Introduction to Plasma-material interactions (PMI) in Fusion Devices

U. von Toussaint

With material generously supplied by K. Krieger, M. Rubel, H.S. Bosch, R. Neu, J. Roth, J. Linke, A. Manhardt, K. Schmid, M. Reinelt, AUG Team, JET TF-E Team, TEXTOR-Team

Materials for the plasma facing wall of a fusion reactor are determined by plasma-material interactions

↓

What are the driving forces for the study of these interactions?

Assessment of

Material lifetime

Tritium inventory

Formation of debris

Economical aspects

Safety aspects

Outline

Introduction	Controlled nuclear fusion Why a vacuum vessel? Technical boundary conditions Plasma-wall contact concepts Plasma-material interaction
Lifetime of components / plasma impurities	Material erosion processes Degradation of mechanical strength by heat and neutrons Plasma acceptance for impurities
Heat removal	Engineering concepts Material mobilisation by transients Degradation by neutrons
Radioactive inventory / integrity of wall configuration	Formation of T inventories Migration of wall material

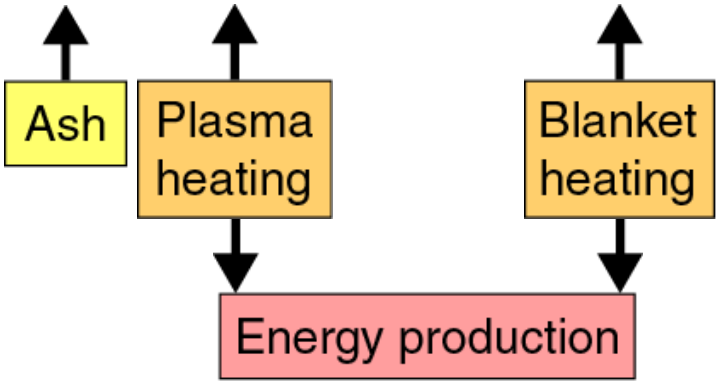
Outline

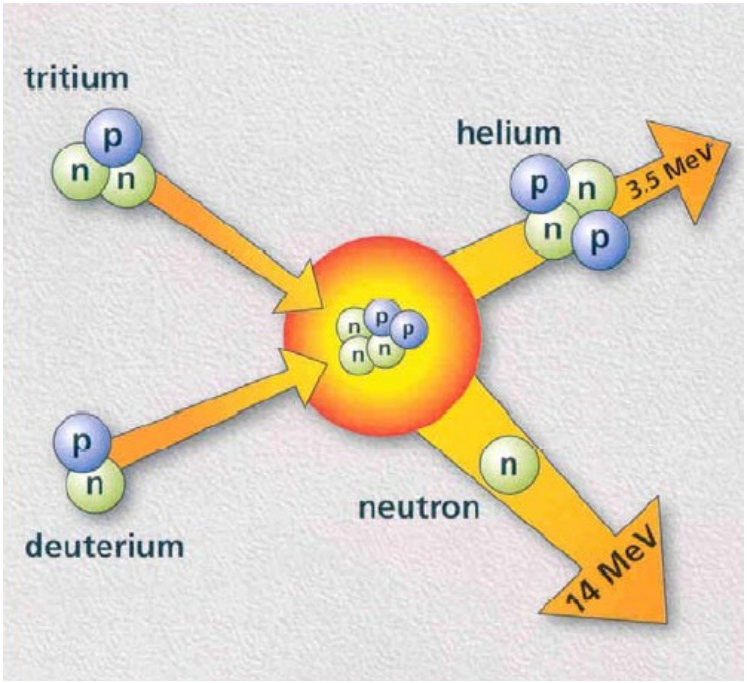
Introduction	Controlled nuclear fusion Why a vacuum vessel? Technical boundary conditions Plasma-wall contact concepts Plasma-material interaction

Nuclear fusion reaction

Most promising reaction (highest <σv>):

$$D + T \rightarrow \alpha\ (3.5\ MeV) + n\ (14.1\ MeV)$$

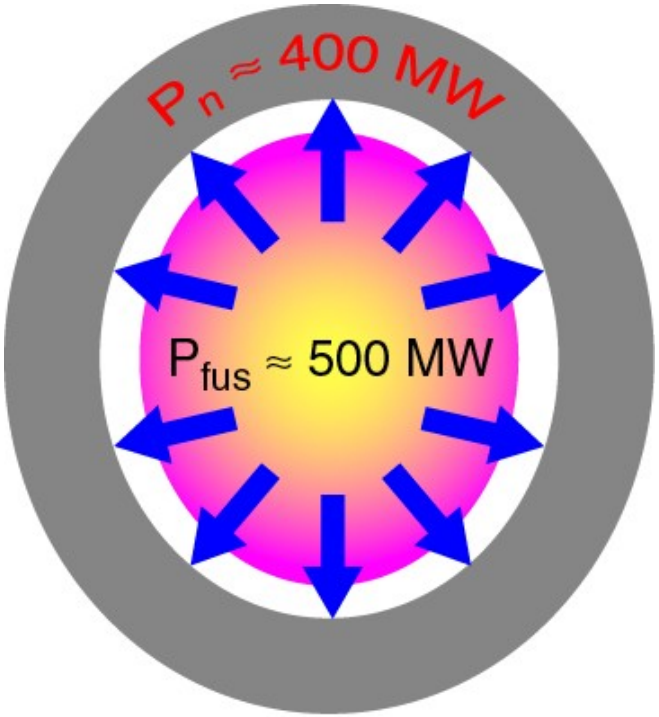




Reaction of 1g (0.2 mol) D-T mixture ↛ ≈ 1.2×10^{23} reactions → E_α = 67.5 GJ, E_n = 271.8 GJ

Implications for reactor operation → Energy and particle exhaust; Radioactivity (fuel&structure)

The role of material walls



1. VACUUM CONDITIONS

Unlike the sun, a fusion plasma can only be maintained under ultra high vacuum conditions -

base pressure $\approx O(10^{-8}$ *mbar)*

2. EXTRACTION OF POWER

The α-particle power and auxiliary injected power used to heat the plasma must be finally extracted through the plasma facing wall

Power carried by neutrons is converted to heat in blanket wall

neutrons also breed tritium in blanket

3. HELIUM REMOVAL

The removal of the helium ash requires thermalisation and neutralisation of plasma ions

Power Exhaust and Limitation of the Plasma

Heating power leaves the plasma in form of:

- ❑ radiation
- ❑ kinetic energy of escaping particles.

⇩

Direct contact of the plasma with the vessel walls must be avoided.

Imperfections in the magnetic configuration or displacement of the plasma might lead to concentrated heat deposition on areas that are difficult to control and cool.

⇩

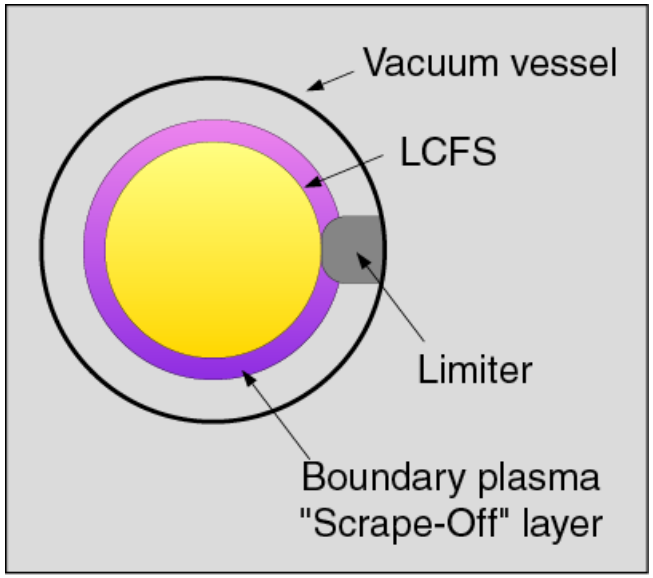
The plasma edge must be controlled (limited).

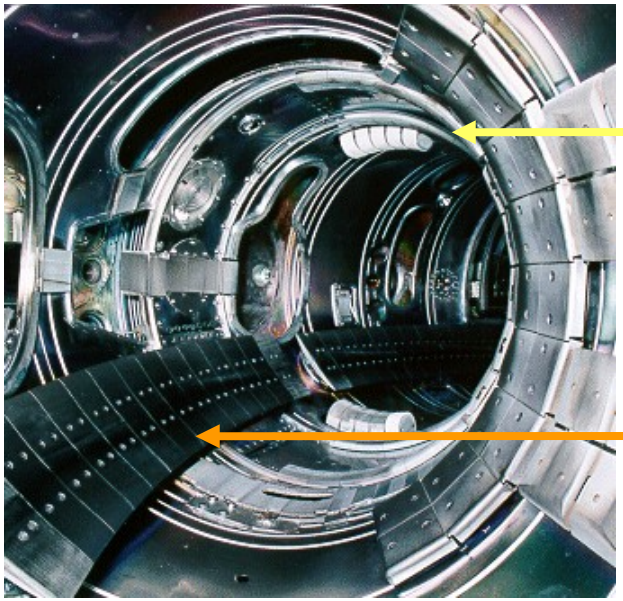
Plasma limiters

Limiter:
A material structure protruding from the main wall used to intercept particles at the plasma edge.

Last Closed Flux Surface (LCFS):
The magnetic surface that touches the innermost part of the limiter.

