Dynamics of Dust Motion in Tokamak Edge Plasma

Sergei Krasheninnikov

University of California, San Diego, USA

With contributions from:

Y. Tomita[1], R. D. Smirnov[2], R. K. Janev[1], and T. K. Soboleva[3]

[1]National Institute for Fusion Science, Toki, Gifu, Japan
[2]The Graduate University for Advanced Studies, Toki, Gifu, Japan
[3]UNAM, Mexico D.F., Mexico and Kurchatov Institute, Moscow, Russia

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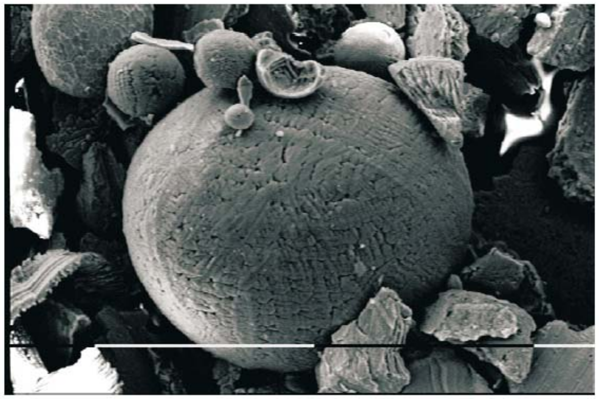
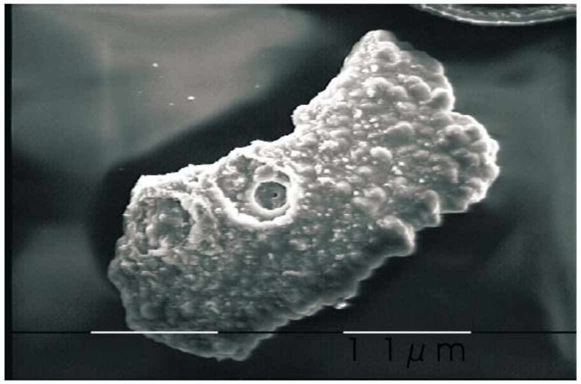
I. Introduction

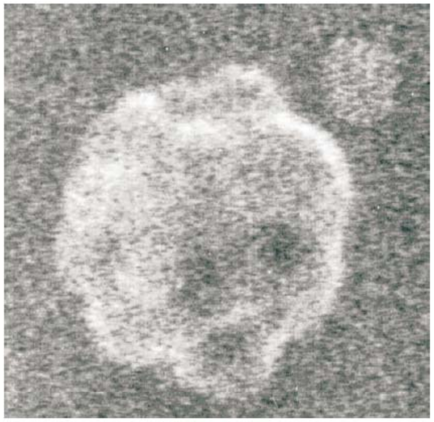
- Significant amount of dust particles is observed in the chambers of fusion devices



0.1 mm

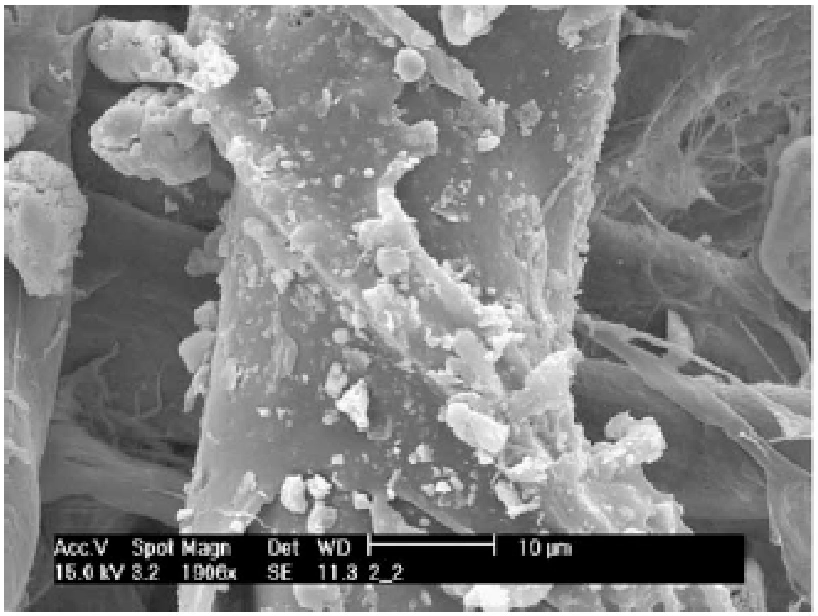


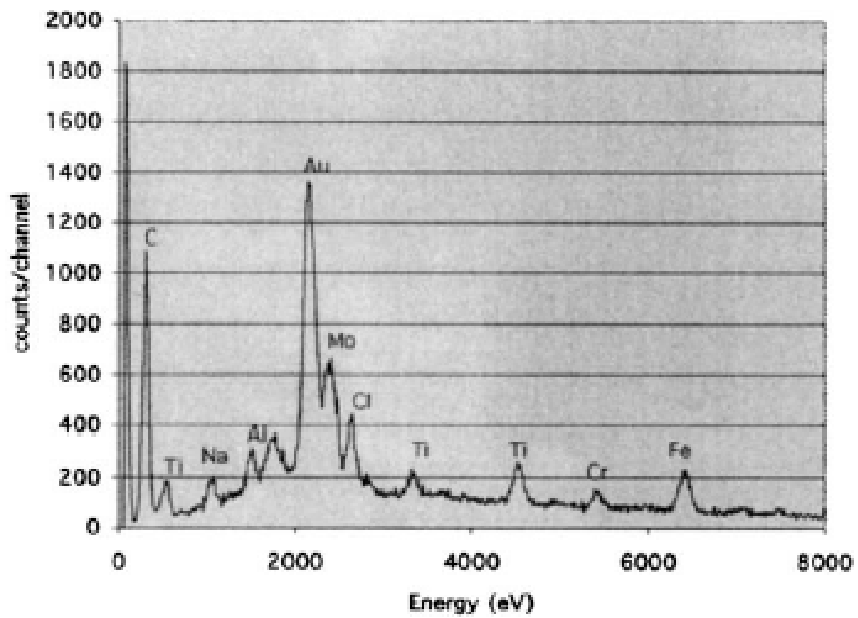
1μm



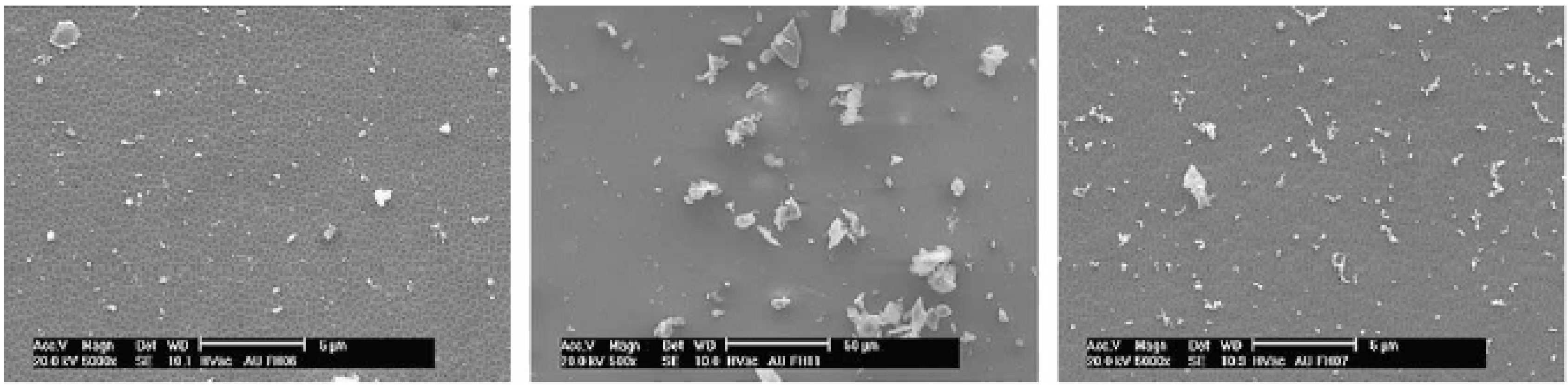
200 nm

(Winter, Plasma Phys. Contr. Fusion, 1998)





