On Dust Particle Dynamics in Tokamak Edge Plasma

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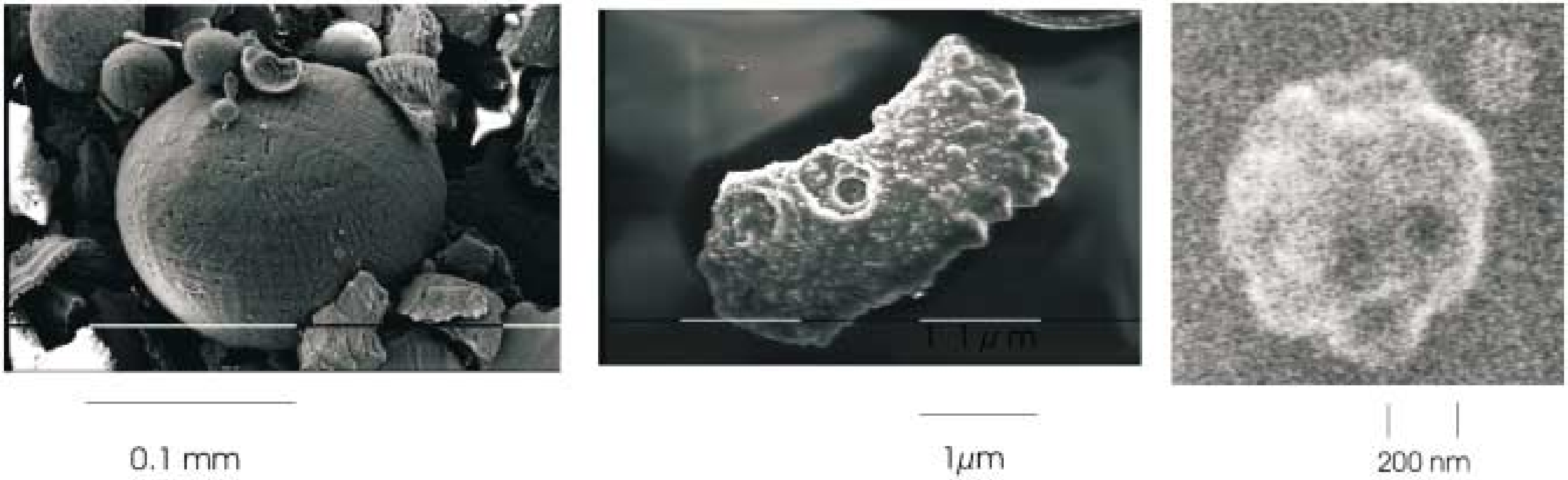
I. Introduction

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



Winter PPCF 1998

- But so far an impact of dust on the performance of current fusion devices is not clear

1) evidence of dust particles in fusion devices

a) *JIPPT-IIU* (NIFS, Japan)

[K. Narihara, et al., Nuclear Fusion 37 (1997) 1177]