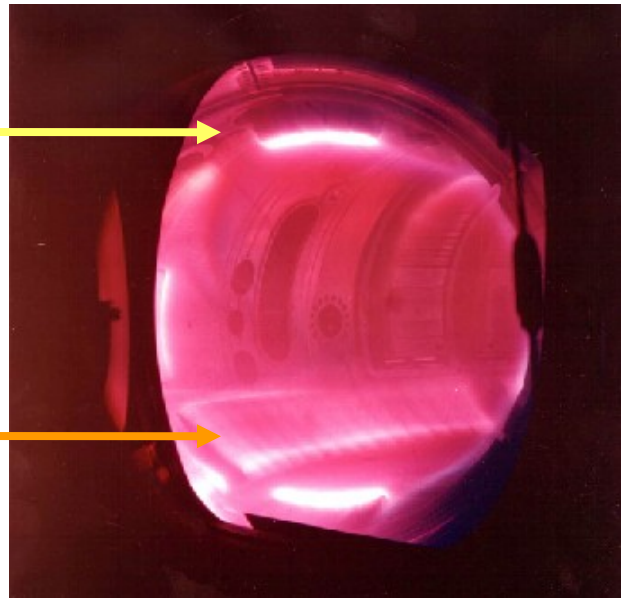
Scrape-off Layer (SOL):
The plasma region located in the limiter shadow i.e. between the LCFS and the vessel wall.





Poloidal limiter

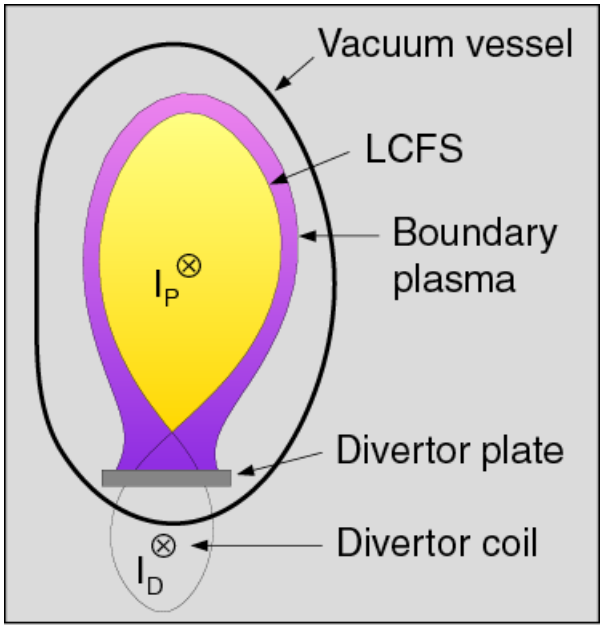
Toroidal limiter

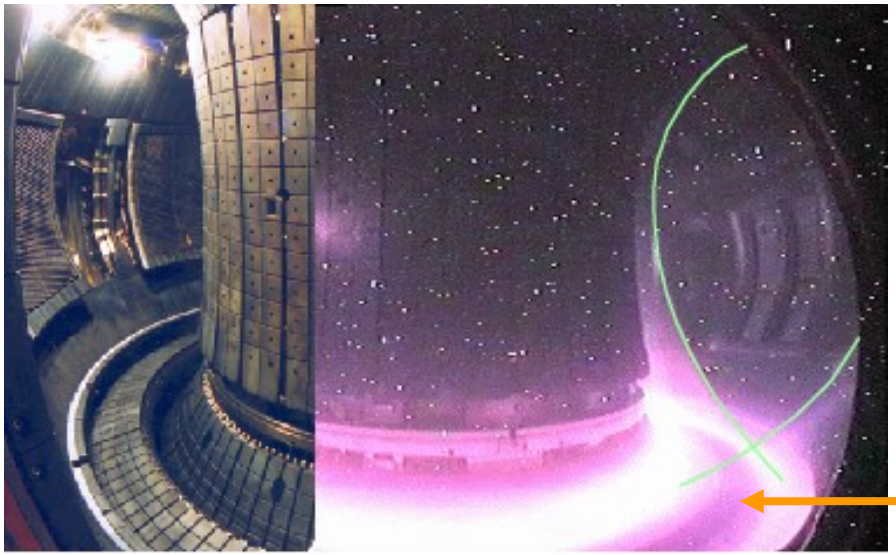


Plasma divertors

Divertor:
A separate region in the vacuum vessel
to which escaping ions are exhausted
|| B by means of auxiliary magnetic coils.

The magnetic boundary between
confined plasma and edge/divertor plasma
is called **separatrix** ≡ LCFS