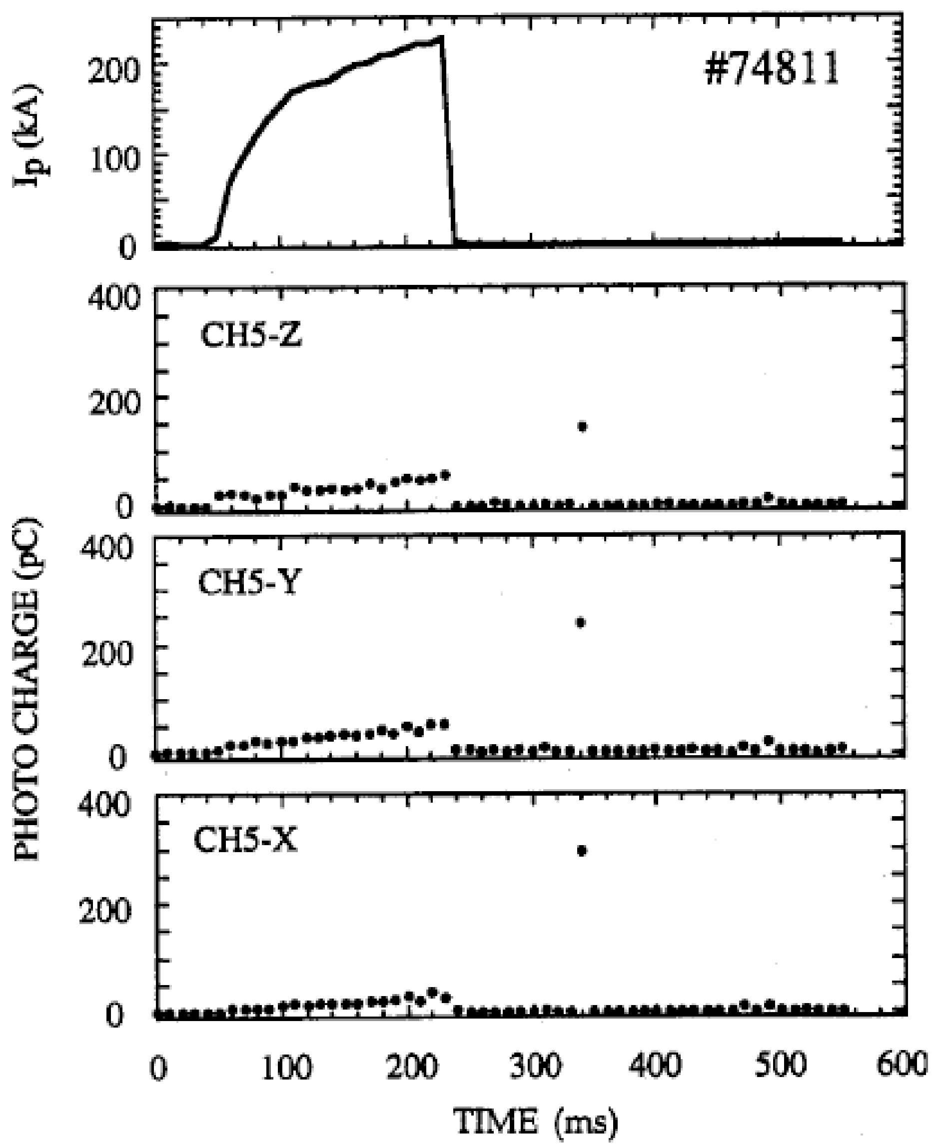
Carbon, steel and titanium particle collected from the LHD coil armor (Sharpe et al., J. Nucl. Mater, 2003)



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

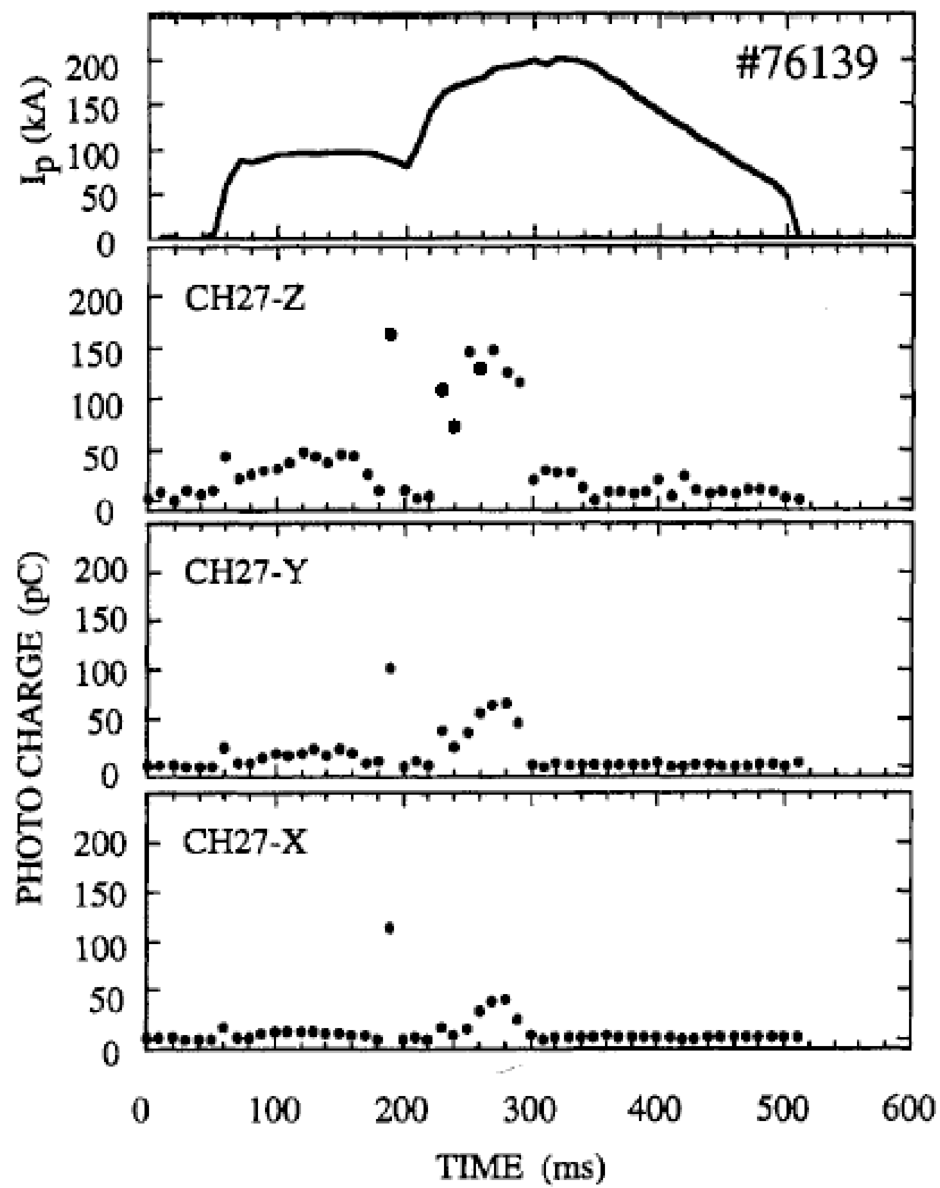
Dust particles collected from (a) lower, (b) middle, and (c) upper regions of Asdex-U (Sharpe et al., J. Nucl. Mater, 2003)

- In JIPPT-IIU dust particles were detected by large signal in Thomson scattering diagnostics
- In most cases they were observed after disruption and in a few cases during standard discharges (Narihara et al., Nuclear Fusion, 1997)



- However, (~2 μm) carbon dust particles, deliberately injected into JIPPT-IIU, have been detected 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)

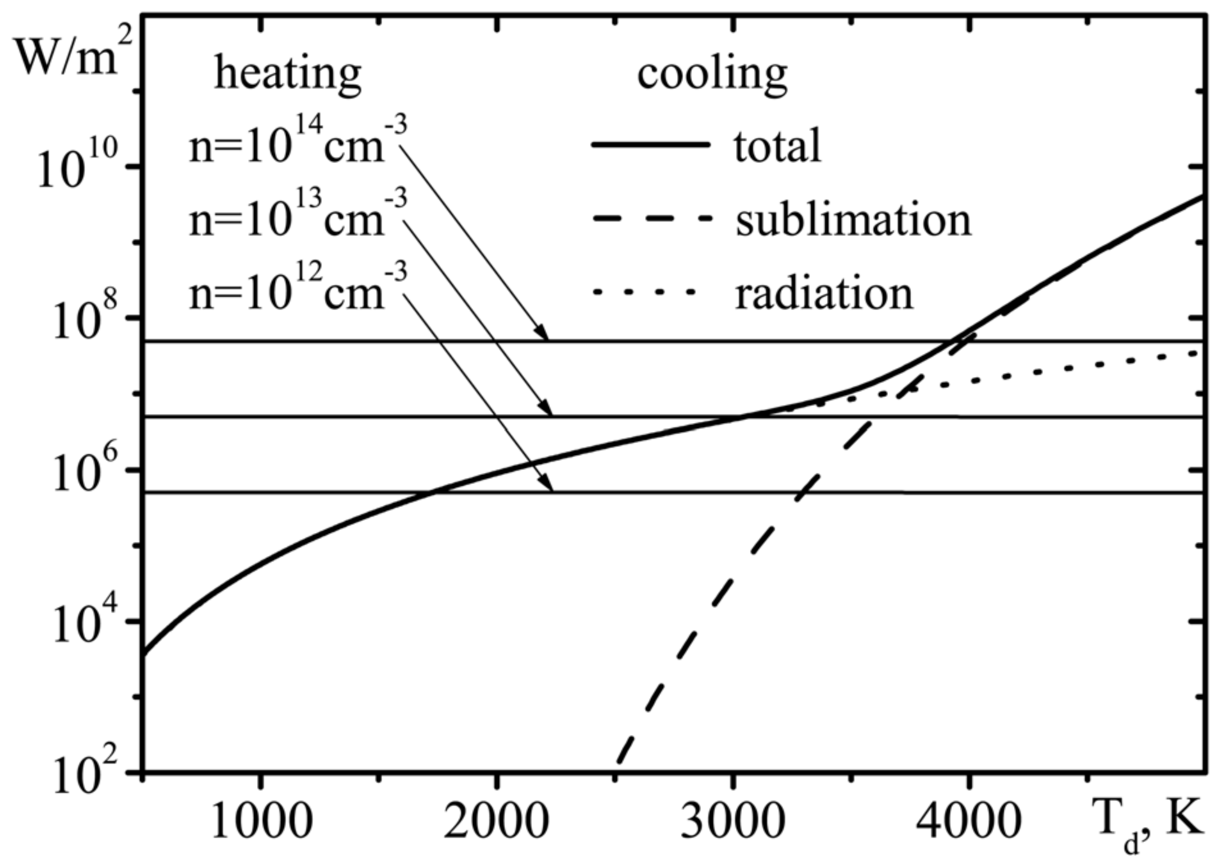


- So far an impact of dust on the performance of existing fusion devices is not clear
- If dust does not affect core confinement/contamination, an impact of dust on current experiments can be ignored
- But, in burning plasma experiments an existence of significant amount of dust particles poses additional threat:
    - dust can contain toxic and radioactive materials and retain tritium
- Therefore, physics of dust in fusion devices can and should be studied in current tokamak experiments!

