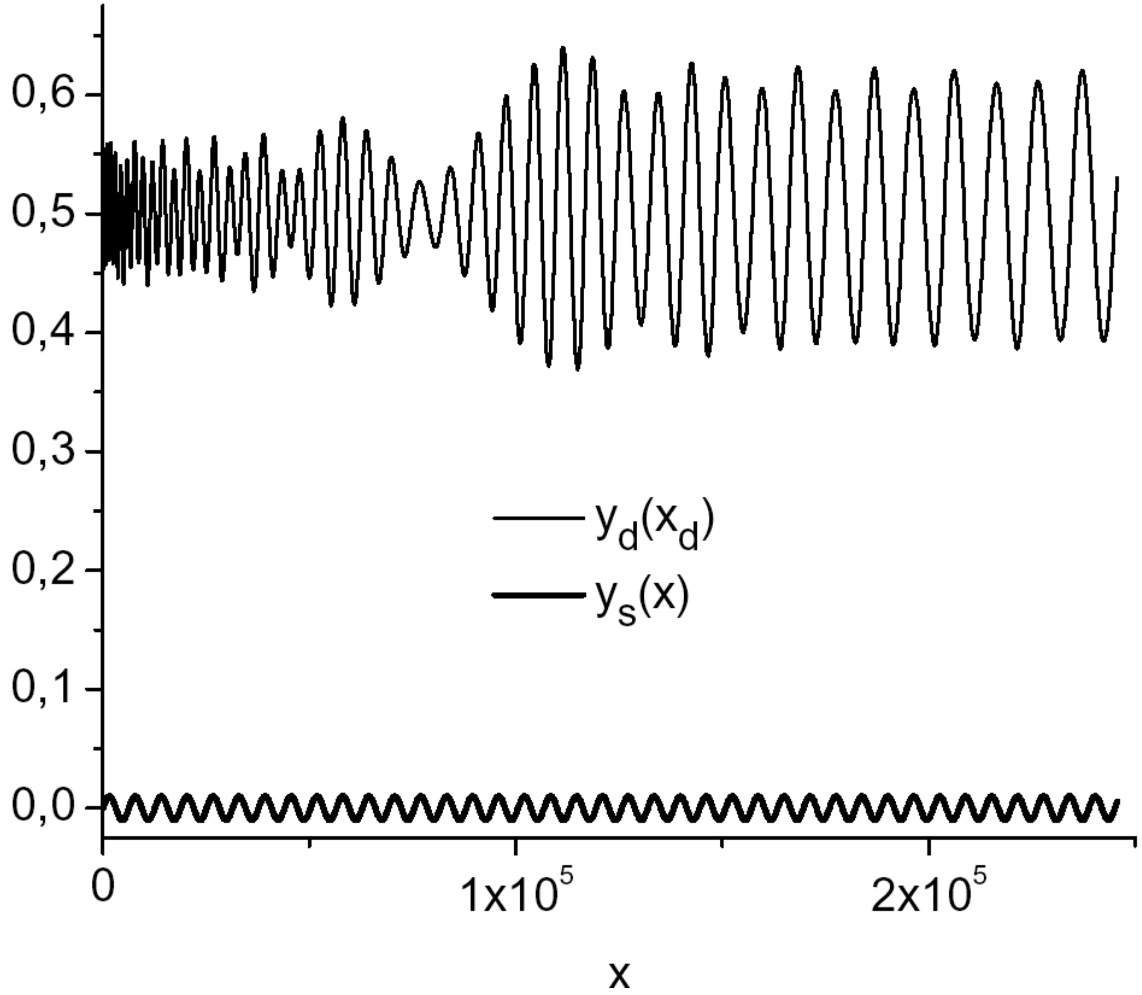
- Even less dramatic surface corrugation can be a reason for dust particle flights (Krasheninnikov, et al., PPCF **47** (2005) A339)



- Surface in LHD

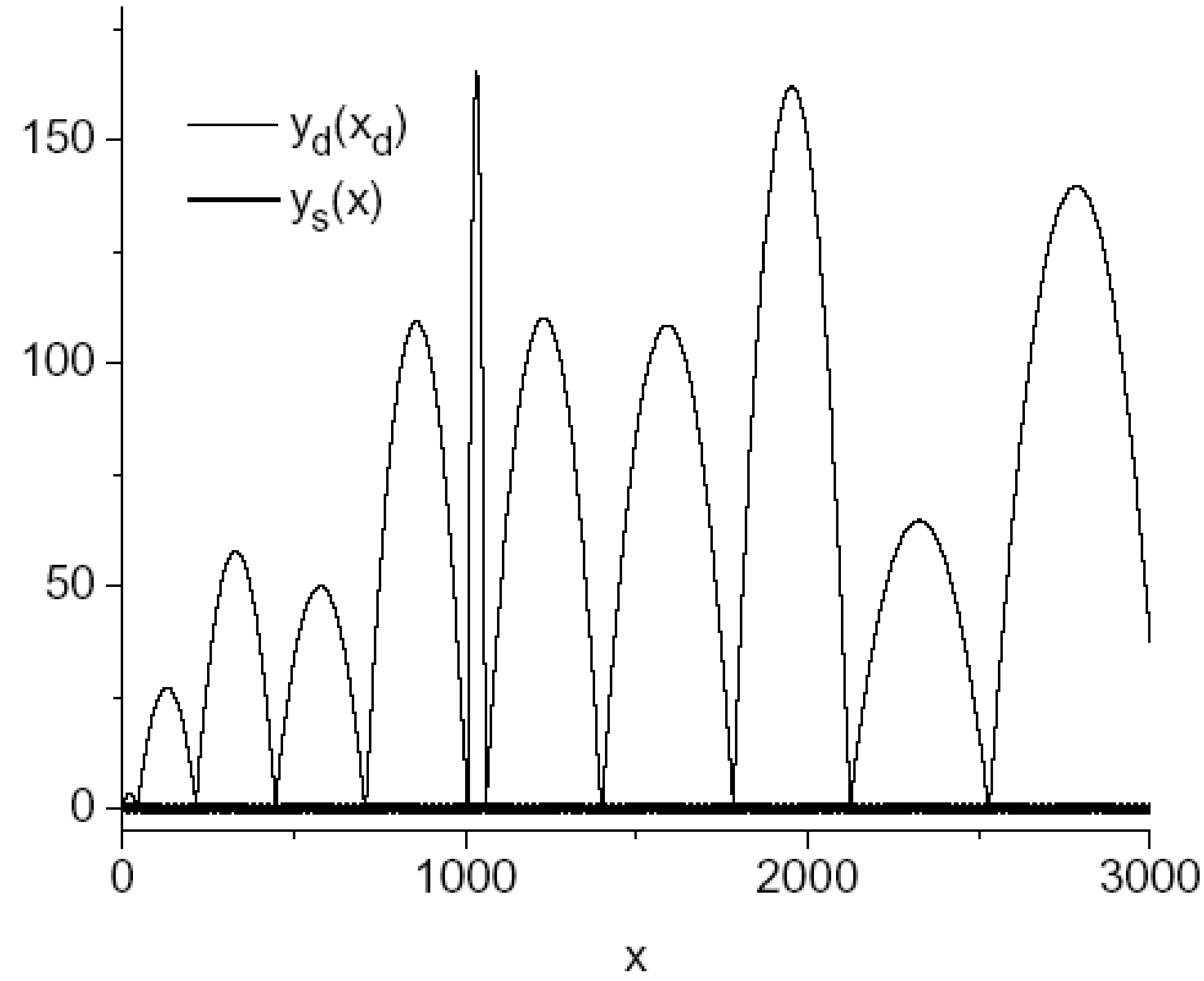
(Sagara et al., J. Nucl. Mater, 2003)