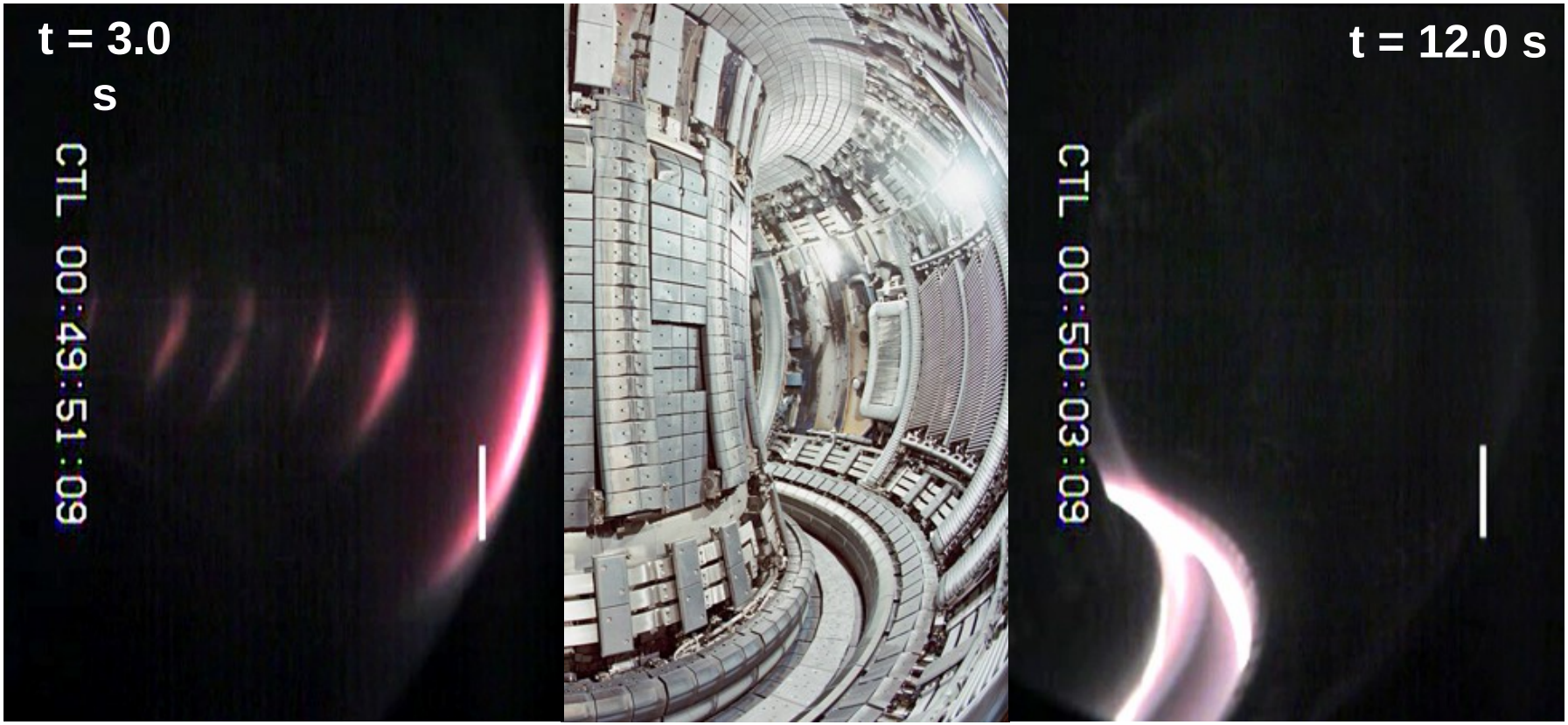
The divertor in
ASDEX Upgrade

Limiter vs. divertor operation

Divertor tokamaks need limiters for discharge ramp-up and shutdown

Example: JET

#62218: plasma visible light emission

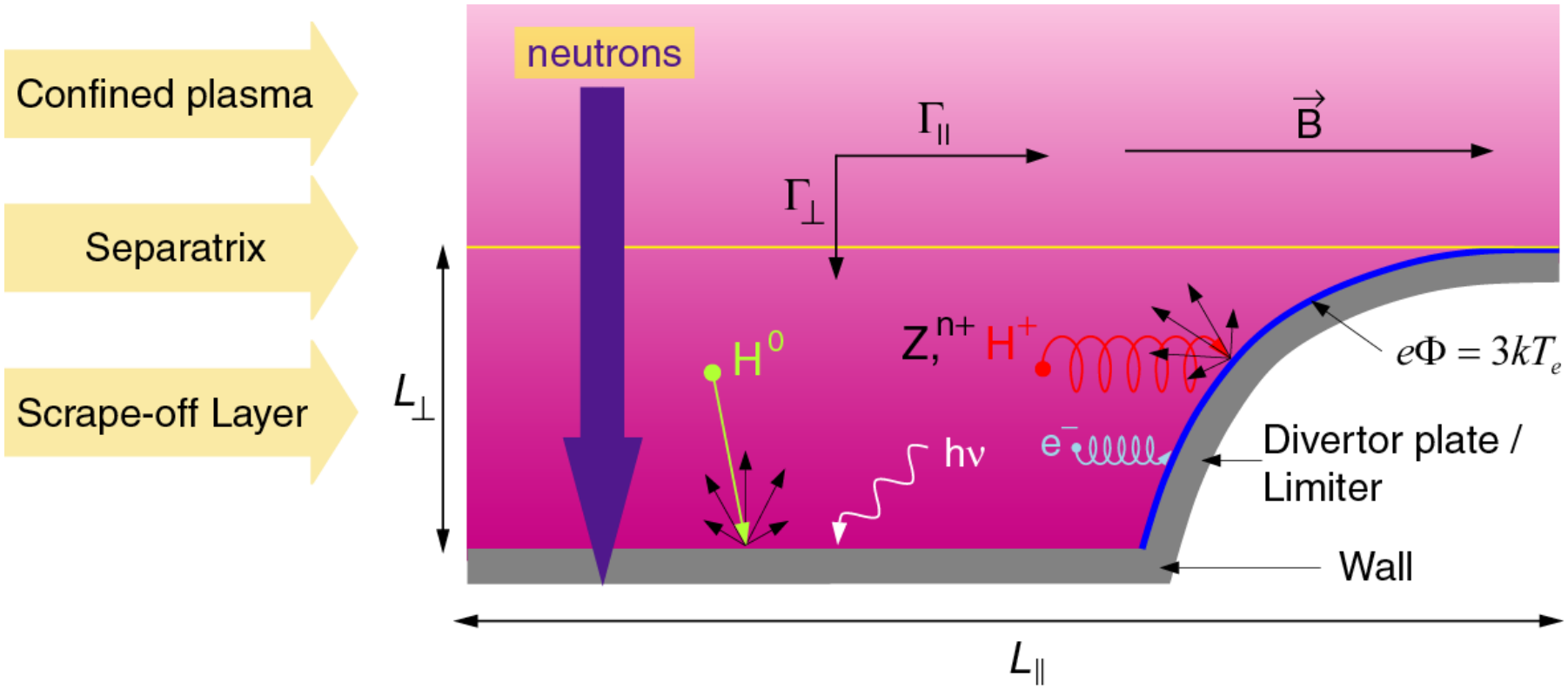


Limited

Diverted

R.A. Pitts, EPS 2005

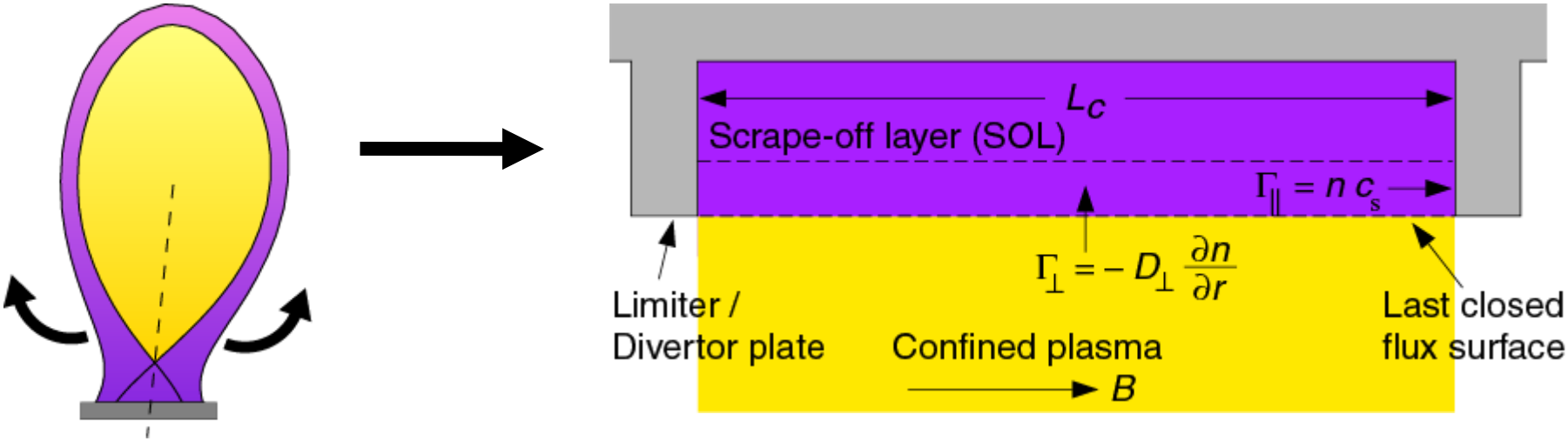
Plasma-material interaction



How deep is the edge plasma?

Edge-Transport-modelling...

Basic properties of edge plasma



$$\dot{N}_\perp = D_\perp \left.\frac{\partial n}{\partial r}\right|_{LCFS} L_C W = D_\perp \frac{n_{LCFS}}{\lambda} L_C W$$

$$\dot{N}_\parallel = \int_{r_{LCFS}}^{\infty} \frac{n_{LCFS}}{2} \exp\left(-\frac{r - r_{LCFS}}{\lambda}\right) c_s W\, dr = \frac{n_{LCFS}}{2} \lambda\, c_s W$$

Particle balance $\dot{N}_\perp = 2\dot{N}_\parallel$ ⇝ $\lambda = \sqrt{D_\perp L_C / c_s} = O(1\text{cm})$

see eg. Nucl. Fusion **52** (2012) 013009, R. Goldston

Plasma surface $4\pi^2 aR$

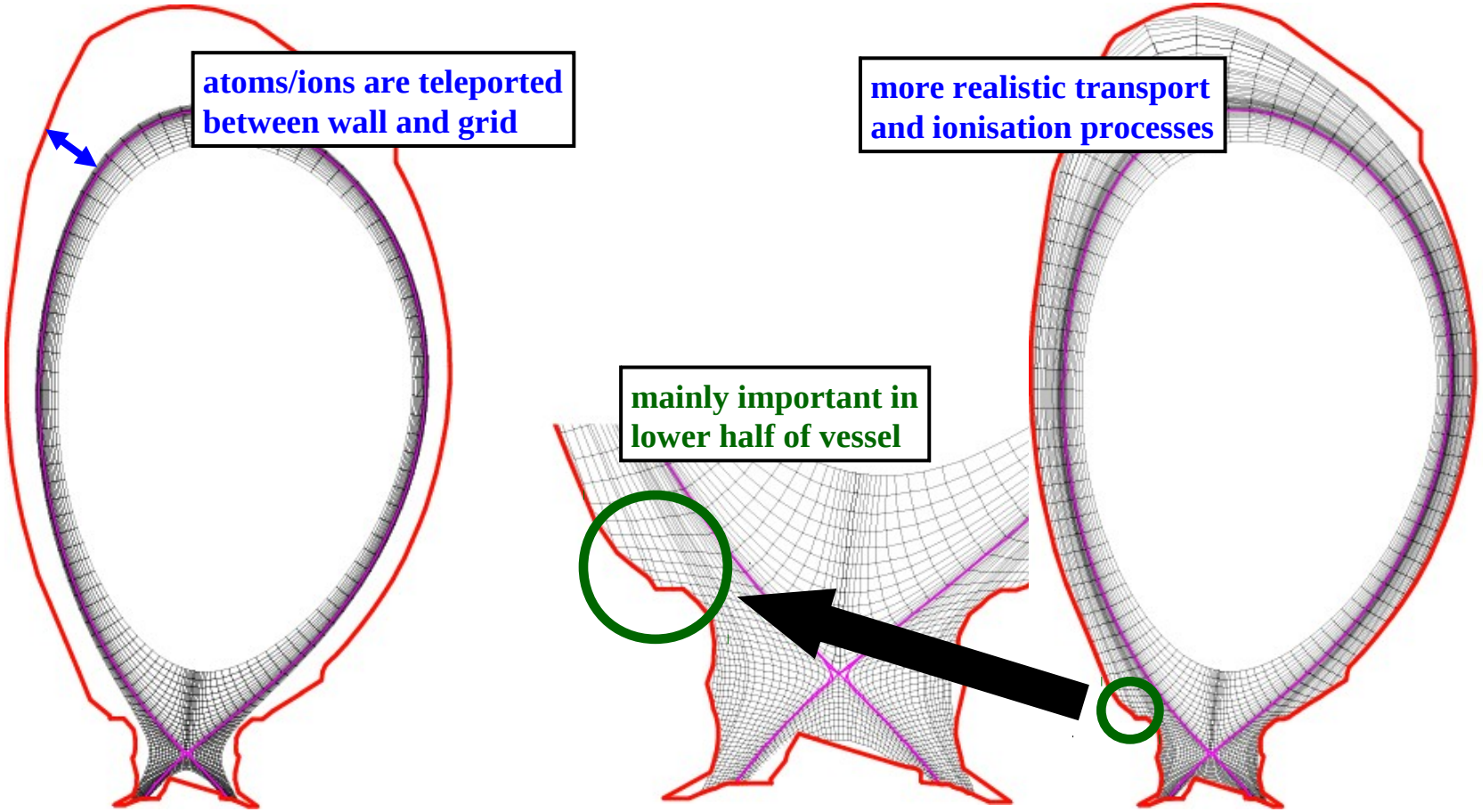
Plasma wetted divertor area $2\pi R\lambda$