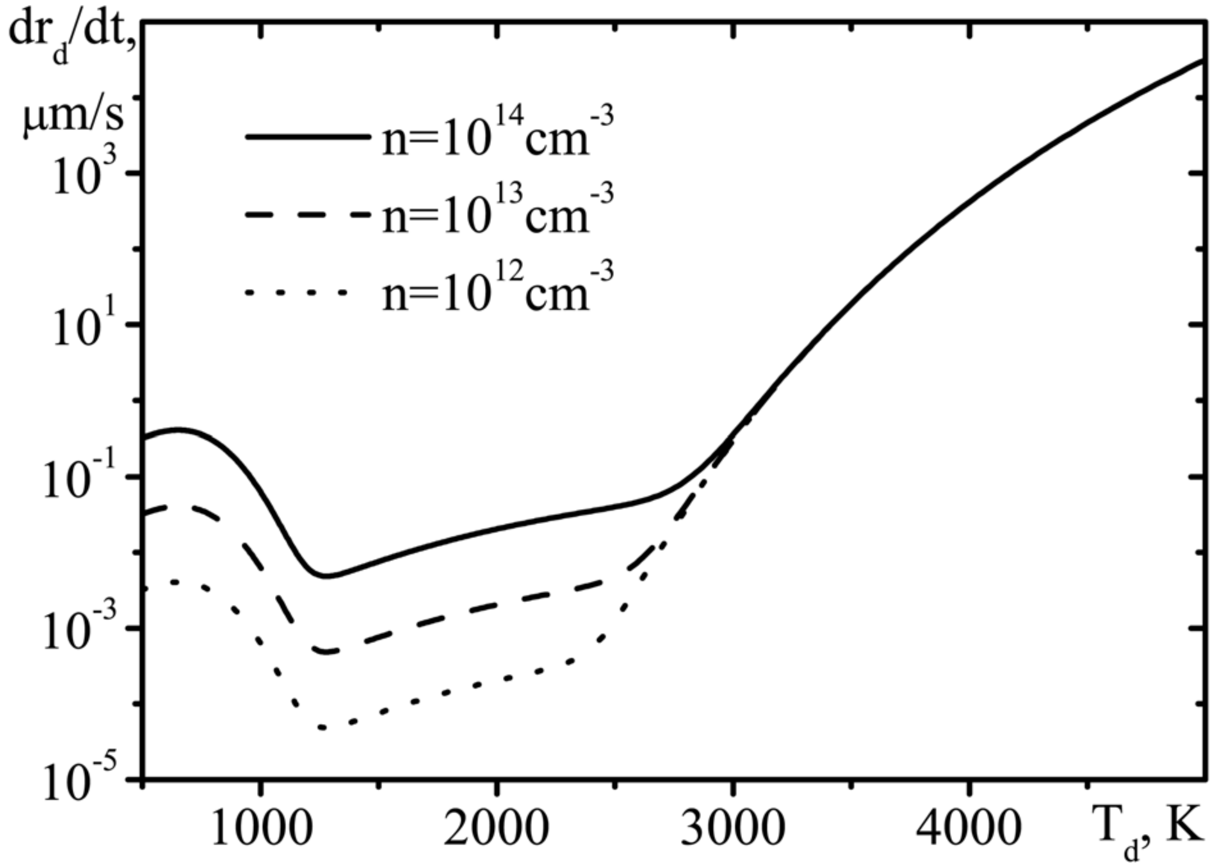
II. Lifetime of dust in tokamak plasma

Can dust particle survive in fusion plasma?

- Consider power and mass balance of carbon dust particles accounting for BB radiation, evaporation, RES, and physical and chemical sputtering
- To simplify our estimates we assume that $T_i \approx T_e = T \sim 10$ eV and plasma density is about 3×10^{13} cm^{-3}. Such parameters are rather typical for tokamak divertor plasma



W/m2
heating
cooling
n=10^14 cm^-3
n=10^13 cm^-3
n=10^12 cm^-3
total
sublimation
radiation
10^10
10^8
10^6
10^4
10^2
1000
2000
3000
4000
T_d, K



- In fusion edge plasmas dust particle of ~1 μm scale can live long enough (> 0.01 s). Therefore, dynamics of dust is important!

III. Dust in magnetized sheath

- 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 $$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}$$

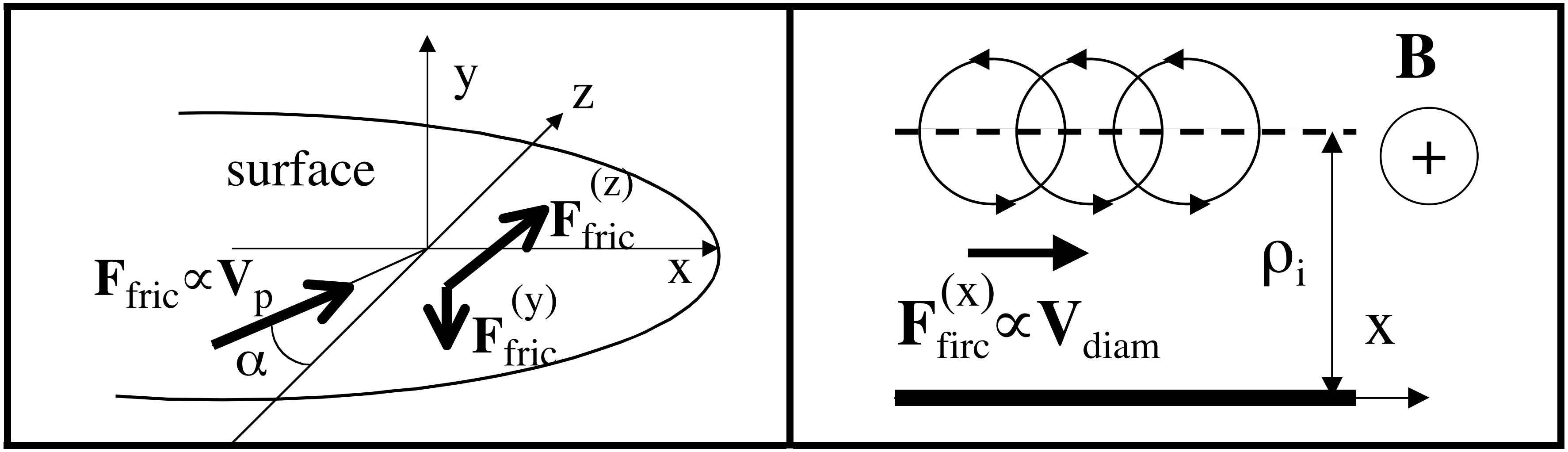
$$\mathbf{F}_E = -eZ_d\mathbf{E} \quad (\text{electric}), \qquad \mathbf{F}_{fric} = \varsigma_F \pi r_d^2 M_i n V_i \left(\mathbf{V}_p - \mathbf{V}_d\right) \quad (\text{friction}),$$

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

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

- Electric and friction forces dominate in tokamak edge plasmas

- In fusion devices dust is formed at the wall, therefore forces in near wall region (sheath) determine dust dynamics



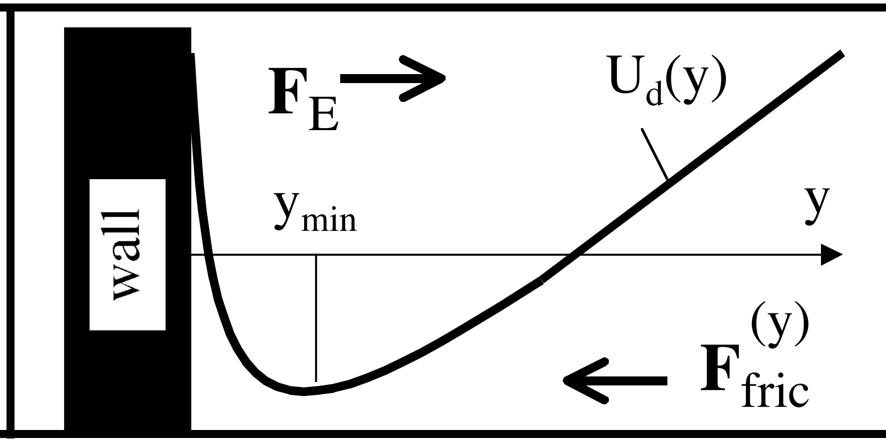
- In the sheath region friction is large $F_{fric}^{(z)} \approx F_{fric}^{(x)} \approx F_{sh} \equiv \varsigma_F \pi r_d^2 nT$

- However, $F_{fric}^{(x)}$ is reduced outside sheath ($y \gtrsim \rho_i \sim 10^{-2}$ cm), while $F_{fric}^{(z)}$ stays large in entire recycling region ($y \lesssim \ell_{ion} \sim 1$ cm)