_large scattering signal in Thomson scattering system

_most cases: after discharge with disruption

_ several cases : during discharges

__ 2 _   m : small solid particles such as flakes and microparticles

_ ~ 100 ms after disruption

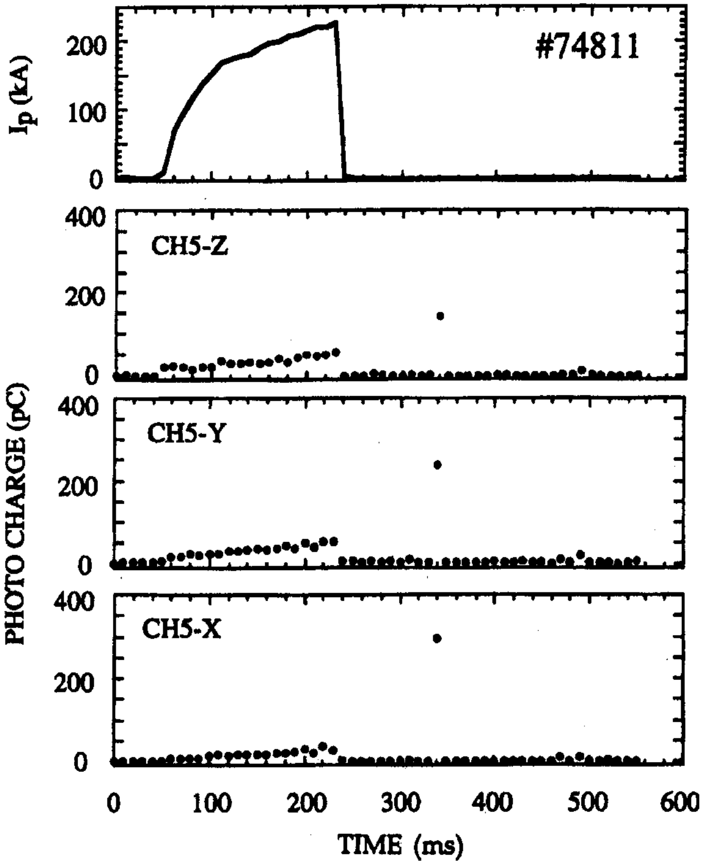
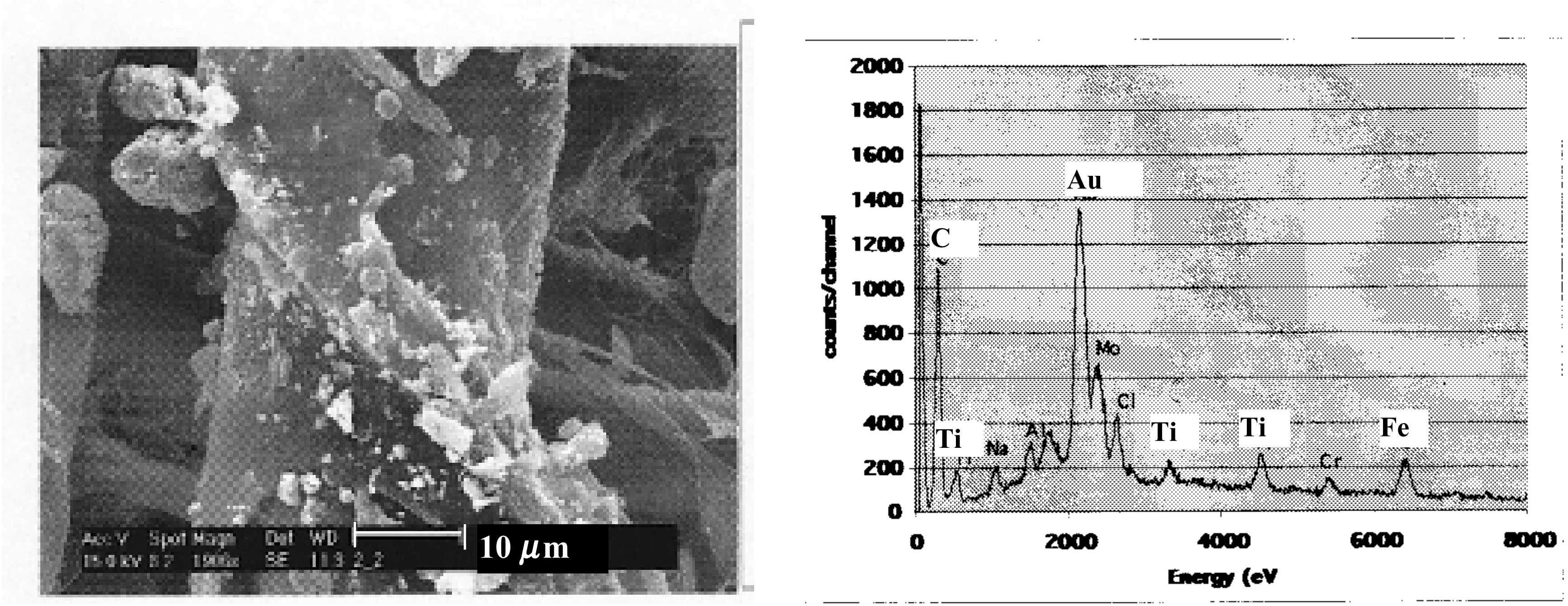
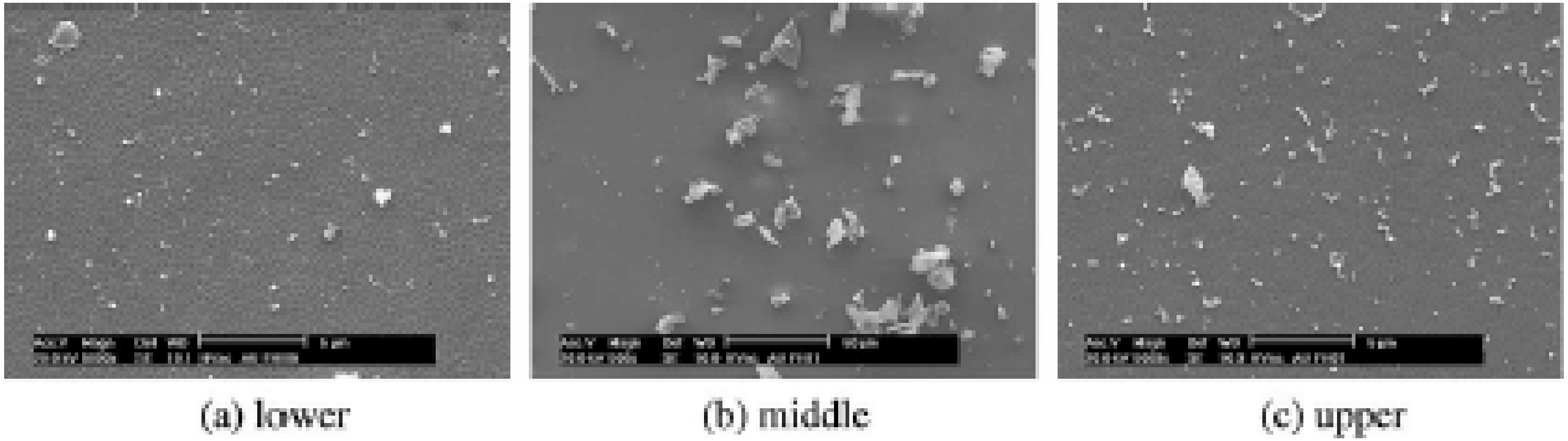


FIG. 1. (a) Raw scattering signals on the fift
polychromator. X, Y and Z denote the spec
channels. Large scattering signals appeare
350 ms. *Similar signals appeared on channe*
21, 22, 25 and 27 at different times. A plasm
current Ip is shown for reference.