⇝ Flux amplification $\frac{\pi a}{\lambda} \approx 100$

Modelling − computational grids

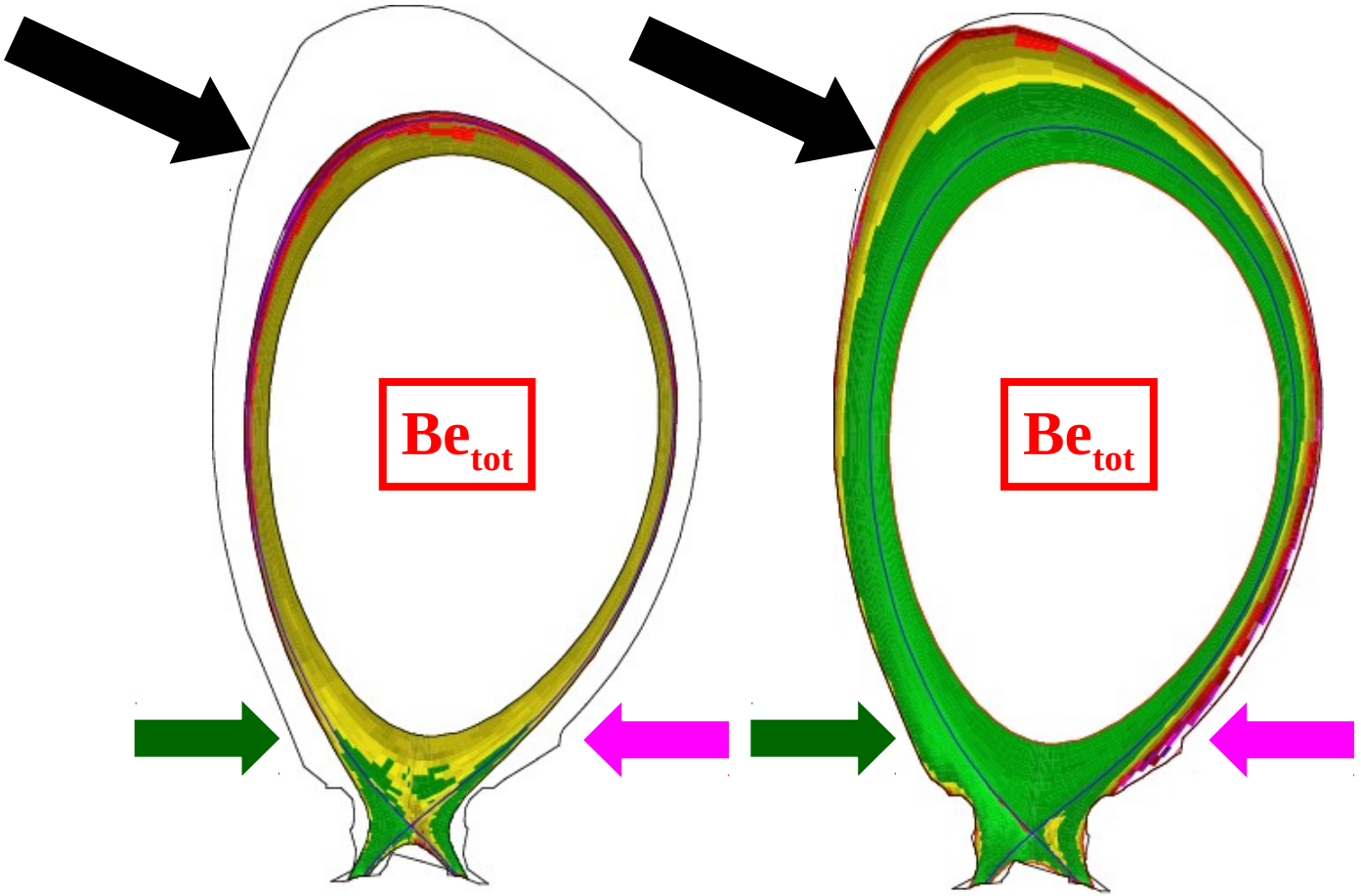
- Standard grid topology is restricted to plasma-wall contact at target plates
- Missing processes at "white spots":
  - || and ⊥ transport to wall
  - ionisation & transport of eroded atoms

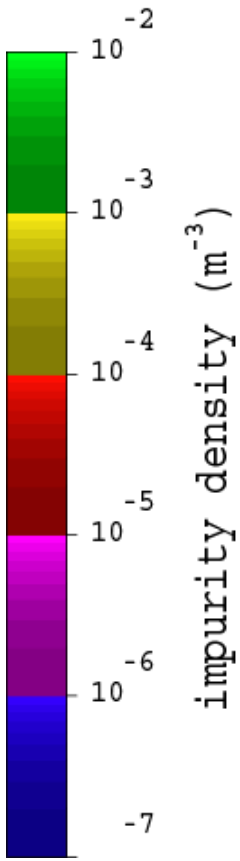
- Extend grid and tailor to 1st wall
- Fill with plasma using extrapolation from original grid



Calculated Be density

- Assumption: only Be sources at wall segments exposed to || flux
- Standard grid
- deposition || B also in parts of main chamber wall