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

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

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

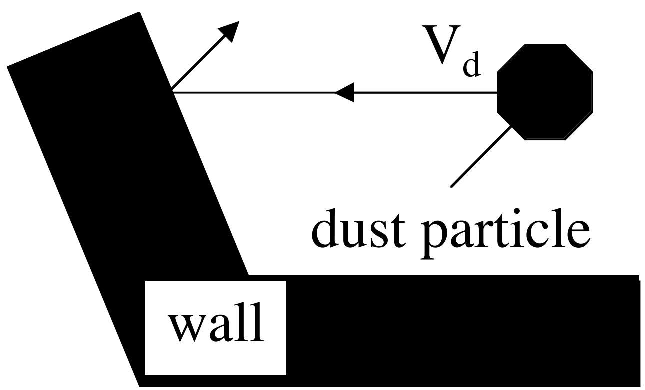


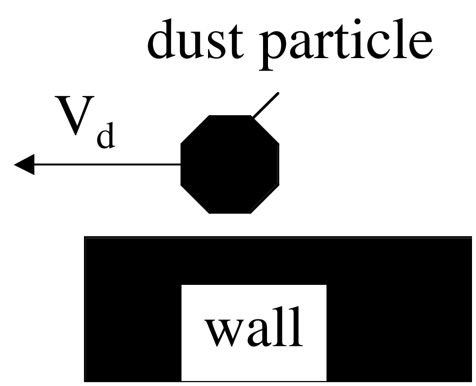
- Small oscillations of dust particle in the vicinity of y_{min} can be described by the following equation

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

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

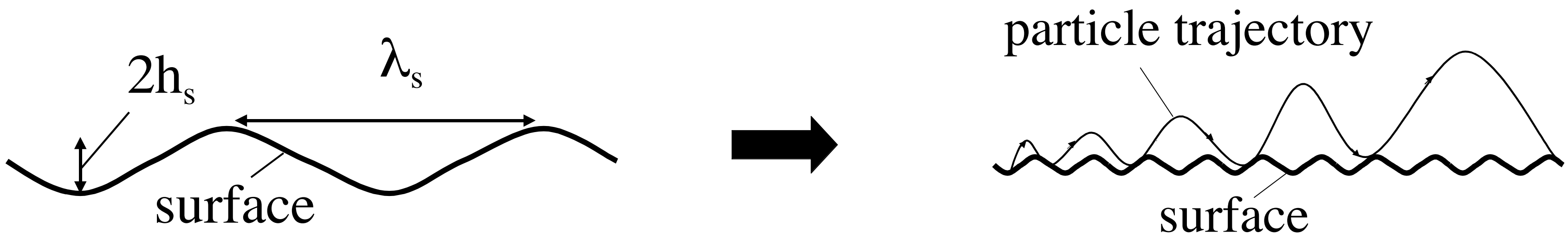
- Both z- component (flow along **B** field) and x- component (diamagnetic and $\mathbf{E}\times\mathbf{B}$ flows) of friction forces are unbalanced
- As a result, in $\sim 10^{-3}$ s (or after being dragged along the surface for ~ 1 cm) micron scale dust particle gains speed $\sim 3\times 10^{3}$ cm/s
- Therefore, surface imperfections (corners, steps) can cause dust to leave sheath region and "fly" through plasma on large distance





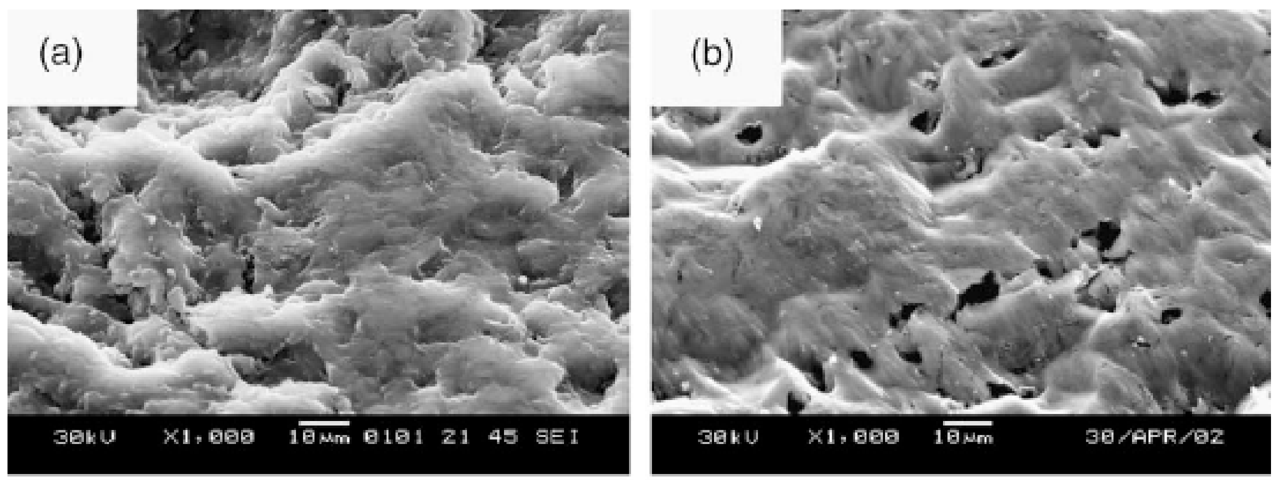
IV. Impact of surface corrugation and dust flights

- Even less dramatic surface corrugation can be a reason for dust particle flights



- Surface in LHD

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



Small amplitude of surface wave $h_s << \rho_i$

- Equation of dust particle motion in the sheath region for a slightly corrugated wall

$$\frac{d^2 y_d}{dt^2} = -\Omega_d^2 \left(y_d - y_{min}(x) \right), \qquad y_{min}(x) = \bar{y}_{min} + h_s \sin(k_s x),$$

$$\frac{dV_x}{dt} = \frac{F_{fric}^{(x)}}{M_d} \quad \Rightarrow \quad V_x = \frac{F_{fric}^{(x)}}{M_d} t$$

- Resonance $V_x k_s = \Omega_d$ occurs at $t_{res} \approx \Omega_d M_d \big/ k_s F_{fric}^{(x)}$ and impact is large when $S_{res} \equiv t_{res}\Omega_d >> 1$: $\quad \delta y_d(t) \approx h_s \left(\pi S_{res} \right)^{1/2}$

Large amplitude of surface wave $h_s > \rho_i$

- In order to overcome the effect of centrifugal force and confine dust particle in within sheath it is necessary to obey

$$\frac{M_d V_d^2}{R_s} \approx h_s M_d (V_d k_s)^2 \lesssim F_{fric}^{(y)} \approx \rho_i M_d (\Omega_d)^2$$

where $R_s \approx 1/h_s k_s^2$ is the effective radius of wall surface curvature

- For $h_s > \rho_i$ dust particle looses confinement within the sheath before reaching resonance conditions $V_d k_s = \Omega_d$

Numerical modeling

- First we assume that surface is corrugated in x-direction and describe dust particle motion on the (x, y) plane with

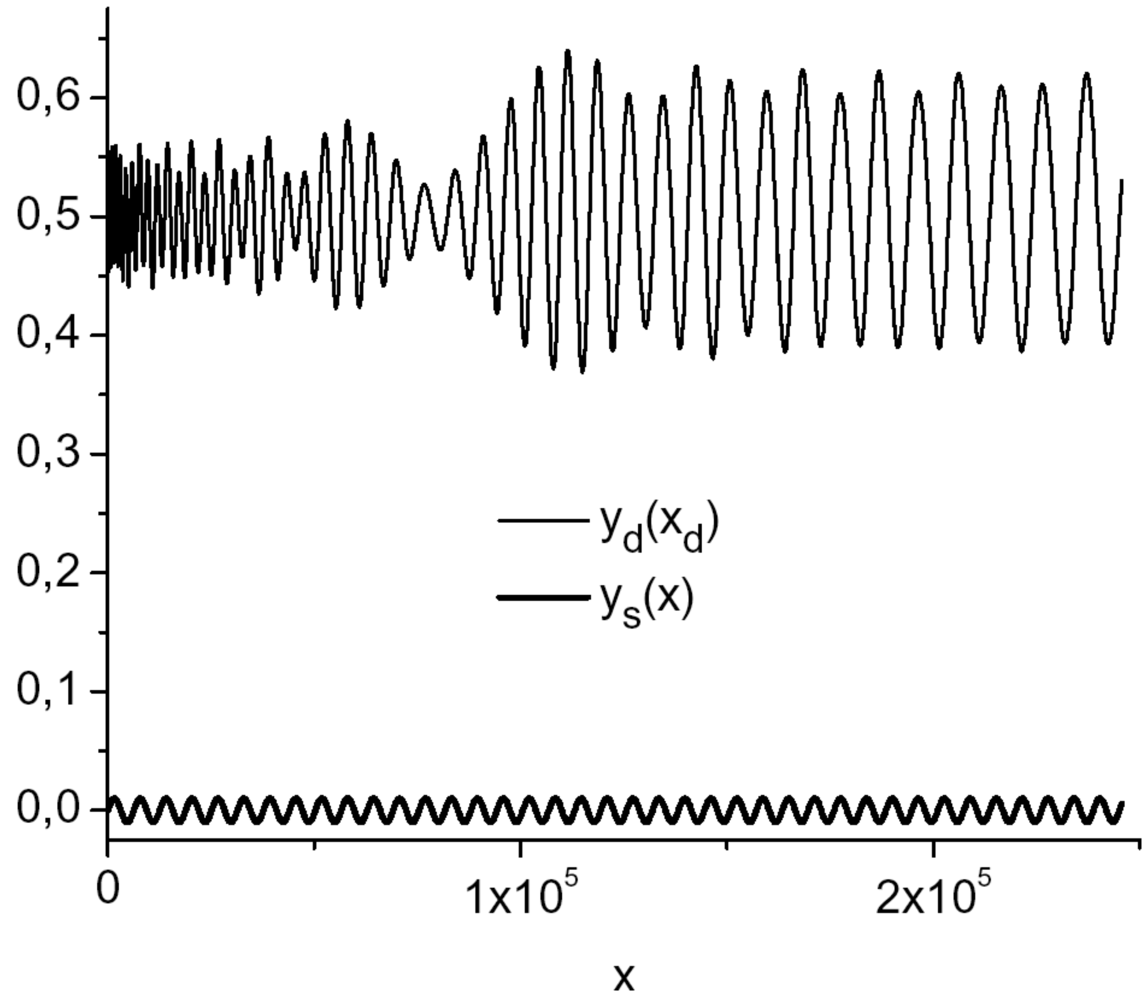
$$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}, \qquad \mathbf{F} = -\nabla\Phi_\perp - \nabla\Phi_{||} \times \mathbf{e}_z,$$