[J. Sharpe, A. Sagara, et al., J. Nucl. Mater. 313-316 (2003) 455]



Carbon, steel, and titanium particles collected from LHD coil armor. The gold results from the coating of particles which is used to avoid charging effects on the non-conductive filter substrate.



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

Fig. 1. Representative SEM photomicrographs of particulate collected from (a) lower, (b) middle, and (c) upper regions of ASDEX-Upgrade.

Sharpe et al., J. Nucl. Mater 2003

- However, an existence of dust particles in burning plasma experiments poses a high threat: it can contain toxic and radioactive materials and retain tritium

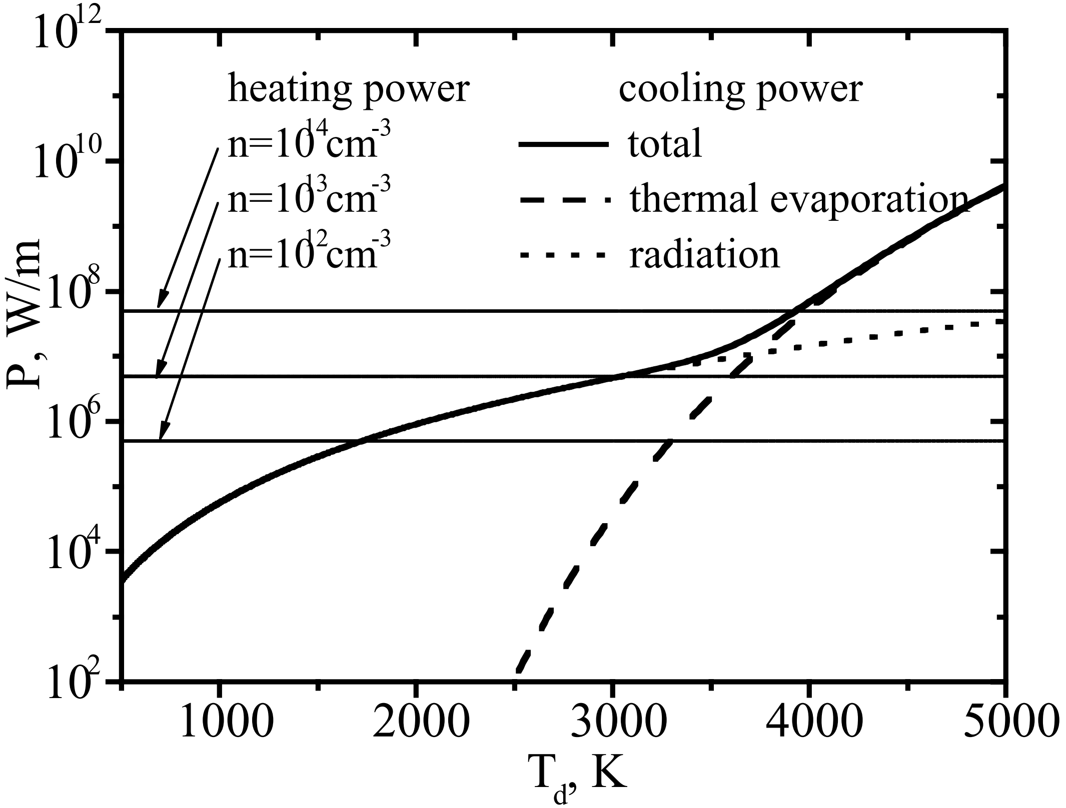
- We show that dust in fusion devices can be very mobile and during one shot dust particles can move through edge plasma on distances much larger that the scrape-of-layer (SOL) width and comparable to tokamak radii