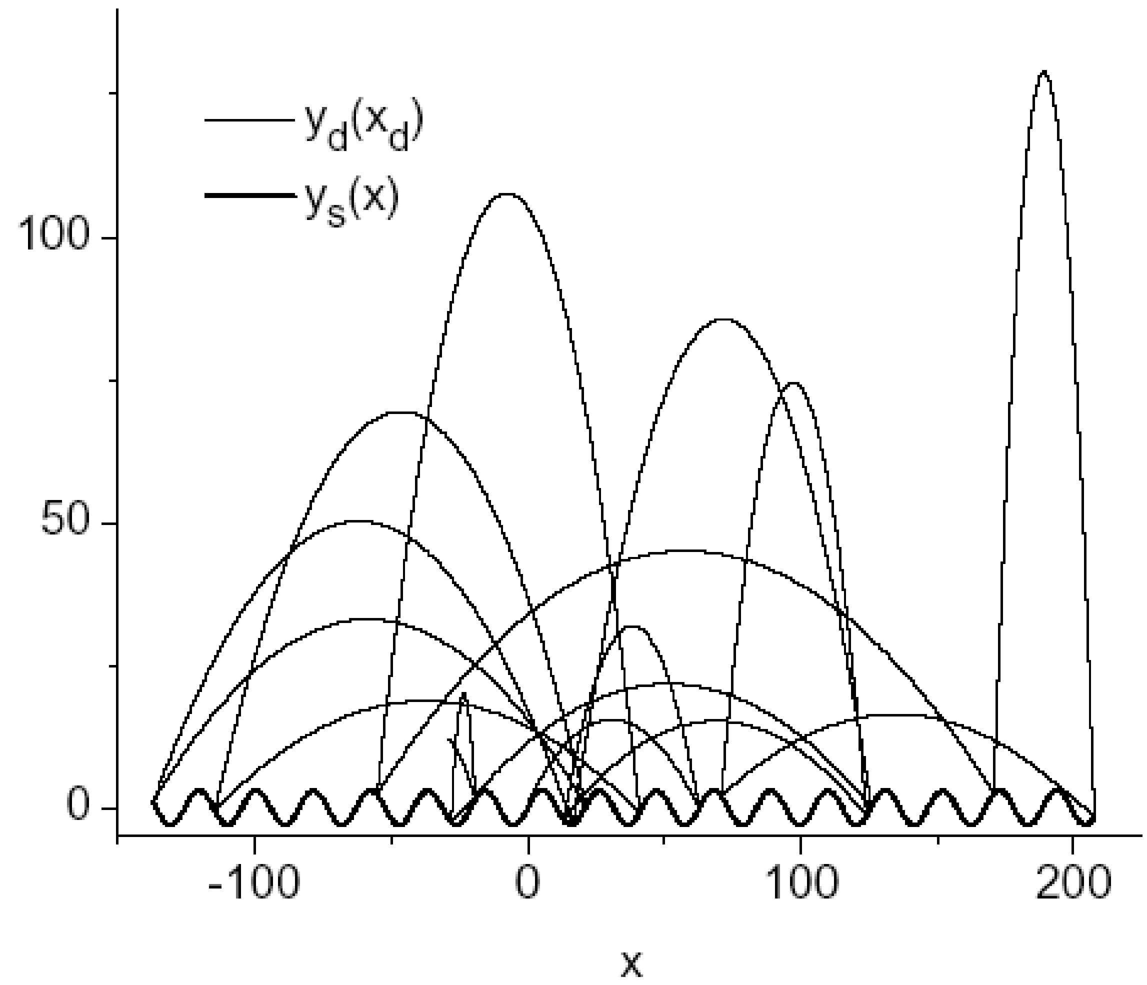


Resonance interaction of dust particle with corrugated surface

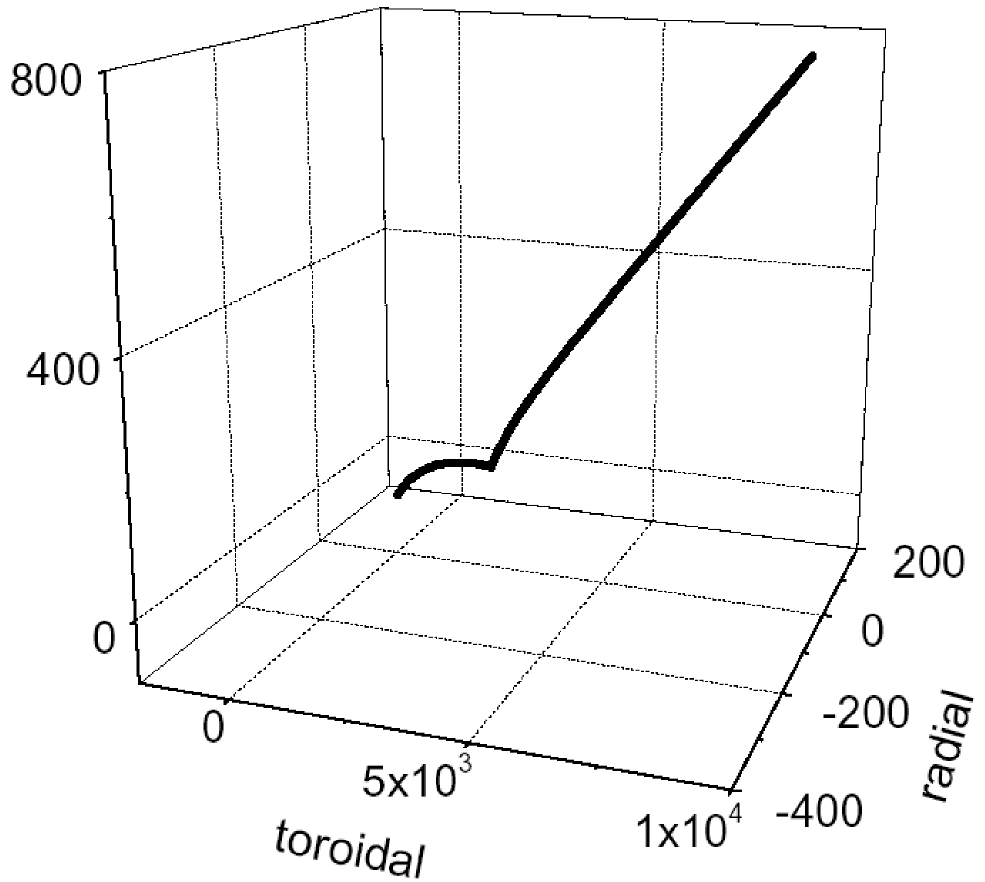
$(h_x / \rho_i = 0.01,\ k_x \rho_i = 10^{-3},\ \alpha = 0.1,\ L_R = \infty)$



Flights of dust particle over corrugated surface
$(h_x/\rho_i = 1,\ k_x\rho_i = 0.3,\ \alpha = 0.1,\ L_R = \infty)$



Stochastic flights of dust particle over corrugated surface