where $\Phi_\perp(x,y) = \hat{\Phi}_\perp(y - y_s(x))$, $\Phi_{||}(x,y) = \hat{\Phi}_{||}(y - y_s(x))$, and $y_s(x)$ determines the shape of the surface

- For the functions $\hat{\Phi}_\perp(y)$ and $\hat{\Phi}_{||}(y)$ we choose

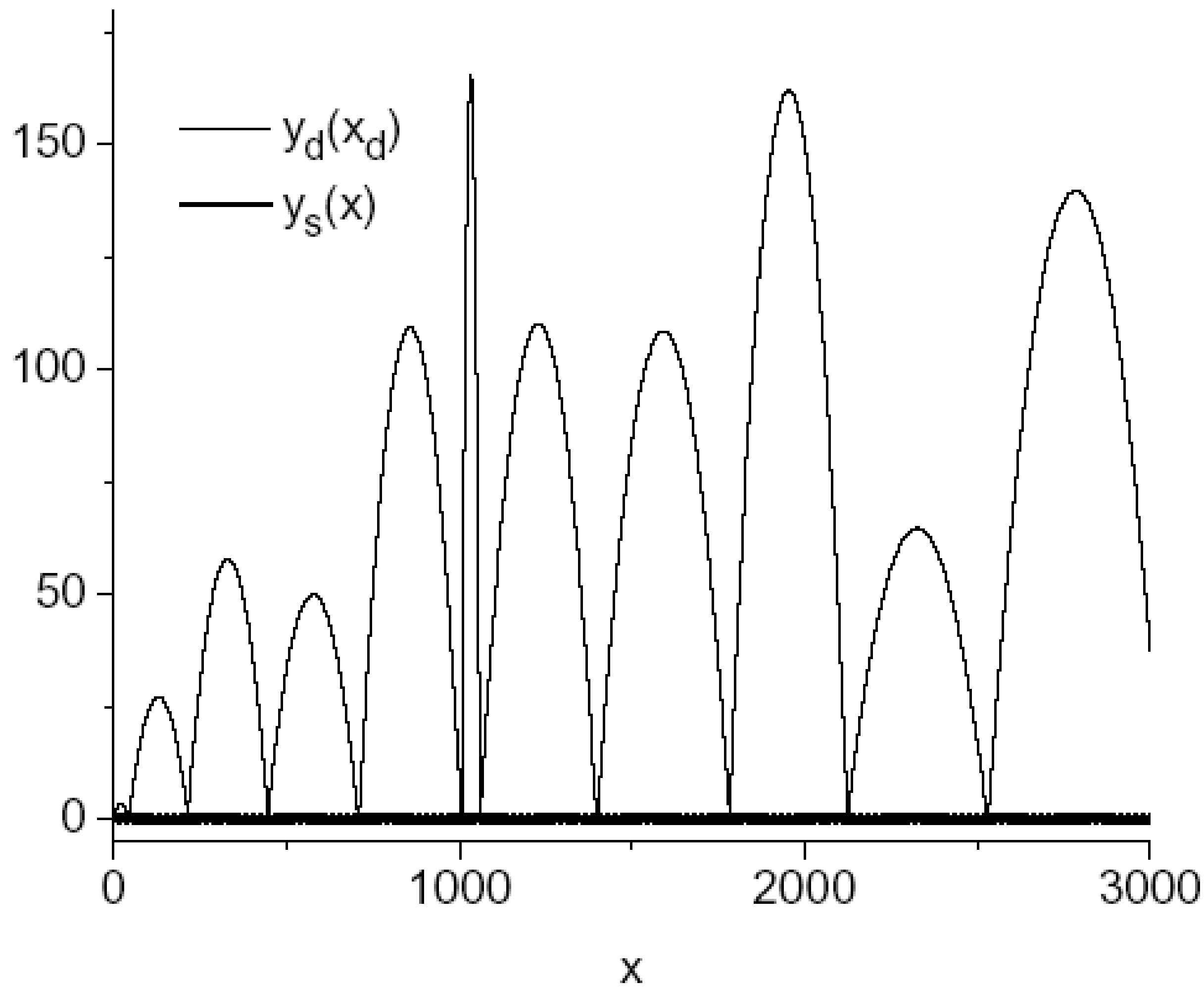
$$\hat{\Phi}_\perp(y) = \alpha F_{sh}\{y + \rho_i \exp((y_{min} - y)/\rho_i)\}, \quad \hat{\Phi}_{||}(y) = F_{sh}\rho_i \exp(-y/\rho_i)$$