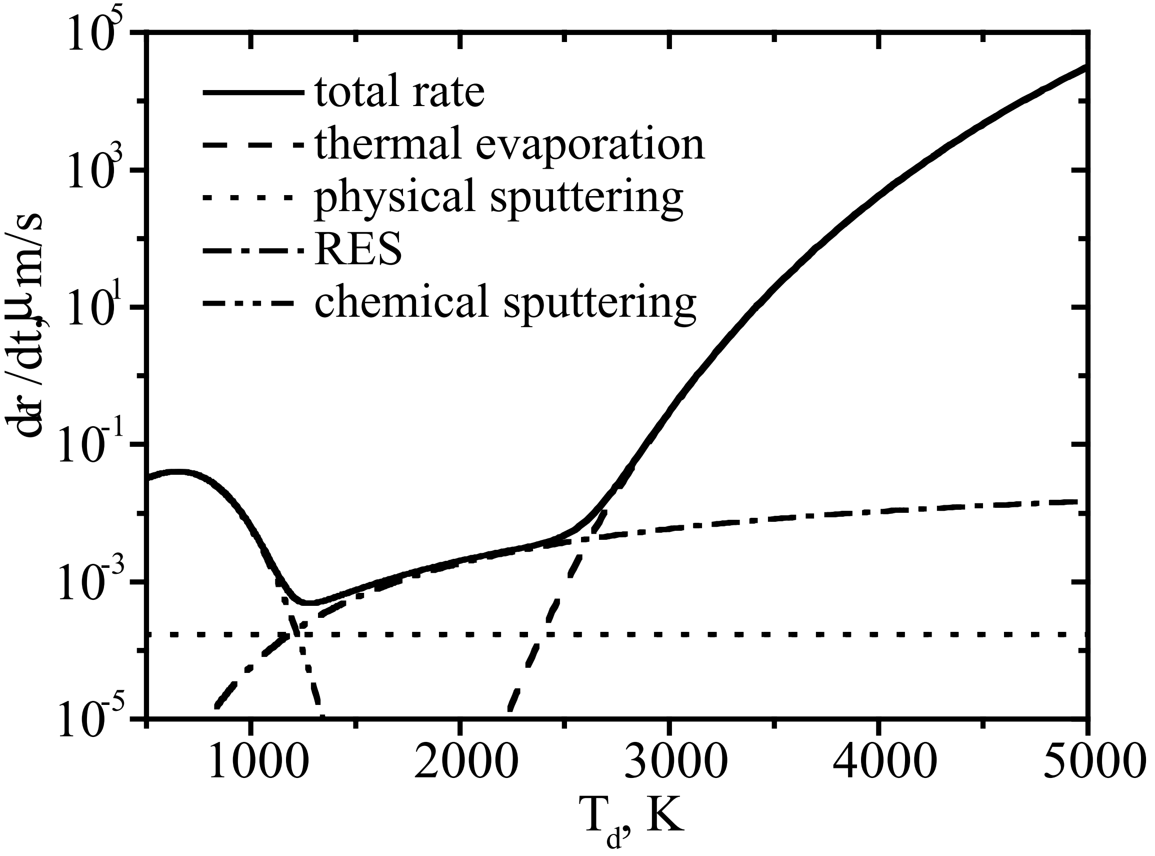
- Our estimates indicate that it is plausible that transport of dust particles can be an important mechanism of impurity transport into core plasma

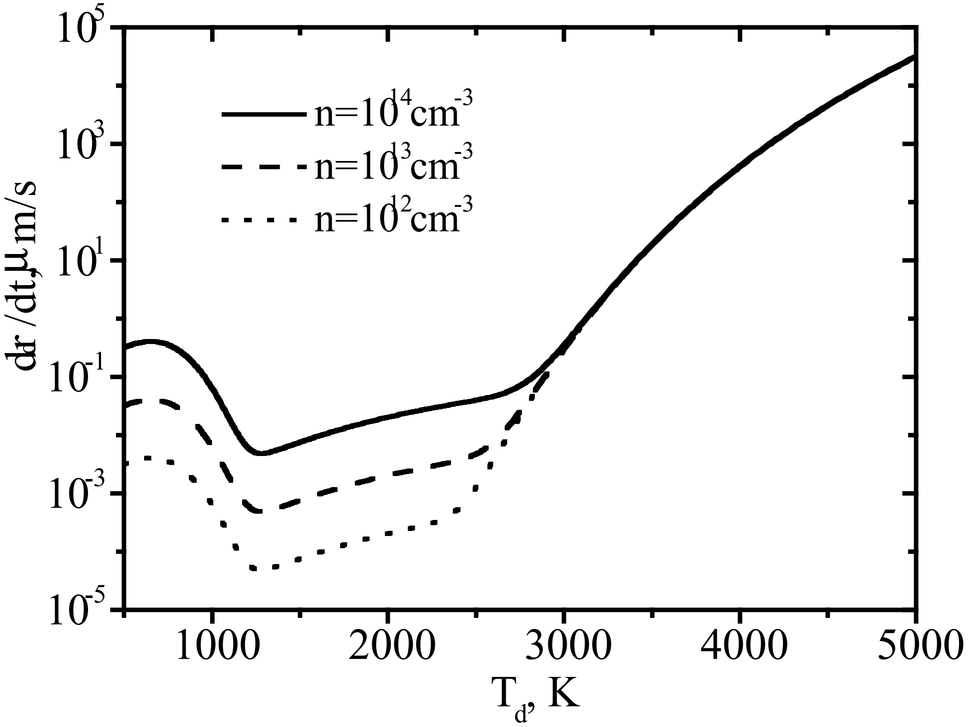
II. Dust power and particle balance in tokamak

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
- In order to simplify our estimates we will assume that electron and ion temperatures are close to $T_i \approx T_e = T \sim 10$ eV and plasma density is about $3\times10^{13}\,\mathrm{cm}^{-3}$. Such parameters are rather typical for tokamak divertor plasma


heating power
$n=10^{14}cm^{-3}$
$n=10^{13}cm^{-3}$
$n=10^{12}cm^{-3}$
cooling power
total
thermal evaporation
radiation
P, W/m^2
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1000
2000
3000
4000
5000
T_d, K


total rate
thermal evaporation
physical sputtering
RES
chemical sputtering
dr /dt, μm/s
T_d, K
10^5
10^3
10^1
10^-1
10^-3
10^-5
1000
2000
3000
4000
5000



- Yes, in fusion edge plasma dust particle of ~1 μm scale can live long enough to contribute to dust particle transport!