($h_x / \rho_i = 3$, $k_x \rho_i = 0.3$, $\alpha = 0.1$, $L_R = \infty$)



3D flights of dust particle over corrugated surface
$(h_x/\rho_i = 3,\ h_z/\rho_i = 5,\ k_x\rho_i = 0.3,\ k_z\rho_i = 0.01,\ \alpha = 0.1,\ L_R = 100)$

Dust particle can penetrate deeply into edge plasma. **How far?!**

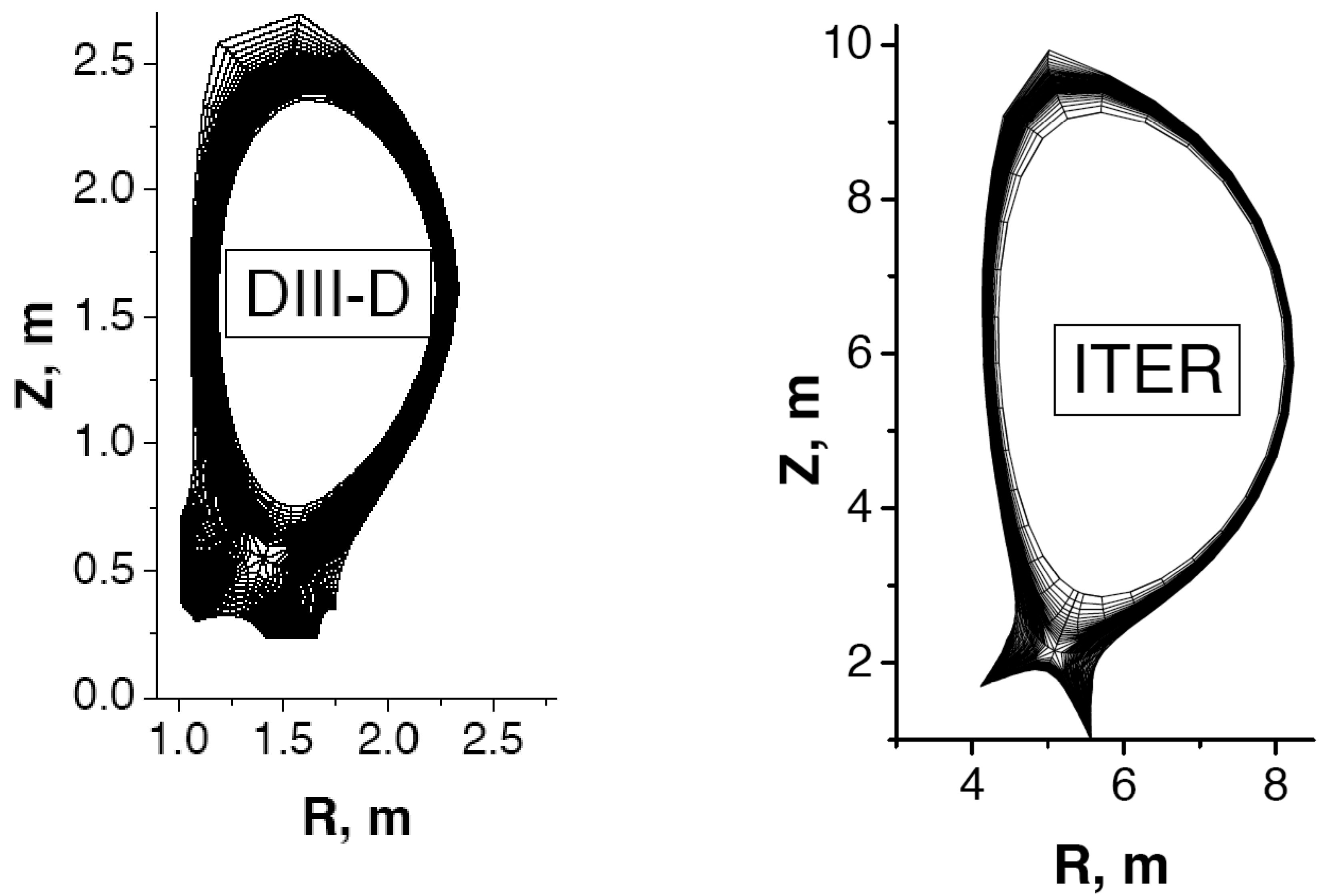
III.c Code DUSTT: dust transport in tokamak plasmas