- We assume particle specula reflection from the surface

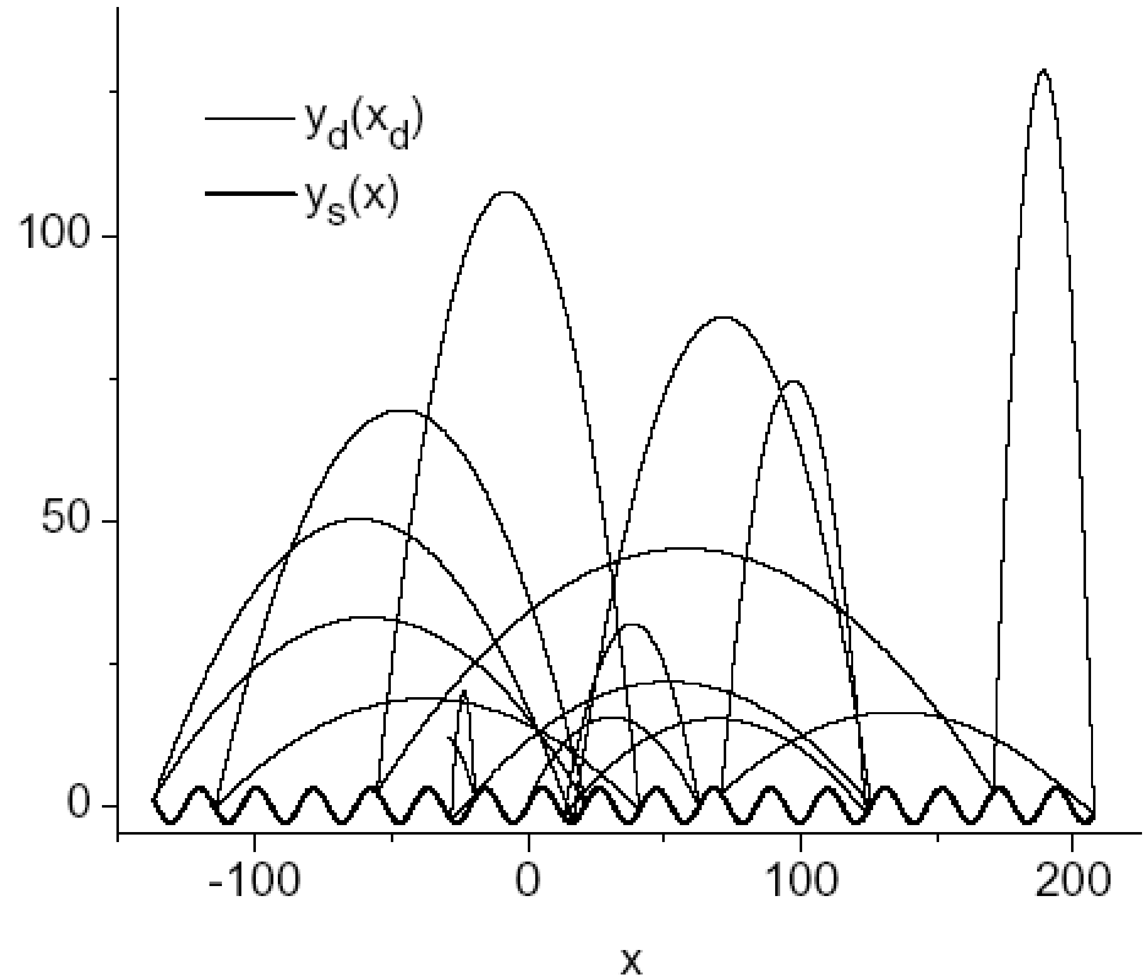


Resonance interaction of dust particle with corrugated surface

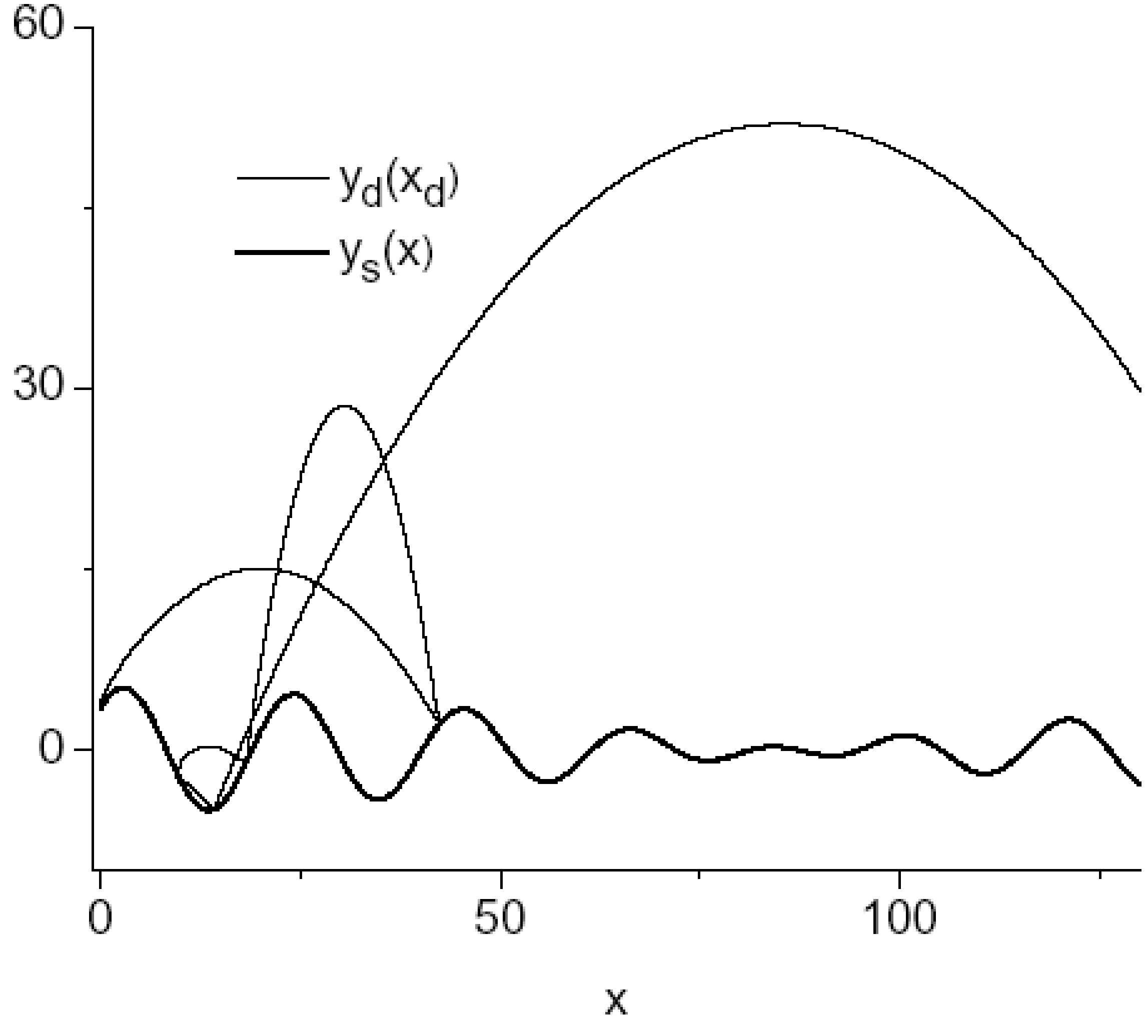
$(h_s / \rho_i = 0.1,\ k_s\rho_i = 10^{-3},\ \alpha = 0.1)$



Flights of dust particle over corrugated surface
$(h_s / \rho_i = 1,\ k_s \rho_i = 0.3,\ \alpha = 0.1)$

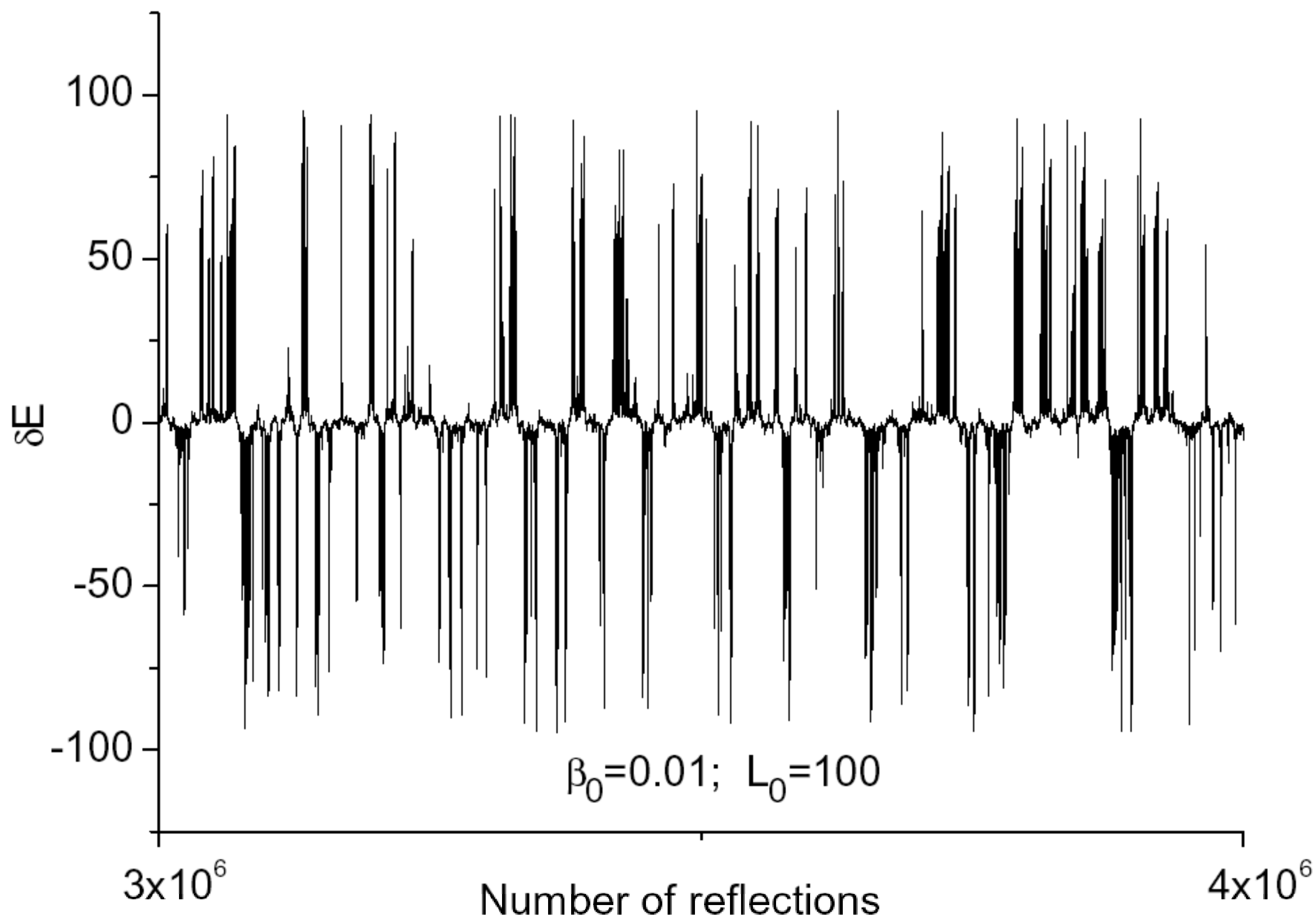


Stochastic flights of dust particle over corrugated surface
($h_s / \rho_i = 3$, $k_s\rho_i = 0.3$, $\alpha = 0.1$)



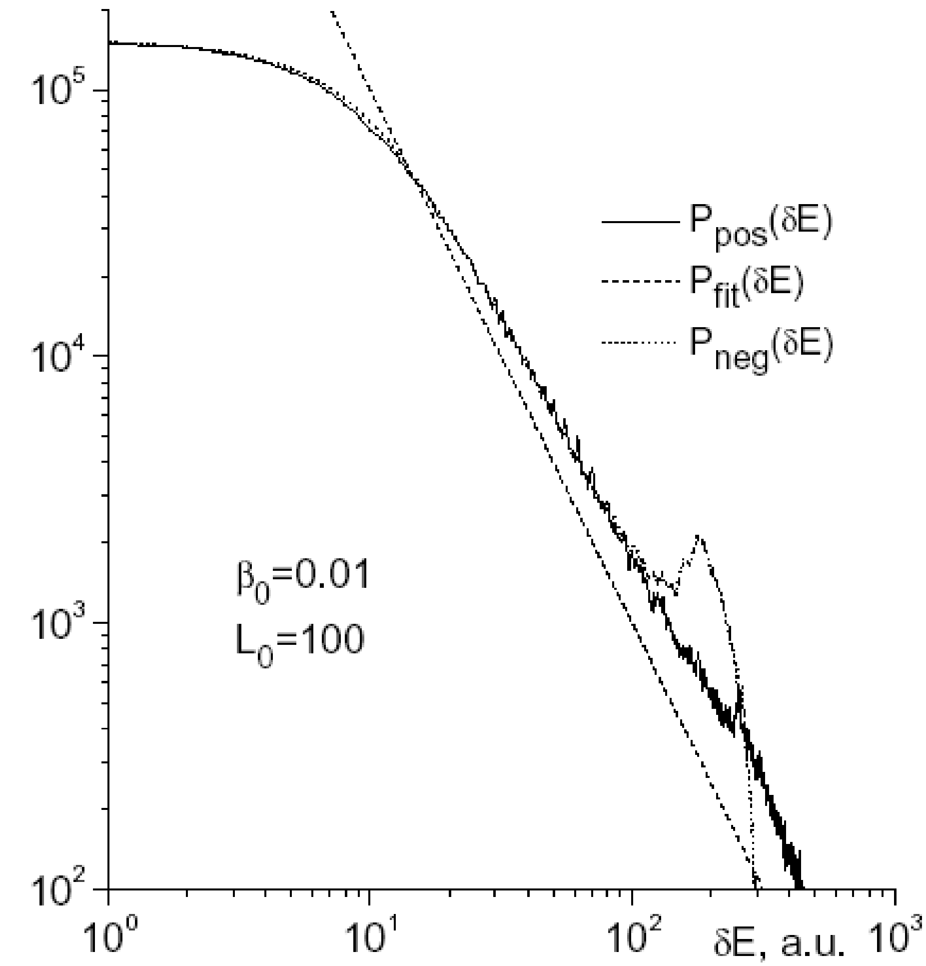
Stochastic flights of dust particle over irregular corrugated surface