III. Dust in magnetized sheath

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

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

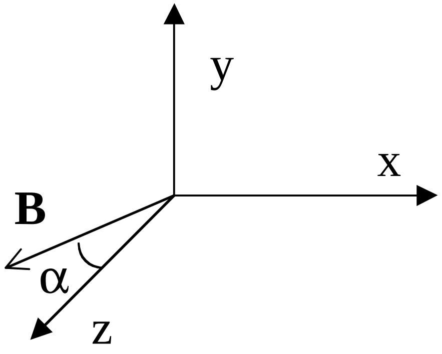
- The forces acting on dust particle

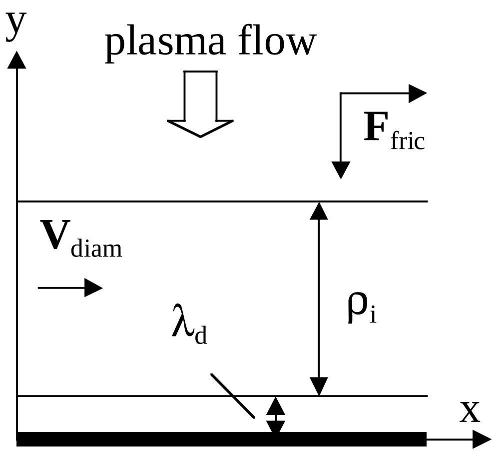
$$M_d \frac{d\mathbf{V}_d}{dt} = \mathbf{F}$$

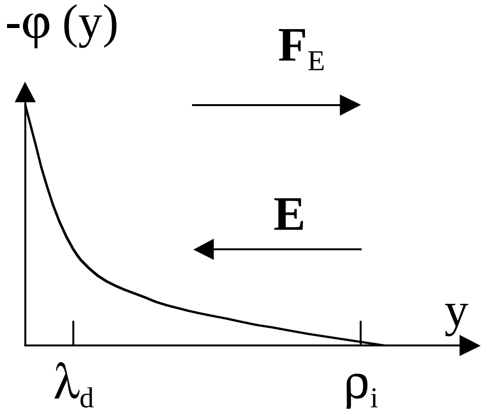
$$\mathbf{F}_E = -eZ_d\mathbf{E}, \qquad \mathbf{F}_{fric} = \varsigma_F \pi r_d^2 M_i n V_i \left(\mathbf{V}_p - \mathbf{V}_d\right),$$

$$\mathbf{F}_g = M_d\,\mathbf{g}, \qquad \mathbf{F}_M = -\pi r_d^3 \varepsilon_M \frac{B_{sat} B_{tor}}{4\pi R}\frac{\mathbf{R}}{R},$$

- Estimates show that electric and friction forces dominate in edge plasmas
- In fusion devices dust, probably, is formed at the wall surface
- Therefore, plasma environment near the wall (sheath) important for dust dynamics

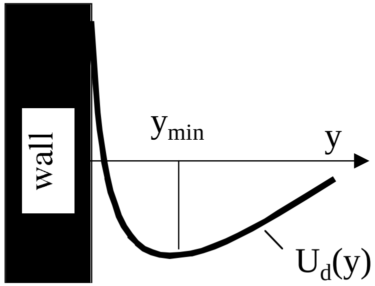






- Dust motion in y-direction can be described by effective potential

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

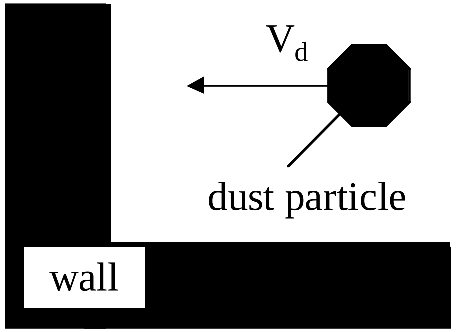


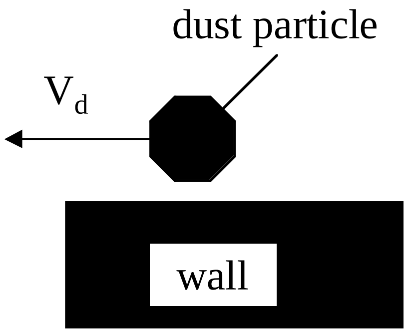
- In case of small oscillations in the vicinity of y_{min}, such oscillations can be described by the following equation

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

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

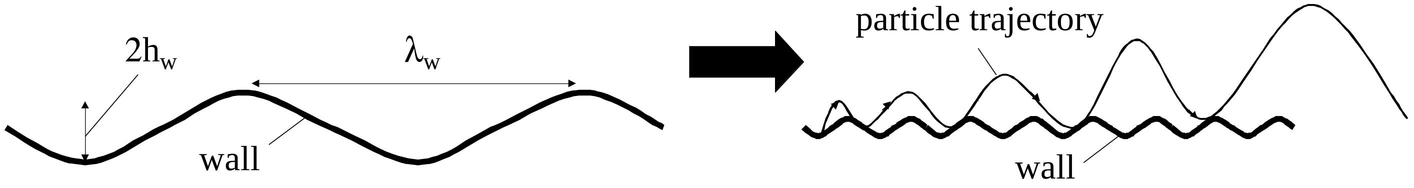
- In both z- and x- directions friction forces continuously accelerate dust particle
- Due to this acceleration dust particle gains speed $\sim 3\times10^{3}\ \mathrm{cm/s}$ in $\sim 10^{-3}\ \mathrm{s}$
- Therefore, surface inhomogeneity (corner, step) can cause particle to fly