- Code solves the dust particle momentum, energy, charge, and mass balance equations in toroidal geometry

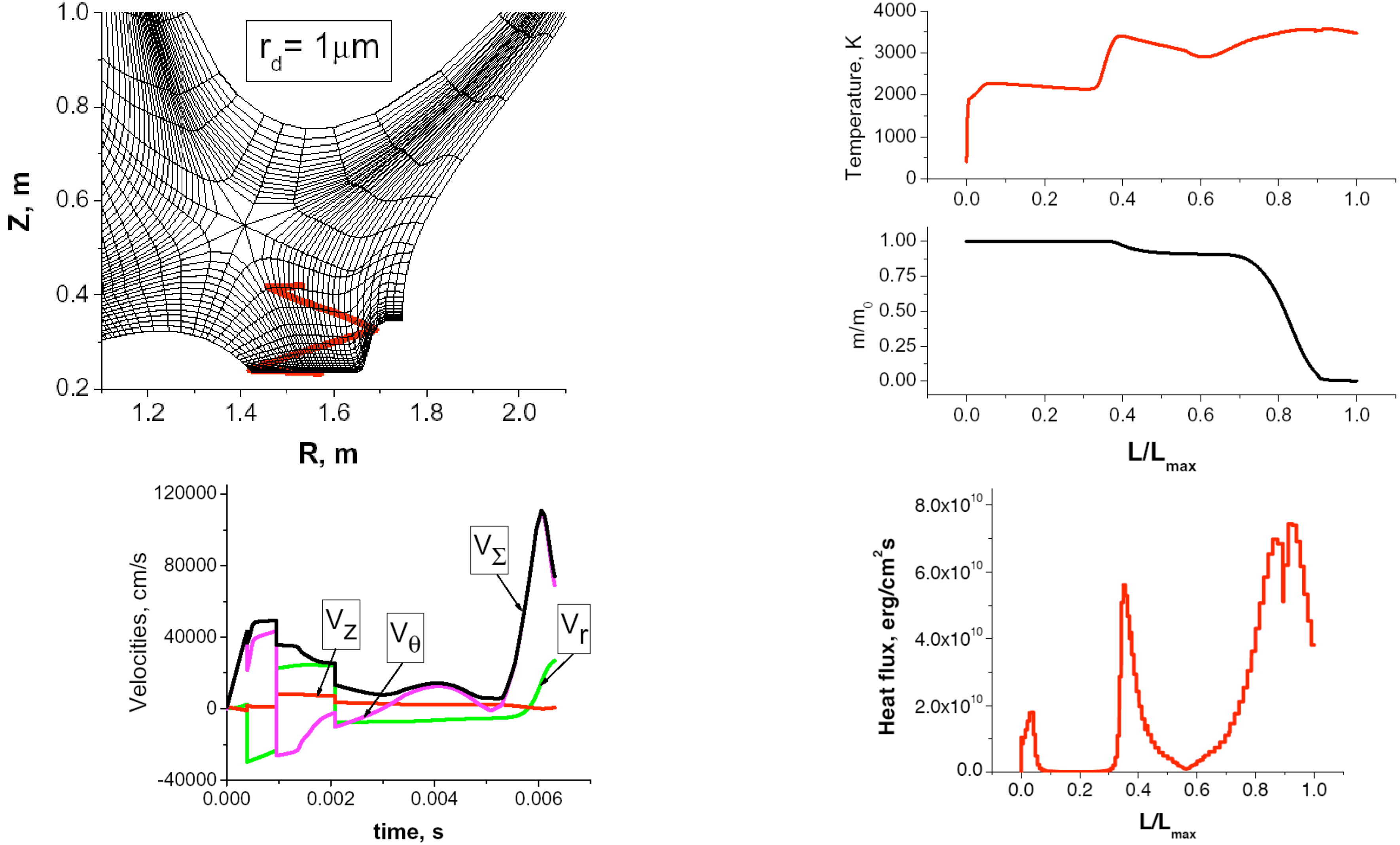
$$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}_d; \qquad \frac{d\mathbf{R}_d}{dt} = \mathbf{V}_d$$

$$\frac{dT_d}{dt} = Q_{(+)} - Q_{(-)}; \qquad \frac{dZ_d}{dt} = I_{(+)} - I_{(-)}; \qquad \frac{dM_d}{dt} = W_{(+)} - W_{(-)}$$

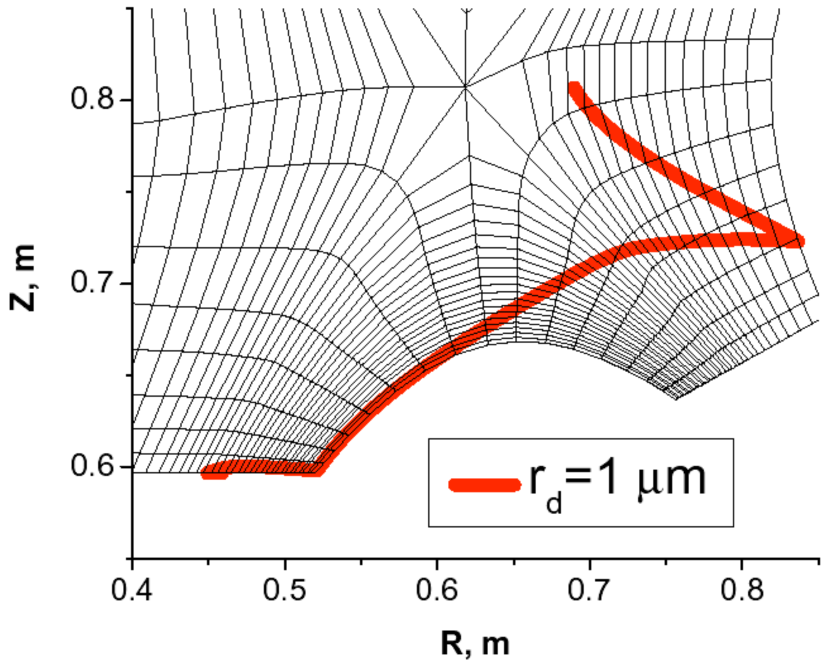
- Plasma parameters can be taken either from experimental data or from the modeling with 2D plasma transport code UEDGE
- The UEDGE mesh is used to solve dust dynamic equations