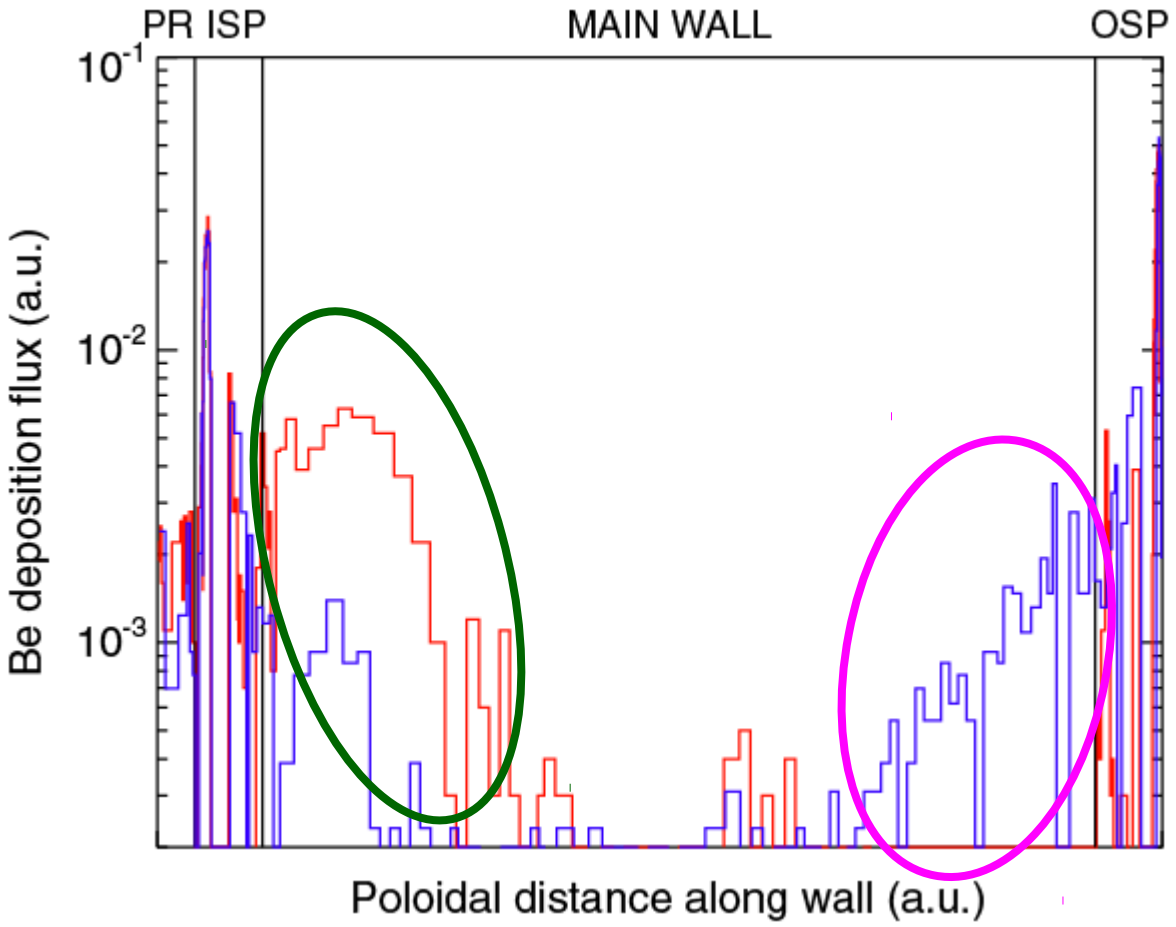




Distribution of Be deposition flux

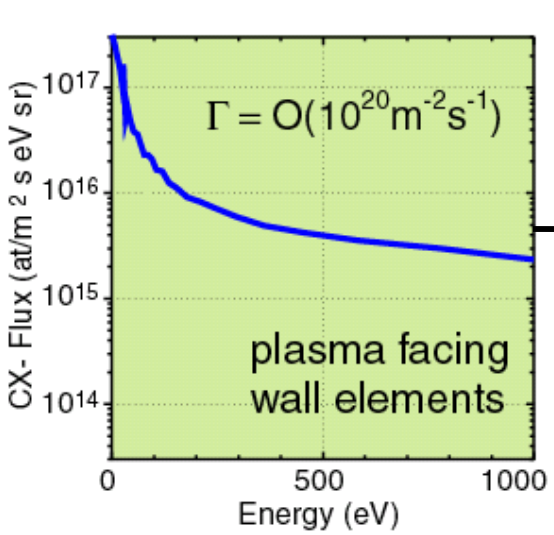
With standard grid

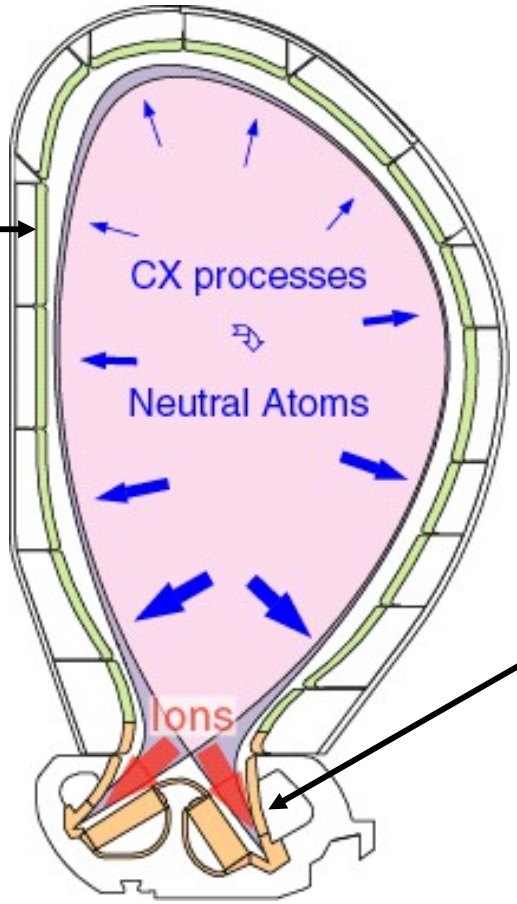
With extended grid

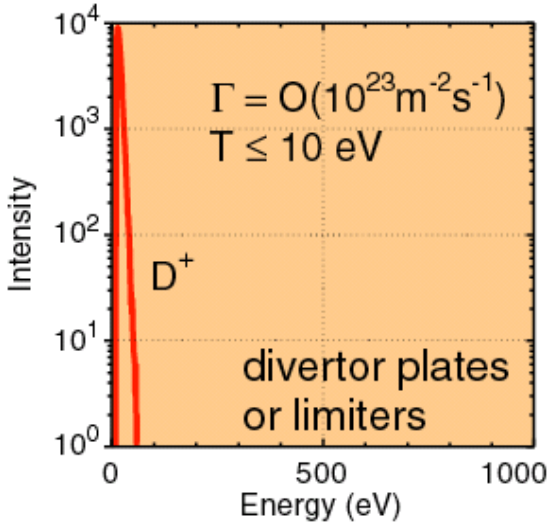


At present still lack of adequate plasma codes for wall fluxes

Stationary particle fluxes







Particles escaping from the confined plasma cover vast range of flux and energy

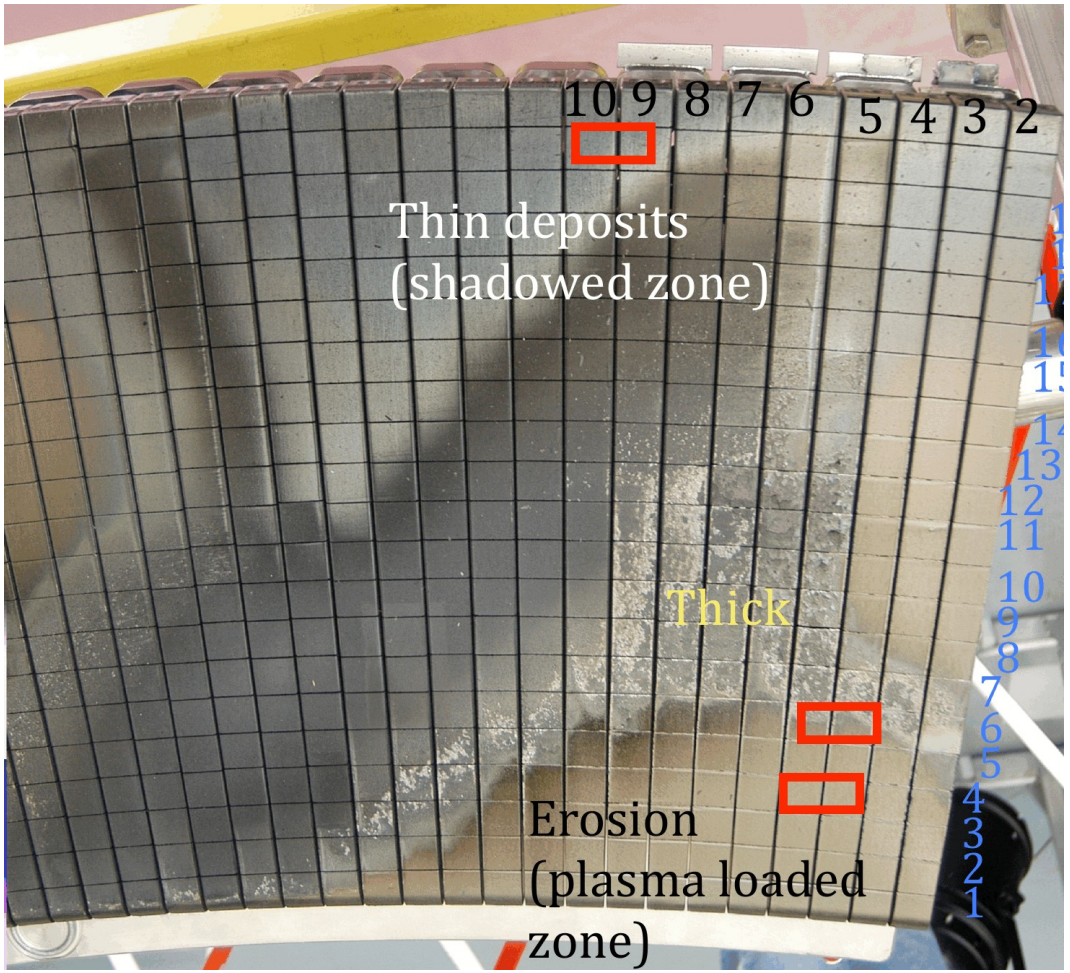
No uniform engineering and plasma physics boundary conditions

Stationary particle fluxes

Spatially very inhomogeneous:

⇩

3-D modelling is necessary **also** in tokamaks



Particles escaping from the confined plasma cover vast range of flux and energy

⇩

No uniform engineering and plasma physics boundary conditions

Outline

Lifetime of components / plasma impurities

Material erosion processes
Degradation of mechanical strength by heat and neutrons
Plasma acceptance for impurities

Erosion effects

- Physical Sputtering
- Chemical Erosion
- Chemical Sputtering
- Radiation Enhanced Sublimation
- Photon Induced Desorption
- Evaporation & Sublimation
- Brittle destruction
- Melting & Splashing
- Arcing
- Neutron Induced Damage

Physical sputtering

- **Physical sputtering** is the ***kinetic ejection of surface atoms*** by incident energetic ions or atoms ***due to collision processes*** (playing billiards with surface atoms)

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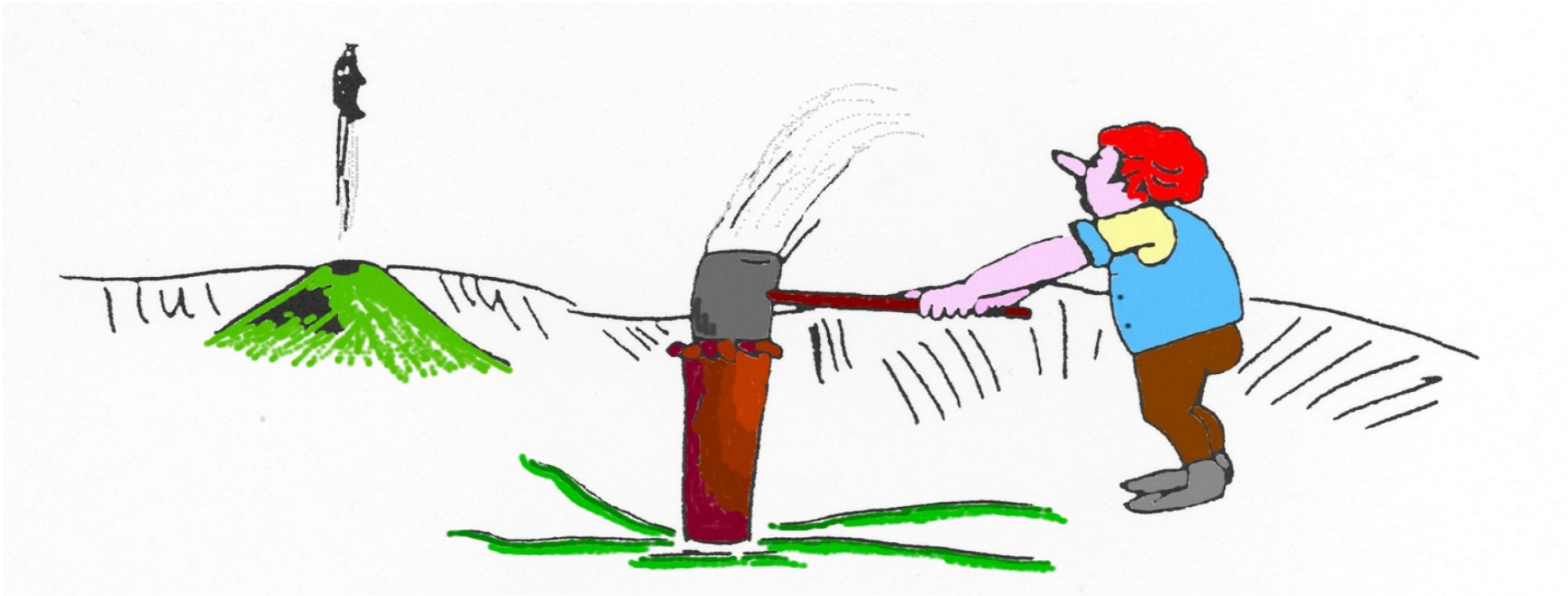
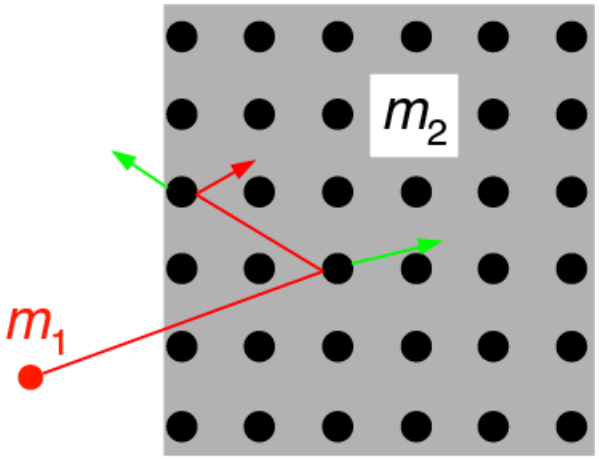


Momentum reversal is required

Physical sputtering

- Particle impact on solid

  ↬ Momentum and energy transfer on lattice atoms



- Energy threshold for sputtering process:

  At least two collisions necessary

  Energy of projectile after 1st collision: $E(1-\gamma)$

$$\gamma = \frac{4 m_1 m_2}{(m_1 + m_2)^2}$$

  Energy transfer in 2nd collision: $E(1-\gamma)\gamma > E_s$

↬ Low energy threshold:

$$E_{th} = \frac{E_s}{\gamma(1-\gamma)} \overset{m_1 \ll m_2}{\simeq} \frac{E_s}{4}\frac{m_2}{m_1}$$

High energy (qualitatively):

Projectile energy ↗

↬ Collision cascades - Penetration depth ↗

↬ Sputtering ↘

Quantitative Evaluation:

Monte Carlo Simulations based on the ***binary collision approximation (bca)*** (by codes like TRIM.SP, TRIDYN, ...)