IV. Impact of surface roughness and dust flights

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



a) Small amplitude of surface wave $h_w << \rho_i$

$$\frac{d^2y}{dt^2} = -\Omega_d^2 (y - y_{min}(x)), \qquad y_{min}(x) = \bar{y}_{min} + h_w \sin(k_w x),$$

$$\frac{d^2x}{dt^2} = \frac{F_{fric}^{(x)}}{M_d} \quad \Rightarrow \quad x = \frac{F_{fric}^{(x)}}{M_d}\frac{t^2}{2},$$

- Resonance occurs at $t_{res} \approx \Omega_d M_d / k_w F_{fric}^{(x)}$ and it is meaningful resonance if $S_{res} \equiv t_{res}\Omega_d >> 1$

  For $S_{res} >> 1$ we can integrate the equations of motion and find

  $$\tilde{y}_d(t) \approx h_w (\pi S_{res})^{1/2} \sin\left(\frac{\pi}{4} - \frac{S_{res}}{2}\right)\sin\left(\Omega_d t + \frac{\pi}{4}\right)$$

  For $|\tilde{y}_d(t)| \gtrsim \rho_i \Rightarrow h_w \gtrsim \rho_i / S_{res}$ we expect large excursion of dust trajectory

b) Large amplitude of surface wave $h_w >> \rho_i$

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

$$\frac{M_d V_d^2}{R_w} = \frac{2F_{fric}^{(x)}\,\Delta}{R_w} \lesssim F_{fric}^{(y)} \approx \alpha F_{fric}^{(x)},$$

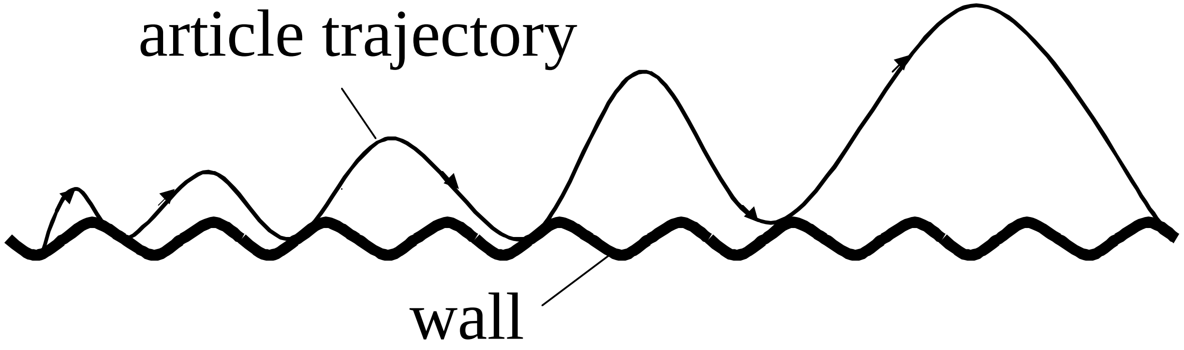
where $R_w \approx 1/h_w k_w^2$ is the effective wall curvature radius and Δ is distance along the wall passed by the particle

Particle cannot be confined anymore within the sheath after

$$\Delta \approx \Delta_{conf} \equiv \frac{1}{2}\frac{\alpha}{h_w k_w^2}$$

- Analyzing resonance conditions we find that for $h_w >> \rho_i$ dust particle looses confinement within the sheath before reaching resonance conditions

- Once particle looses confinement within the sheath it starts to fly and bounce time to time the sheath



We notice that the “rejection” of the particle by the wall can be due to both of the sheath electric field and wall structure itself

Just to illustrate the process of particle flights, we consider the case where the wall surface is corrugated in x-direction according to the following expression

$$y_w(x) = (-1)^i h_w \left\{ 1 - 2\left(\frac{2x}{\lambda_w} - i \right) \right\}, \quad \text{for } i \le \frac{2x}{\lambda_w} \le i+1, \qquad (36)$$

where i is the integer number, and h_w and λ_w are the effective magnitude and wave-length of the corrugation

We will assume that $\lambda_w >> h_w >> \rho_i$ and introduce the angle $\beta_w \equiv 4h_w / \lambda_w << 1$, so that the inclination of the surface to x-coordinate is $\pm\beta_w$

We will assume that the energy of dust particle is large and after it penetrates through the sheath it experiences specula reflection by the wall.

Assume that initially dust particle in the sheath was about the minimum of potential well U_d located in the sheath

Then it will be accelerated along the surface by the force $F_{fric}^{(sh)}$ until it reaches breaking point of the surface at $x = i\lambda_w / 2$ and flies, gaining, by than time the energy

$$E_1 \sim F_{fric}^{(sh)} \lambda_w . \tag{37}$$

With increasing particle energy its re-entry of the sheath occurs at a distance from original take off, which is much larger than λ_w

Therefore we can assume that particle randomly hits positive and negative slop of the wall

As a result, the pitch angle of the particles leaving the sheath

$$\mu_{\mathrm{dw}} = \mathrm{sign}\left(V_{\mathrm{dw}}^{(x)}\right)\frac{V_{\mathrm{dw}}^{(y)}}{V_{\mathrm{dw}}^{(x,y)}}, \qquad (38)$$