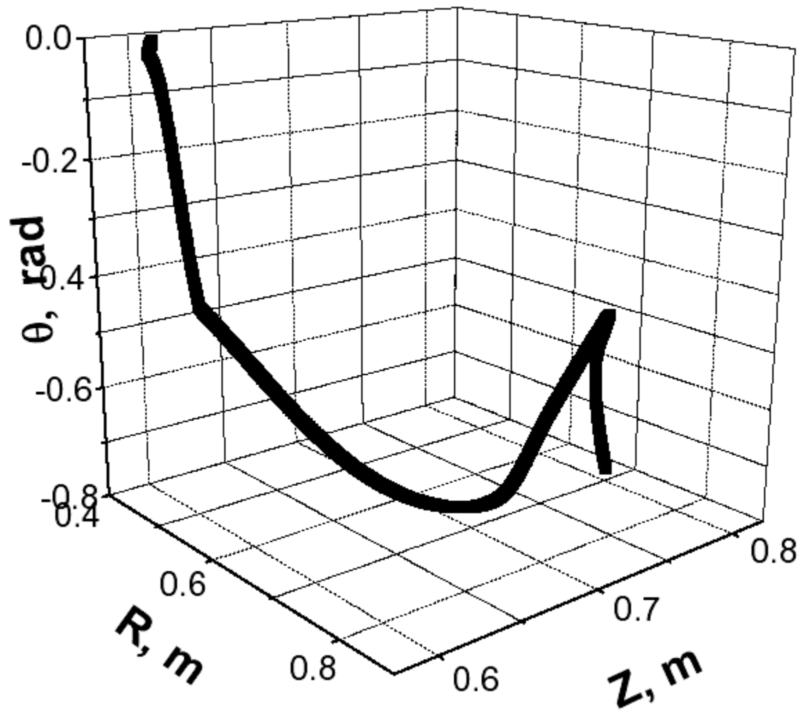


DIII-D
Z, m
R, m
2.5
2.0
1.5
1.0
0.5
0.0
1.0
1.5
2.0
2.5
ITER
Z, m
R, m
10
8
6
4
2
4
6
8

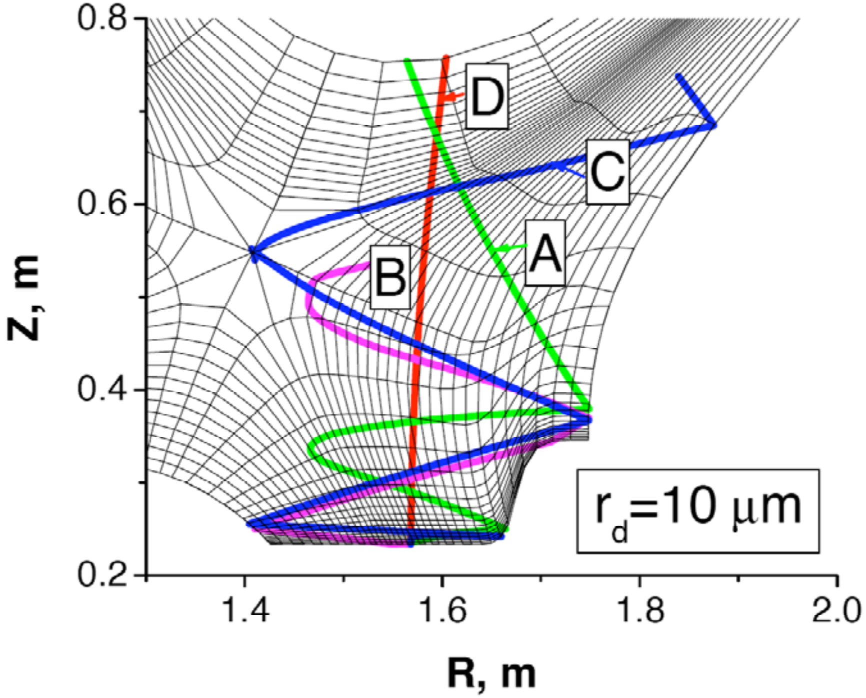


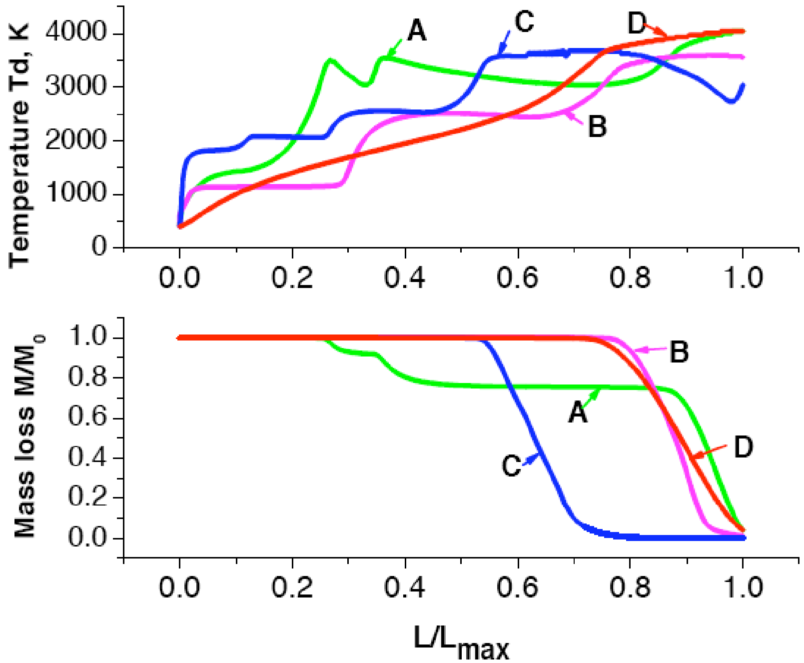
Dust particle dynamics in the DIII-D tokamak