- calculating asymptotic trajectories of consecutive collisions between projectile and target atoms

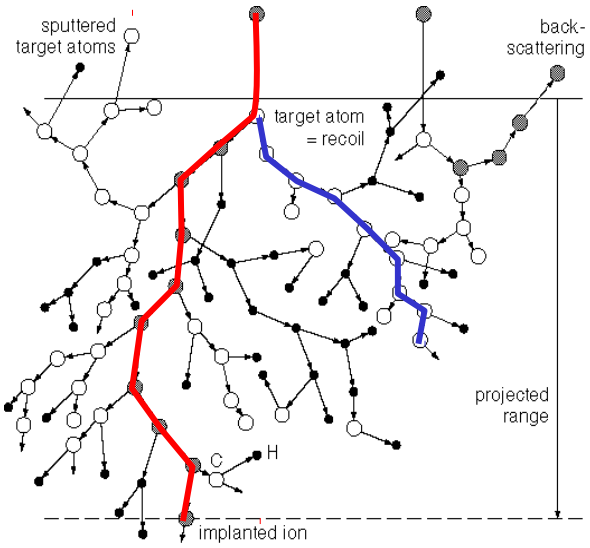
- continuous drag by electronic stopping

- randomly choosing the distance to the next collision partner,
  the collision parameter, and
  the azimuth.

- following the projectile and all colliding target atoms that received a certain minimum energy

- **bca** breaks down for -low energies (<50 eV)
  -molecules

➡ Molecular dynamics (MD) simulations



Comparison MD vs TRIM simulation (K. Tichmann)

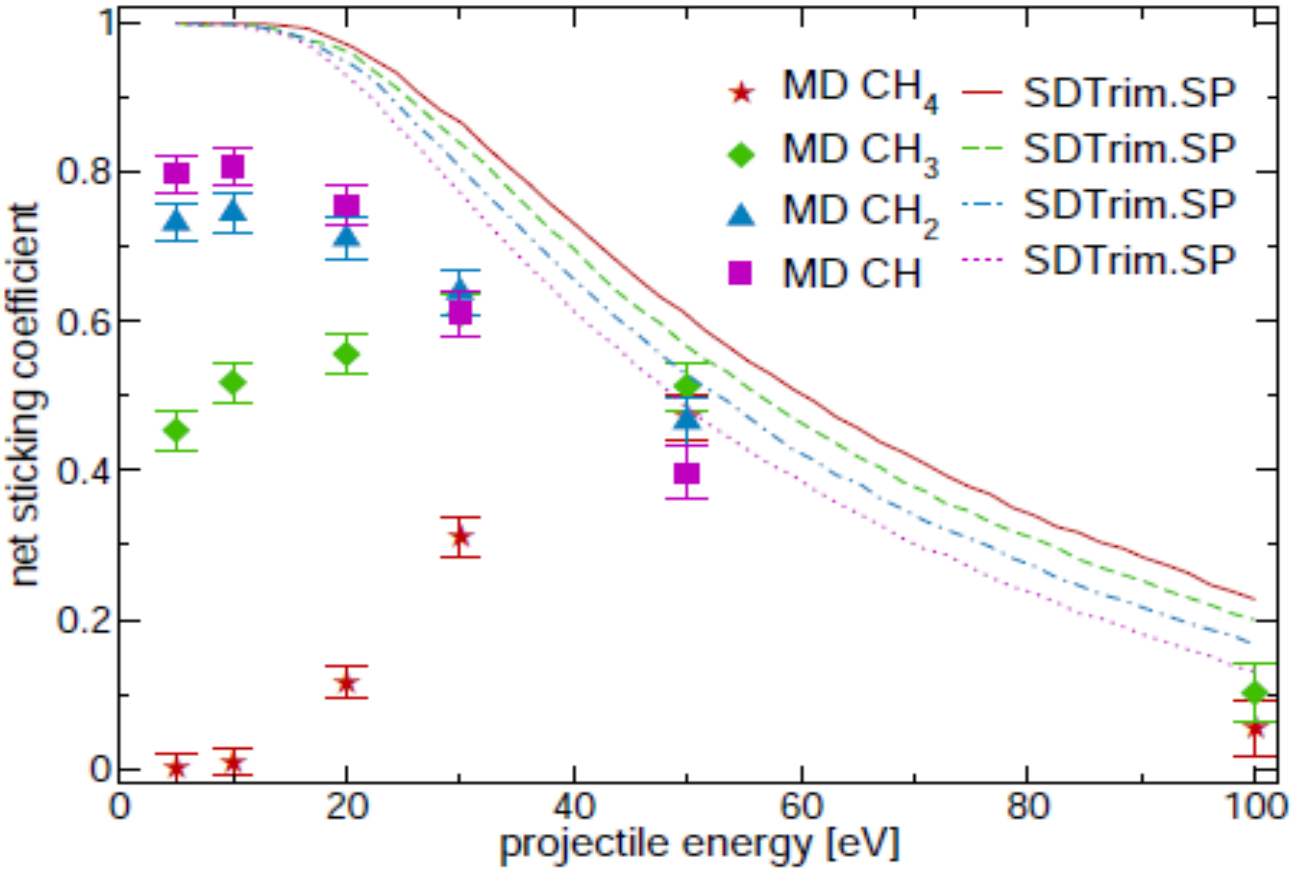


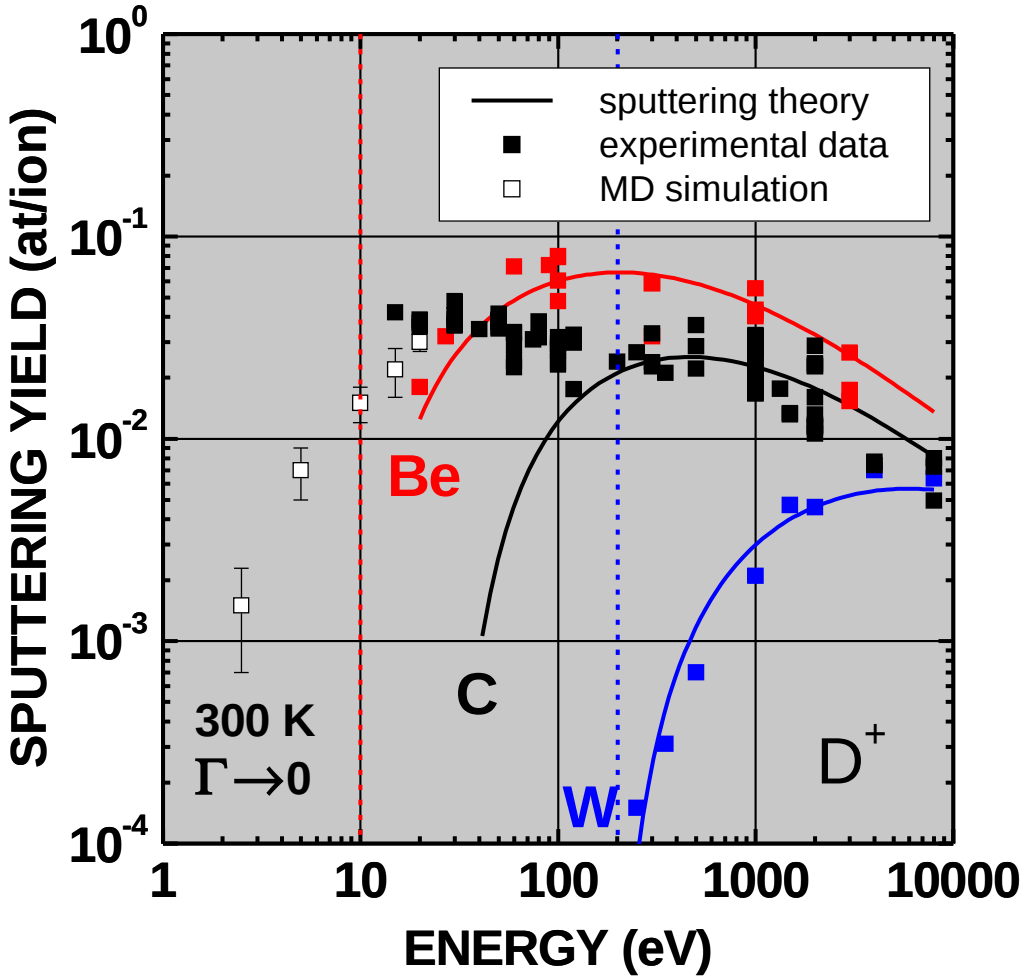
Figure 4: Net sticking coefficients of various CH_x projectiles, incident at 60° to the surface normal. Symbols are results form molecular dynamics calculations, solid lines were calculated by SDTrim.SP

Erosion by (D) sputtering

For beryllium and tungsten theoretical and experimental yields agree very well

Carbon shows additional erosion with only weak dependency on impact energy

CHEMICAL EROSION



Chemical Erosion

- **Physical sputtering** is the ***kinetic ejection of surface atoms*** by incident energetic ions or atoms ***due to collision processes***. (playing billiards with surface atoms).