(where $\left(V_{\mathrm{dw}}^{(x,y)}\right)^2 \equiv 2E_{\mathrm{dw}}^{(x,y)} / M_{\mathrm{d}} = \left(V_{\mathrm{dw}}^{(y)}\right)^2 + \left(V_{\mathrm{dw}}^{(x)}\right)^2$ and where $V_{\mathrm{dw}}^{(\ldots)}$ are the particle velocities taken at the moment when particle leaves the wall) is randomly changed by $\beta_w << 1$ and the evolution of μ_{dw} can be described as a diffusive process

We will consider only this evolution assuming that averaged value of pitch angle, $0 < \langle \mu_{dw} \rangle < 1$

Notice that in this case particle scattering from the wall cannot flip the sign of $V_{dw}^{(x)}$ which, then, coincides with the direction of diamagnetic ion flow in the sheath, which accelerates dust particle

Then $\langle \mu_{dw} \rangle$ can be found from diffusive equation

$$\frac{d\langle\mu_{dw}\rangle^2}{dt} \sim D_\mu, \tag{39}$$

with the effective diffusion coefficient

$$D_\mu \sim \frac{\beta_w^2}{\Delta t_{coll}}, \tag{40}$$

and where Δt_{coll} is the time between two consecutive collisions

Taking into account that Δt_{coll} is determined by reversing the sing of y-component of the velocity by friction force we find

$$\Delta t_{\mathrm{coll}} \sim \frac{\left(2\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle M_{\mathrm{d}}\right)^{1/2}\left\langle \mu_{\mathrm{dw}}\right\rangle}{\alpha F_{\mathrm{fric}}^{\mathrm{sh}}}. \qquad (41)$$

Next we consider the particle energy gain

Dust particle is exposed by accelerating force of diamagnetic flow $F_{\mathrm{fric}}^{\mathrm{sh}}$ for the time, τ_{coll}, when particle moves through the sheath with the thickness $\sim \rho_i$

Therefore, for $\langle \mu_{\mathrm{dw}} \rangle > \beta_{\mathrm{w}}$, we have

$$\tau_{\mathrm{coll}} \sim \frac{\rho_{\mathrm{i}}}{\left(2\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle M_{\mathrm{d}}\right)^{1/2}\langle\mu_{\mathrm{dw}}\rangle}, \tag{42}$$

and

$$\frac{d\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle}{dt} \sim \frac{F_{\mathrm{fric}}^{\mathrm{sh}}\tau_{\mathrm{coll}}\left(2\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle M_{\mathrm{d}}\right)^{1/2}}{\Delta t_{\mathrm{coll}}}. \tag{43}$$

Assuming $\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle > E_1$ from Eq. (38)-(42) we find

$$\left\langle E_{\mathrm{dw}}^{(x,y}\right\rangle \sim F_{\mathrm{fric}}^{\mathrm{sh}}\rho_{\mathrm{i}}\left(\frac{\alpha^2}{\beta_{\mathrm{w}}^8}\frac{t^2F_{\mathrm{fric}}^{\mathrm{sh}}}{M_{\mathrm{d}}\rho_{\mathrm{i}}}\right)^{1/7}, \tag{44}$$

$$\langle \mu_{dw} \rangle \sim \left\{ \alpha \beta_w^3 \left(\frac{t^2 F_{fric}^{sh}}{M_d \rho_i} \right)^{1/2} \right\}^{2/7} . \qquad (45)$$

Taking into account that our analysis is limited by $\langle \mu_{dw} \rangle < 1$, we find that our approximation works for

$$t \lesssim t_\mu = \frac{1}{\alpha \beta_w^3} \left(\frac{M_d \rho_i}{F_{fric}^{sh}} \right)^{1/2} . \qquad (46)$$

By the time $t \sim t_\mu$ dust particle moves at the distance,

$$L_\mu \sim \frac{\rho_i}{\alpha \beta_w^4} , \qquad (47)$$

along the wall in x-direction and gains the energy

$$\left\langle E_{dw}^{(x,y} \right\rangle_{\mu} \sim M_d \left\langle \left(V_d^{(x)}\right)^2 \right\rangle \sim M_d \left\langle \left(V_d^{(y)}\right)^2 \right\rangle \sim \frac{F_{fric}^{sh}\rho_i}{\beta_w^2} \sim \alpha\beta_w^2 F_{fric}^{sh} L_{\mu}. \qquad (48)$$

In order to satisfy inequality $\left\langle E_{dw}^{(x,y} \right\rangle > E_1$ we find the following

restriction

$$h_w < \frac{1}{4}(\lambda_w \rho_i)^{1/2}. \qquad (49)$$

At $t \gtrsim t_{\mu}$ x-component of particle velocity can turn to be negative due to

scattering off the wall

As a result particles can fly back toward their initial position and start to lose the energy

In the case where wavy wall structure like (36) would be in z-direction then treatment of dust particle motion similar to that we performed gives us the following asymptotic dependences

$$\left\langle E_{dw}^{(y,z)} \right\rangle \sim \left(F_{fric}^{(sh)} t\right)^2 \Big/ M_d , \tag{50}$$

$$\langle \mu_{dw} \rangle \sim \left(\alpha\beta_w^2\right)^{1/3} \ln\left(\left\langle E_{dw}^{(y,z)} \right\rangle \Big/ E_1\right), \tag{51}$$

where the notation is obvious

Notice that in this case energy of the particle increases $\propto t^2$ due to ion friction force caused by plasma flow along the magnetic field lines, which exist in entire recycling region