$(\langle h_s \rangle / \rho_i = 1,\ \langle k_s \rangle \rho_i = 0.3,\ \langle \delta k_s \rangle \rho_i = 0.1,\ \alpha = 0.1)$

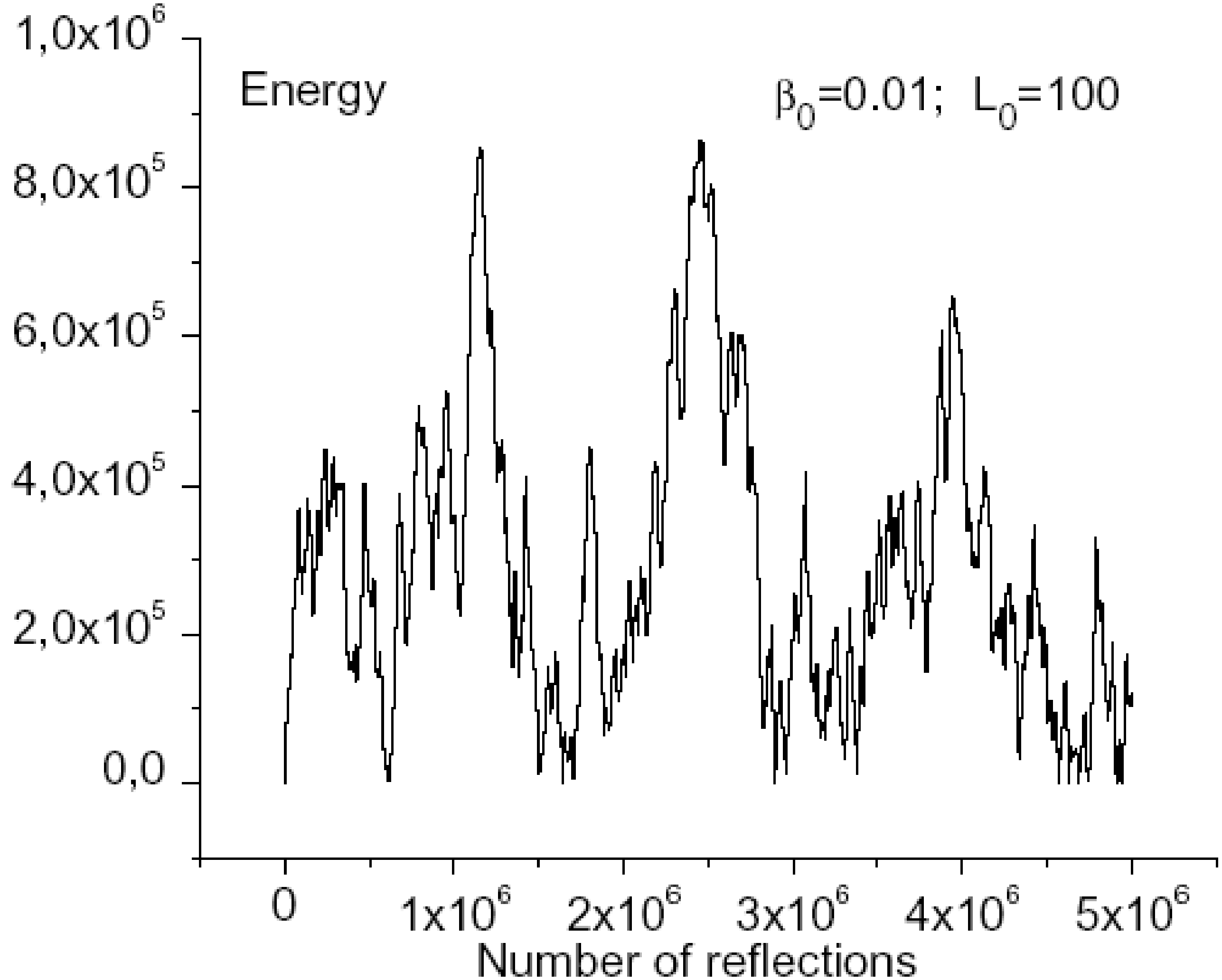


Intermittency in dust particle energy gain ("zig-zag" surface)

$$(y_s(x) = (-1)^i(\beta_0 L_0/4)\{1-2(2x/L_0 - i)\} \text{ for } i \le 2x/L_0 \le i+1)$$

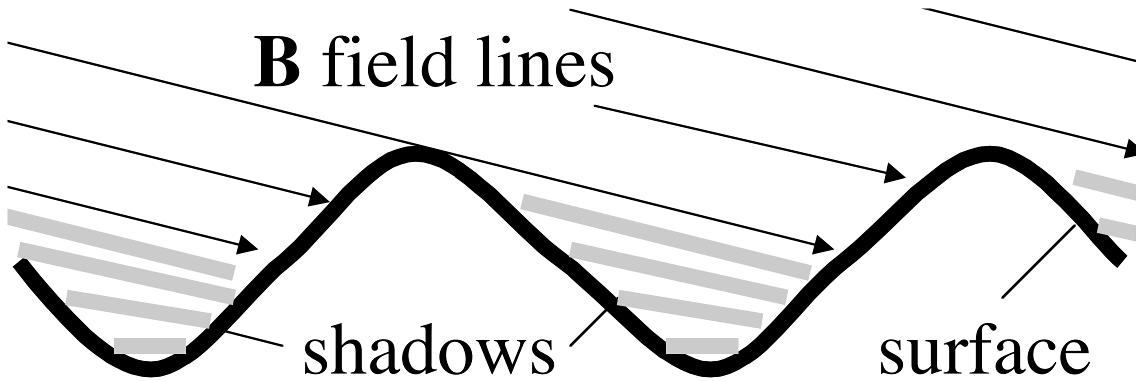


PDF of dust energy gain for “zig-zag” surface, $P_{fit}(\delta E) \propto \delta E^{-2}$



Dust particle energy variation ("zig-zag" surface)

- In the case where surface is corrugated in z-direction (direction of the magnetic field!!!) “shadow” regions may be formed



- Plasma dynamics in “shadow” regions is rather complex and is not understand well yet
- Here we consider the case where corrugation is relatively small and smooth so that no “shadow” regions occur

- With this limitation we can describe dust particle motion on the (y, z) plane with the equations