- **Chemical erosion** is a selective removal of surface atoms by ***chemical reactions***, forming volatile reactants that can desorb.

Chemical erosion

PRINCIPAL MECHANISM

- ❑ Chemical reaction of incident projectiles with target atoms
- ❑ Formation of a volatile chemical compund leaving the solid
- ☜ Occurs only for certain target-projectile combinations

CHEMICAL EROSION IN FUSION DEVICES:

FORMATION OF HYDROCARBONS:

H C CH_4 (+ C_xH_y)

FORMATION OF CARBON OXIDES:

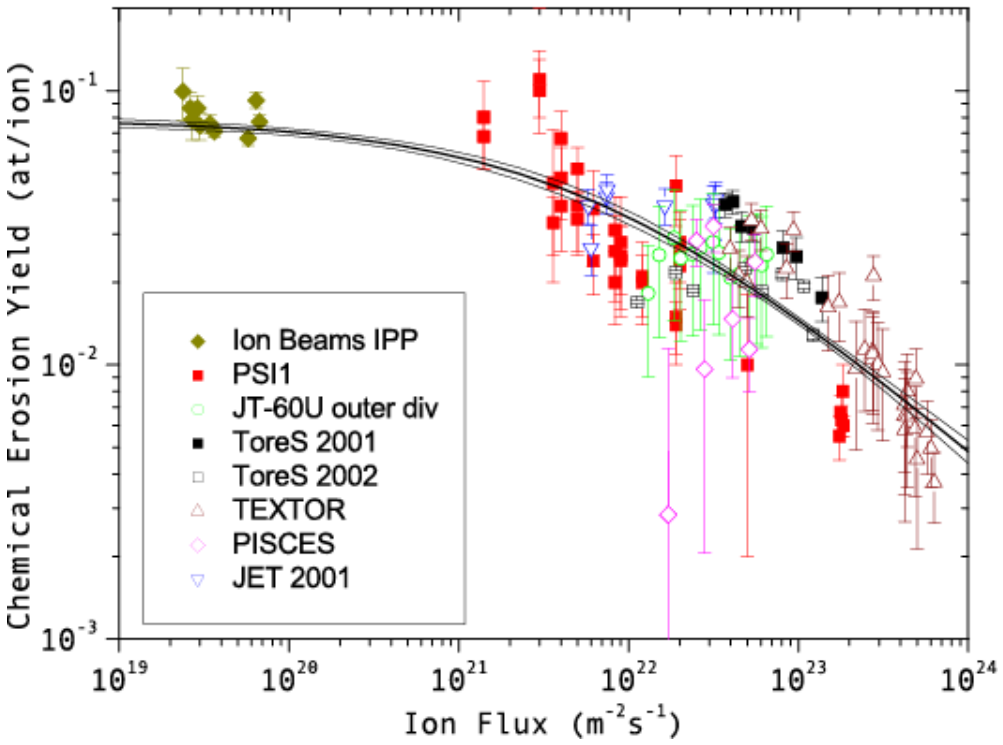
O C CO + CO_2

REACTIONS WITH SOME METALS:

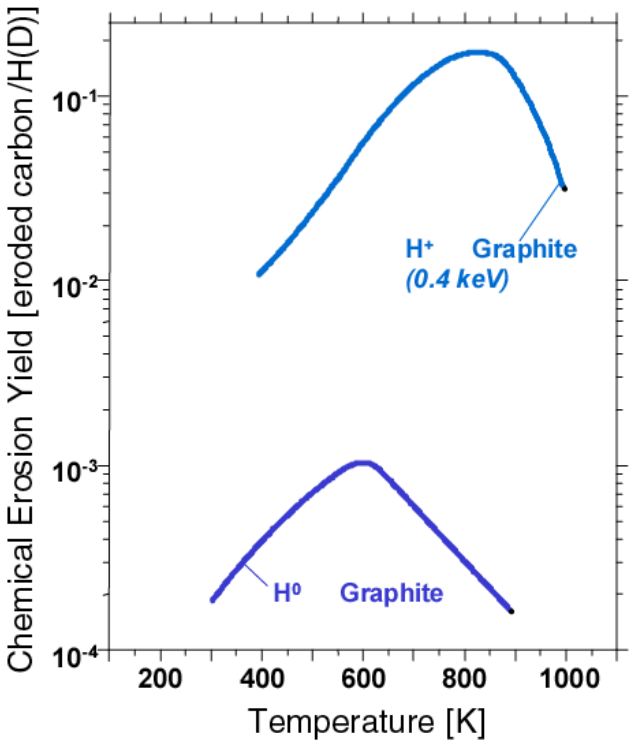
O	Me	Me (O)	(W above 1000 °C)
H	Me (O)	Me (OH)	
H	Me (OH)	Me + H_2O	

Chemical erosion of carbon

chemical erosion decreases for high Γ_D



chemical erosion vanishes at high T_{surf}



good for divertor strike point conditions!

Chemical Sputtering

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- **Chemical erosion** is a selective removal of surface atoms by ***chemical reactions***, forming volatile reactants that can desorb.

- **Chemical Sputtering** is a process whereby ***ion bombardment causes or allows a chemical reaction to occur*** which produces a particle that is weakly bound to the surface and hence easily desorbs in the gas phase:

→ **Synergistic effect** may increase erosion by orders of magnitude!

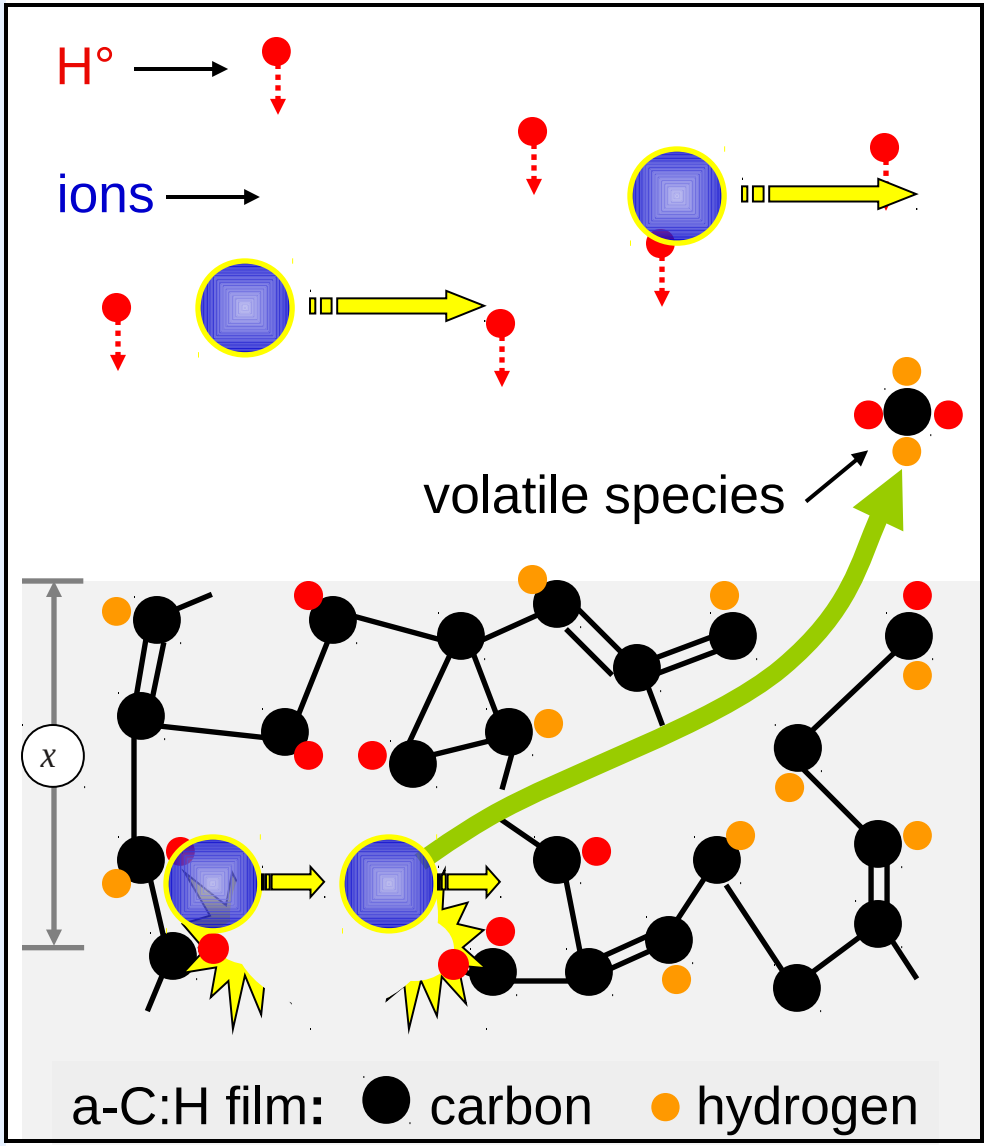
Basic mechanistic picture of chemical sputtering

Ions break C–C bonds.