- Dust particles preferentially move in the direction of plasma flows, which are opposite at inner and outer divertor legs (NSTX tokamak)

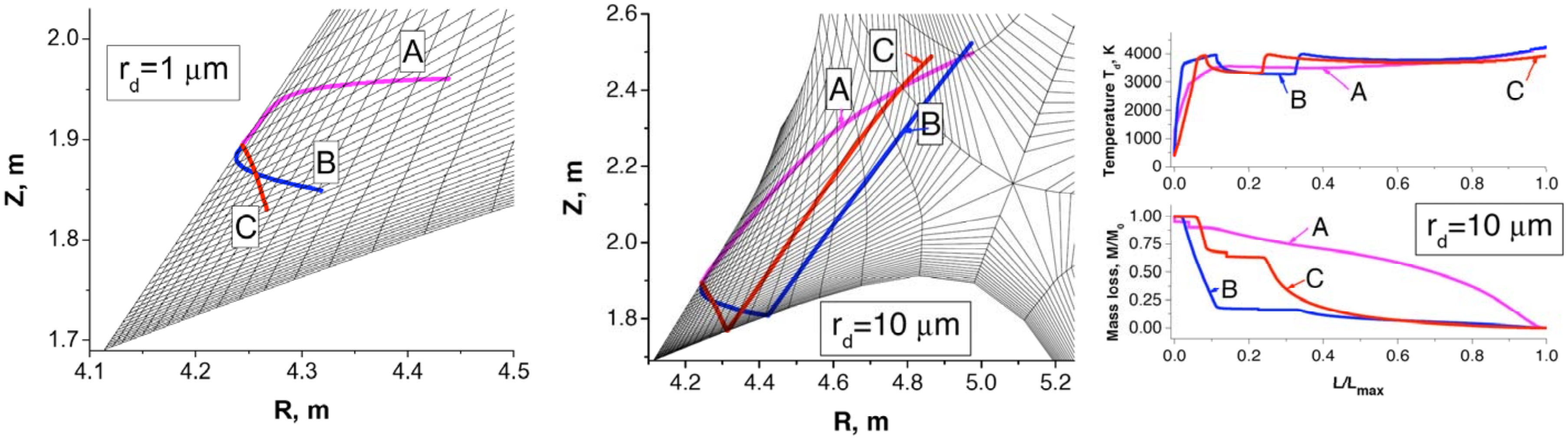




Dust rather easily penetrates through separatrix in the DIII-D tokamak

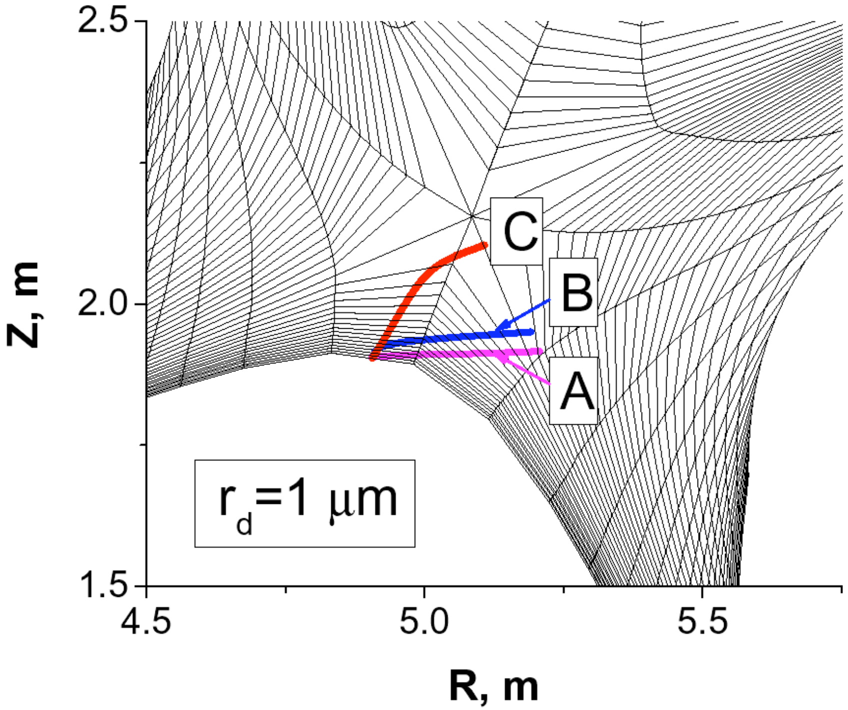
$$(V(t=0) = 10^1\ (A);\ 10^2\ (B);\ 10^3\ (C);\ 10^4\ (D);\ cm/s)$$

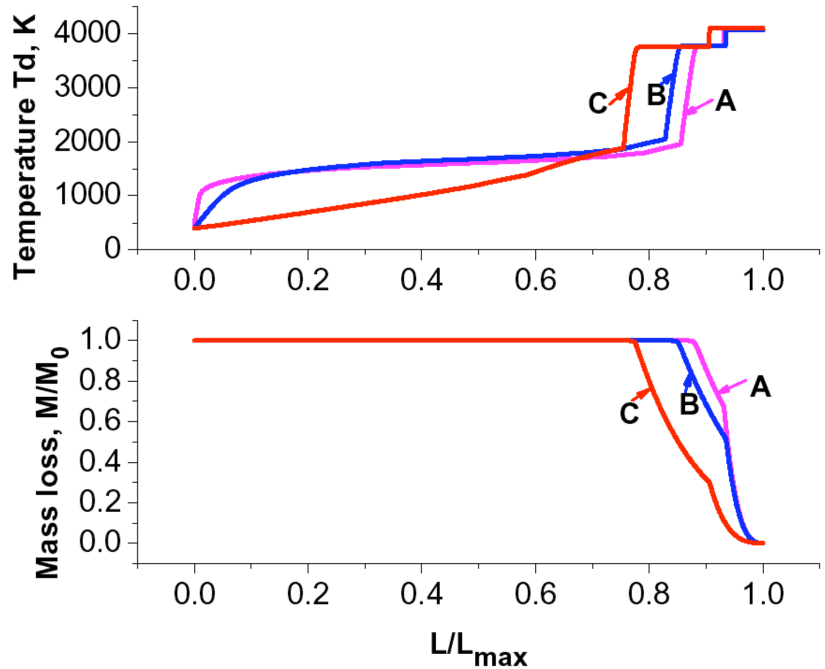
We use UEDGE to obtain the profiles of plasma parameters and flows for the ITER-FEAT (114 MW into the SOL) and then apply DUSTT