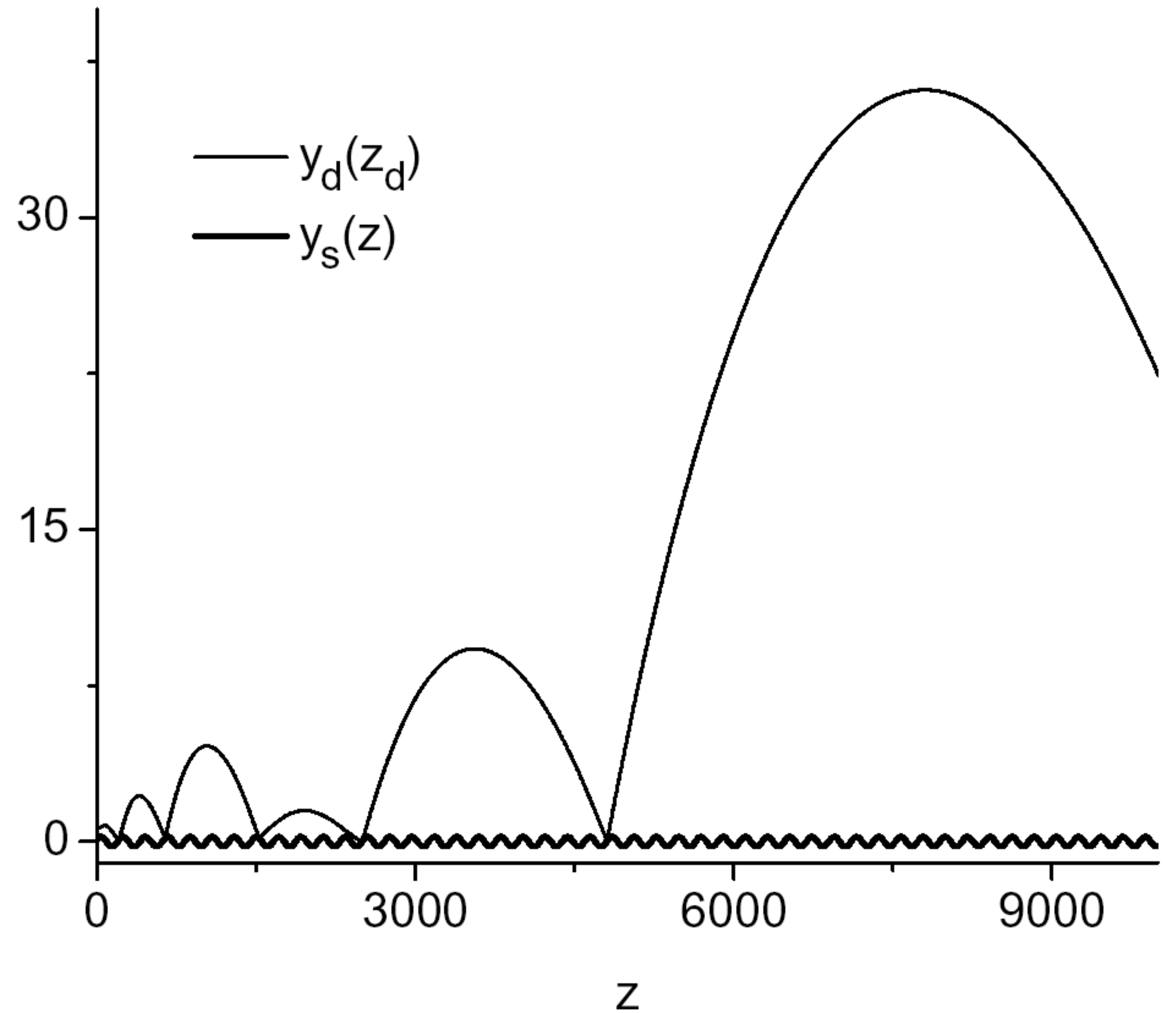
$$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}, \qquad \mathbf{F} = -\nabla\Phi_\perp - \nabla\Phi_{||} \times \mathbf{e}_x,$$

where $\Phi_\perp(y,z) = \hat{\Phi}_\perp(y - y_s(z))$, $\Phi_{||}(y,z) = \hat{\Phi}_{||}(y - y_s(z))$, and $y_s(z)$ determines the shape of the surface

- For the functions $\hat{\Phi}_\perp(y)$ and $\hat{\Phi}_{||}(y)$ we take

$$\hat{\Phi}_\perp(y) = \alpha F_{sh}\left\{y + \rho_i \exp\left((y_{min} - y)/\rho_i\right)\right\}, \qquad \hat{\Phi}_{||}(y) = -F_{sh} y$$

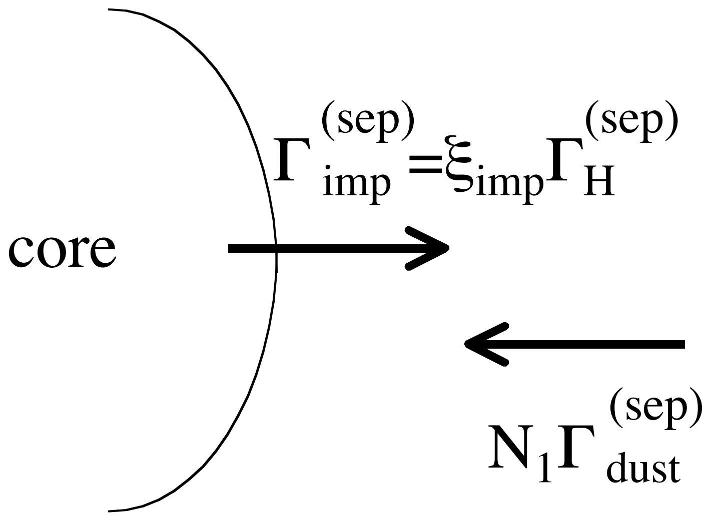
- We assume particle specula reflection from the surface



Flights of dust particle over corrugated surface
$(h_s / \rho_i = 0.5,\ k_s\rho_i = 0.03,\ \alpha = 0.1)$

V. Dust dynamics and core plasma contamination

- Flights of dust particles can result in the motion of dust toward core and contamination of core plasma with impurity



- For $\xi_{imp} \sim 10^{-2}$,

  $\Gamma_H^{(sep)} \sim 10^{21}\ s^{-1}$, and

  $N_1 \sim 10^{13}$ we find:

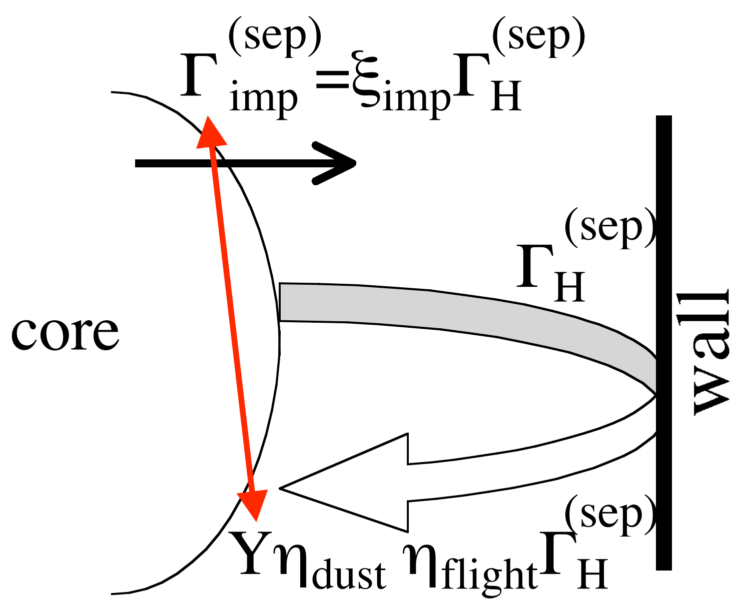
  $\Gamma_{imp}^{(sep)} \sim 10^{19}\ s^{-1} \quad \Rightarrow$

  $\Gamma_{dust}^{(sep)} \sim 10^{6}\ s^{-1}$ and

  $n_{dust} \sim 3 \times 10^{-2}\ cm^{-3}$

Where dust may come from?

- Main chamber wall recycling as a source of dust:



- Y - sputtering yield, η_{dust} - prob. to be converted to dust, η_{flight} - probability to fly toward the core

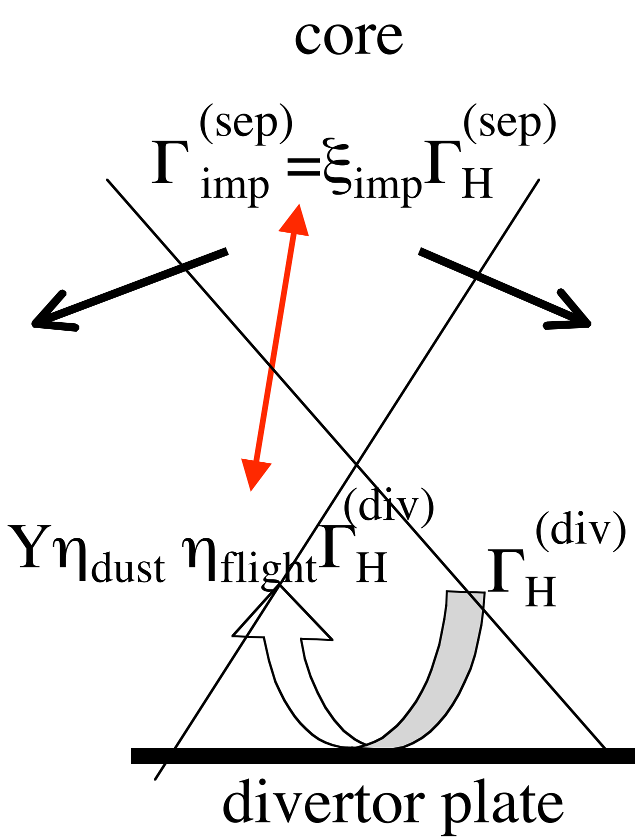
$$\Gamma^{(sep)}_{imp} = \xi_{imp}\Gamma^{(sep)}_{H} =$$

$$= Y\eta_{dust}\eta_{flight}\Gamma^{(sep)}_{H}$$

$$\xi_{imp} \sim Y \sim 10^{-2} \Rightarrow \eta_{dust}\eta_{flight} \approx 1!$$

It looks to be unlikely the case!

- **Divertor as a source of dust looks plausible!**



$$\Gamma_{H}^{(div)} \sim 10^{23} s^{-1} >$$

$$> \Gamma_{H}^{(sep)} \sim 10^{21} s^{-1}$$

$\Rightarrow$ higher sputtering rate $\Rightarrow$ easy to satisfy impurity balance

$$\Gamma_{imp}^{(sep)} = \xi_{imp}\Gamma_{H}^{(sep)} =$$

$$= Y\eta_{dust}\eta_{flight}\Gamma_{H}^{(div)}$$

- Y~3%, η_{dust}~3%, and η_{flight}~10% give relevant impurity flux $\Gamma_{imp}^{(sep)} \sim 10^{19}\ s^{-1}$

VI. Conclusions

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

- It is feasible that dust formation in and transport from divertor region play an important role in core plasma contamination
- However, even then, dust particle density around separatrix is $\sim 3\times10^{-2}\ \mathrm{cm}^{-3}$, 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!