V. Dust and core contamination

- Such flights of dust particles can result in their motion toward core and contamination of core plasma with impurity
- Assuming that main material dust consist of is carbon we find that in each dust particle with $r_d \sim 3\times10^{-4}$ cm and $\tilde{\rho}_d \sim 2\ \mathrm{g/cm}^3$ there are $N_C \sim 10^{13}$ carbon atoms

- In order to maintain impurity fraction, ξ_{imp}, in the core, the carbon influx through separatrix should be about $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} = \xi_{\mathrm{imp}} \Gamma_{\mathrm{H}}^{(\mathrm{sep})}$, where $\Gamma_{\mathrm{H}}^{(\mathrm{sep})}$ is the flux of hydrogenic species though separatrix
- For $\xi_{\mathrm{imp}} \sim 10^{-2}$ and $\Gamma_{\mathrm{H}}^{(\mathrm{sep})} \sim 10^{21}\ \mathrm{s}^{-1}$ we find $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} \sim 10^{19}\ \mathrm{s}^{-1}$ and it would take the flux, $\Gamma_{\mathrm{d}}^{(\mathrm{sep})} \sim 10^{6}\ \mathrm{s}^{-1}$, of dust particle to establish required impurity influx

- Assuming that dust particles penetrate into the core through an area $\sim 3\times10^{4}\ \mathrm{cm}^{2}$ and dust particle speed is $\sim 10^{3}\ \mathrm{cm/s}$ we find dust particle density at separatrix $n_{d} \sim 3\times10^{-2}\ \mathrm{cm}^{-3}$

Where this dust may come from?

- Assume that carbon dust is originated at the walls of main chamber due to plasma flux to the wall
- However, since carbon sputtering yield, Y_C, is about a few percent, in order to maintain about one percent of core impurity fraction, supplied to the core as a dust, we should assume that roughly ~100% of sputtered carbon is transformed into dust and then flies to the core

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

It looks to be unlikely the case!

- **Another possibility, dust formation in the vicinity of divertor striking points, looks much more plausible!**
- Indeed, due to strong plasma recycling in the divertor, plasma flux to divertor targets, $\Gamma_{\mathrm{H}}^{(\mathrm{div})}$, can easily be as high as $0^{23}\ \mathrm{s}^{-1}$
- Then carbon influx into core $\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} \sim 10^{19}\ \mathrm{s}^{-1}$ with dust can be

  written as follows

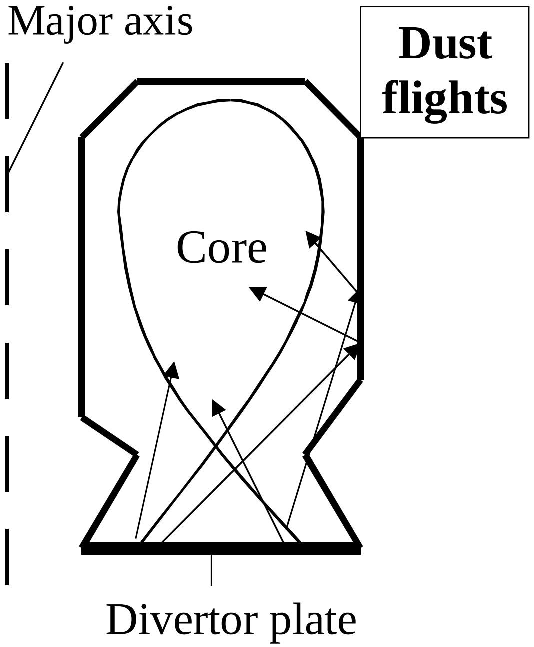
$$\Gamma_{\mathrm{imp}}^{(\mathrm{sep})} = Y_{\mathrm{C}} \eta_{\mathrm{dust}} \eta_{\mathrm{flight}} \Gamma_{\mathrm{H}}^{(\mathrm{div})}$$

where η_{dust} is the fraction of sputtered carbon converted into dust,

η_{flight} is the “flying” fraction of dust, which flies to the core

- With, for example, Y_C~3% of sputtering yield, it gives sputtered carbon flux in divertor to be $\sim 3\times10^{21}\ \mathrm{s}^{-1}$
  - If only η_{dust}~3% of these carbon atoms will be transformed to dust and, then, only η_{flight}~10% of dust particles will be "launched" towards the core, the relevant impurity influx $\Gamma_{imp}^{(sep)} \sim 10^{19}\ \mathrm{s}^{-1}$ through the saparatrix will be established

$$\Gamma_{imp}^{(sep)} = Y_C \eta_{dust} \eta_{flight} \Gamma_H^{(div)} \sim 10^{19}\ \mathrm{s}^{-1}$$



VI. Conclusions

- Due to acceleration by plasma flows, dust particles can have a very high speed ($\sim 10^3$ cm/s and even higher)
- Interactions of dust particles with surface inhomogeneities (including micro-roughness as well as steps, corners, etc.) can cause dust particle flights toward tokamak 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 $\sim 3\times10^{-2}$ cm^{-3}, which makes it difficult to diagnose