Large dust particles may penetrate all the way to separatrix even through rather dense divertor plasma

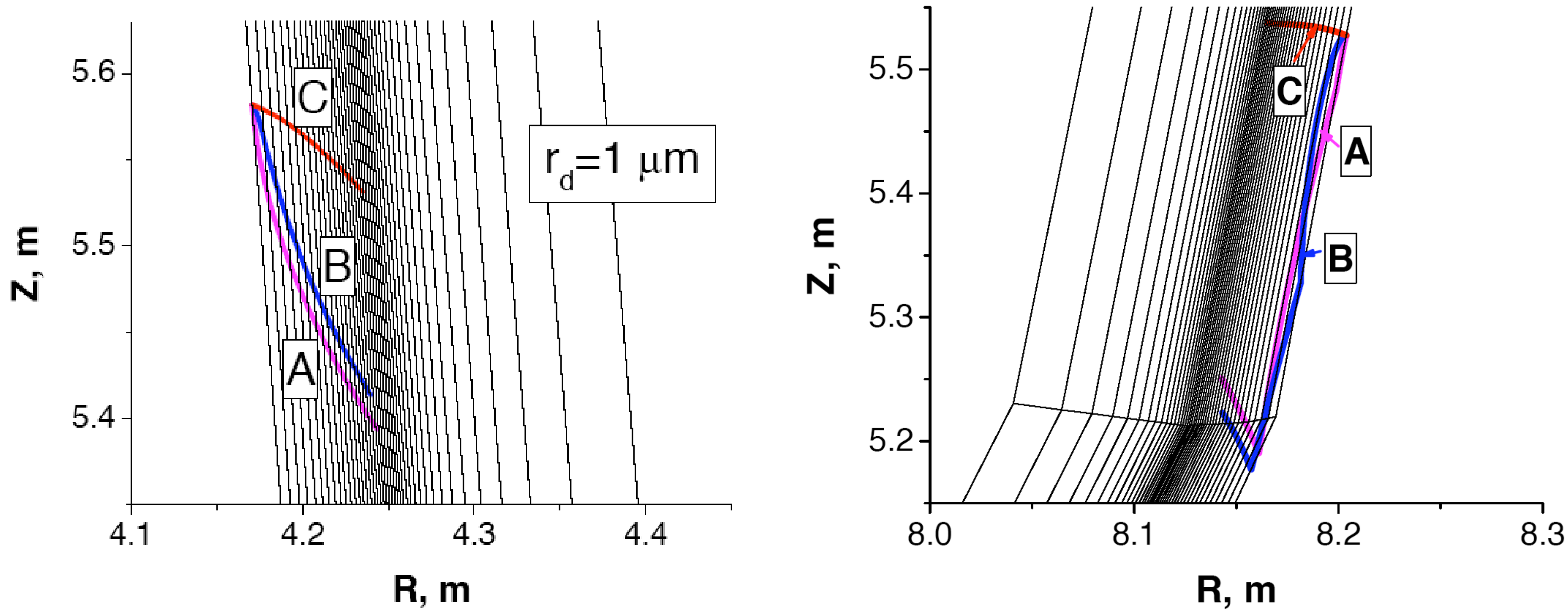
$$((V(t=0) = 10^2\ (A); 10^3\ (B); 10^4\ (C); cm/s)$$



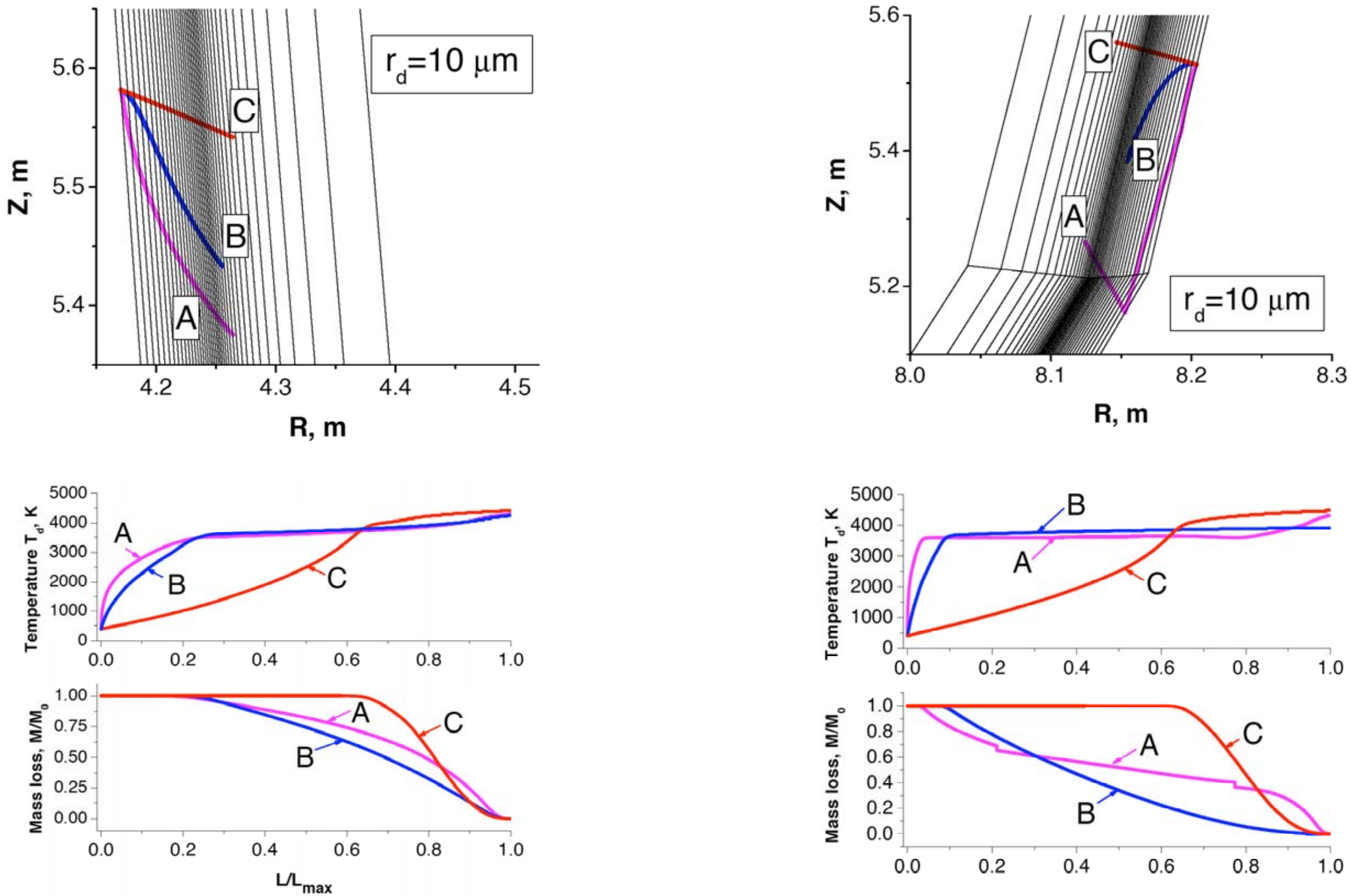


Dust particles launched from private region

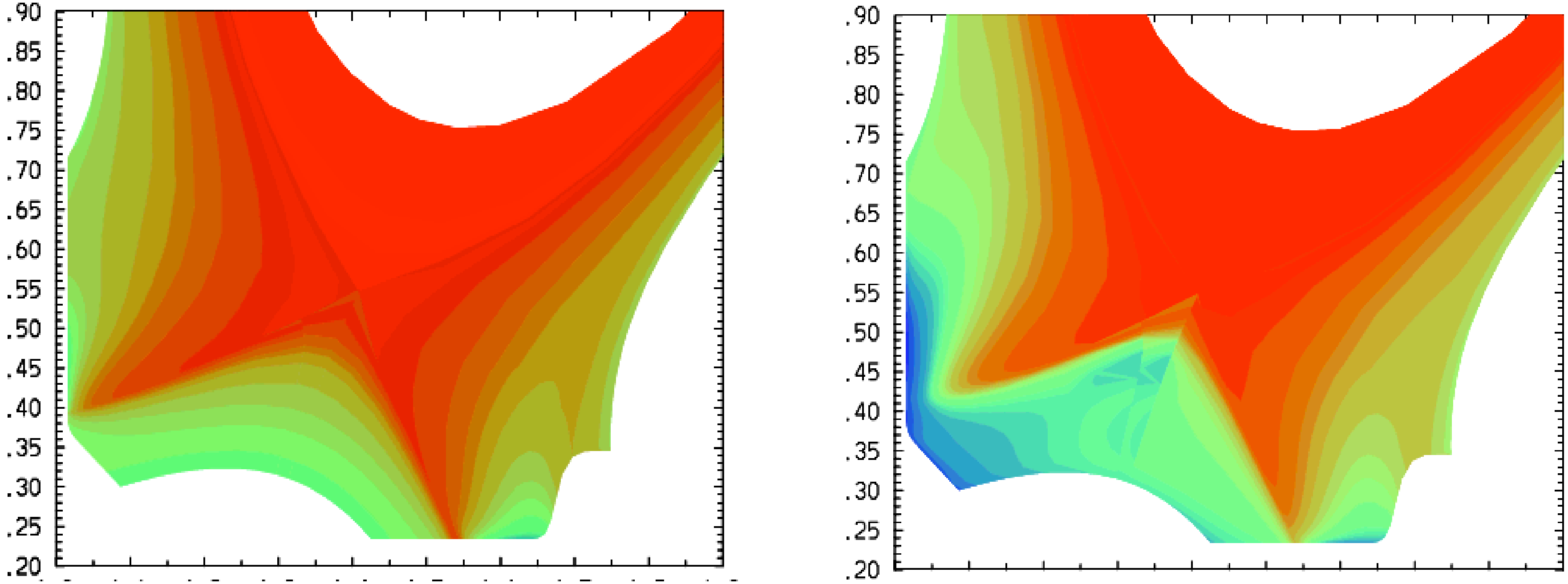
can easier reach separatrix



Toroidal acceleration of dust particles by plasma flow along **B** results in the centrifugal force, which are pushing dust particles in radial direction



- Dust flights into edge plasma cause deeper penetration of impurity and strongly alter edge plasma parameters: increase of carbon radiation, plasma temperature drop, and divertor detachment



T_e contours in DIII-D, impact of carbon penetration enhancement (2D UEDGE modeling)

IV. Conclusions

- Due to acceleration by plasma flows, dust particles can have a very high speed, $10^3 - 10^4$ cm/s
- As a result it can move on the distances comparable to major radius in one shot (This may explain some puzzles with dust experiments on JIPPT-IIU)
- Interactions of dust particles with surface inhomogeneities (including micro-roughness as well as corners, etc.) or plasma turbulence can cause dust particles to fly through SOL plasma toward tokamak core

- It is feasible that dust can play an important role in core plasma contamination in both current devices and ITER
- However, even then, dust particle density around separatrix is $\sim 3 \times 10^{-2}\ \text{cm}^{-3}$, which makes it difficult to diagnose
- Understanding of dust physics in fusion plasma is of a great importance for burning plasma experiments due to potential threat of plasma core contamination and retention of radioactive materials and tritium
- **Therefore, more experimental data and theory of dust generation mechanisms and dust dynamics in fusion plasmas are needed!**