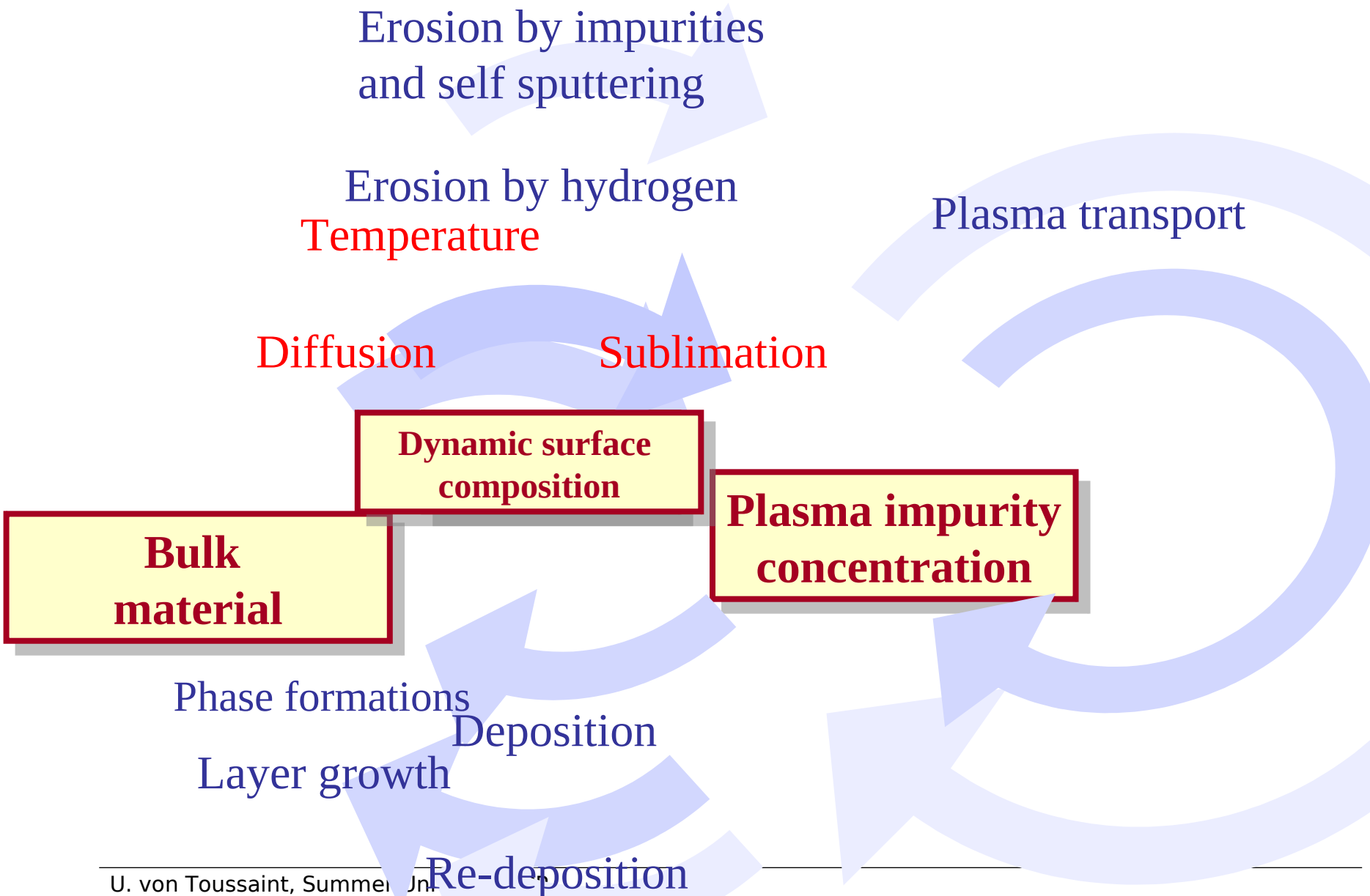
H binds to these bonds and prevents their recombination.

Repeated bond breaking and H attachment incrementally “unhinges” a hydrocarbon molecule from the film.

As soon as a last bond of a hydrocarbon molecule to the carbon network is broken, the molecule leaves the film surface.



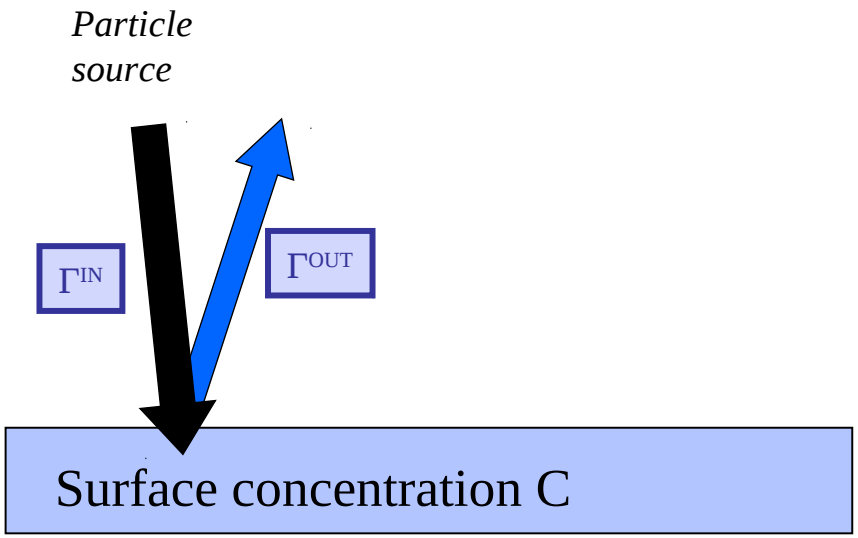
Dynamic system



Physical sputtering

Lab: OPEN system

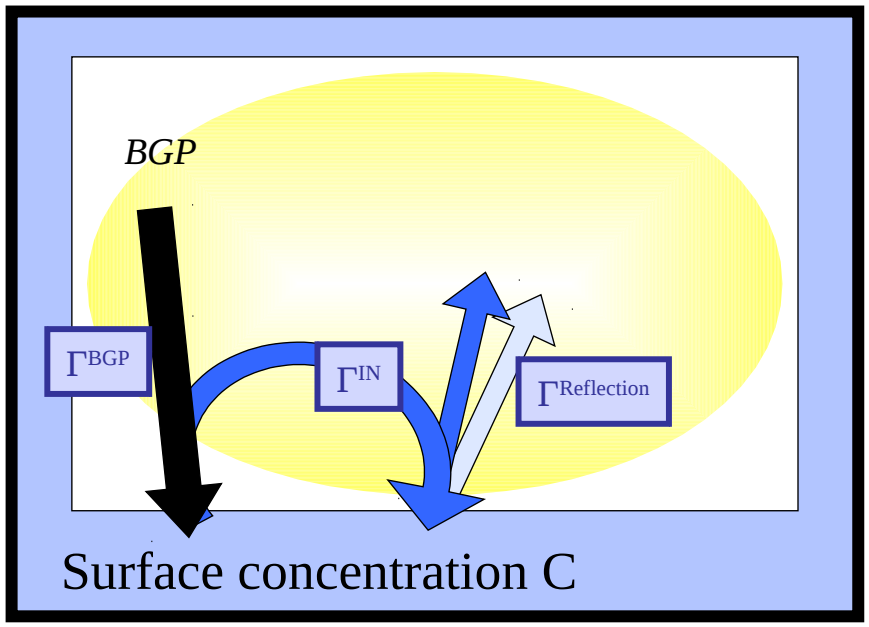
$$\Gamma^{OUT} = C\Gamma^{IN} Y^{Sputter}$$



Fast particles → Sputtering

Physical sputtering

Tokamak: CLOSED system



$$\Gamma^{Sputtered} = C\left(\Gamma^{BGP} + \Gamma^{IN}\right) Y^{Sputter}$$

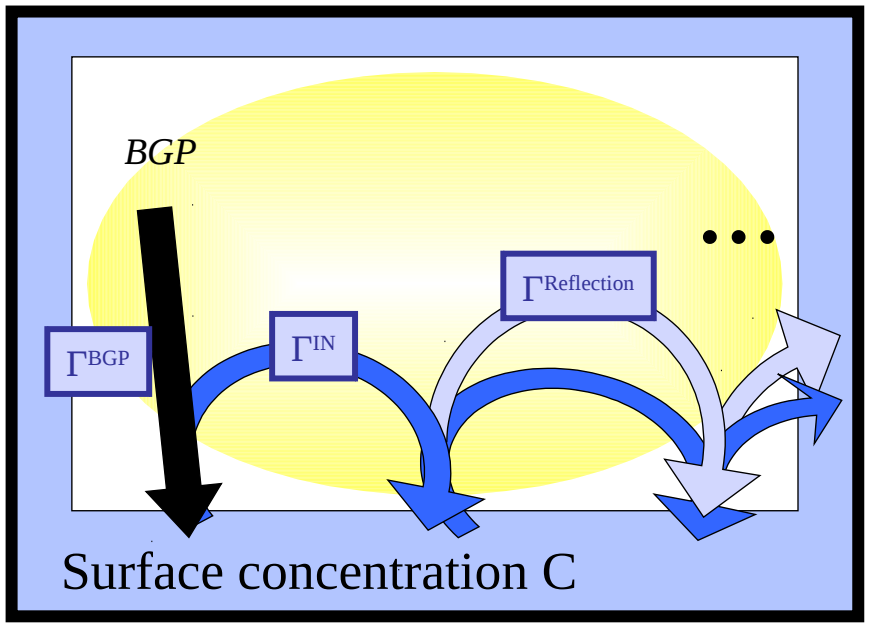
$$\Gamma^{IN} = \sum_{sources} \left(\Gamma^{\text{Sputtered}} + \Gamma^{Reflection}\right) R$$

$$\Gamma^{\text{Reflection}} = \Gamma^{IN}\, Y^{\text{Reflection}}$$

BGP → Sputtering
Deposition
Reflection
Re-erosion

Physical sputtering

Tokamak: CLOSED system



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$$\Gamma^{Reflection} = \Gamma^{IN}\, Y^{Reflection}$$

$$\Gamma\left(\text{time, space, species, chargestate}\right)$$

$$Y\left(\text{species, kinetic energy}\right)$$

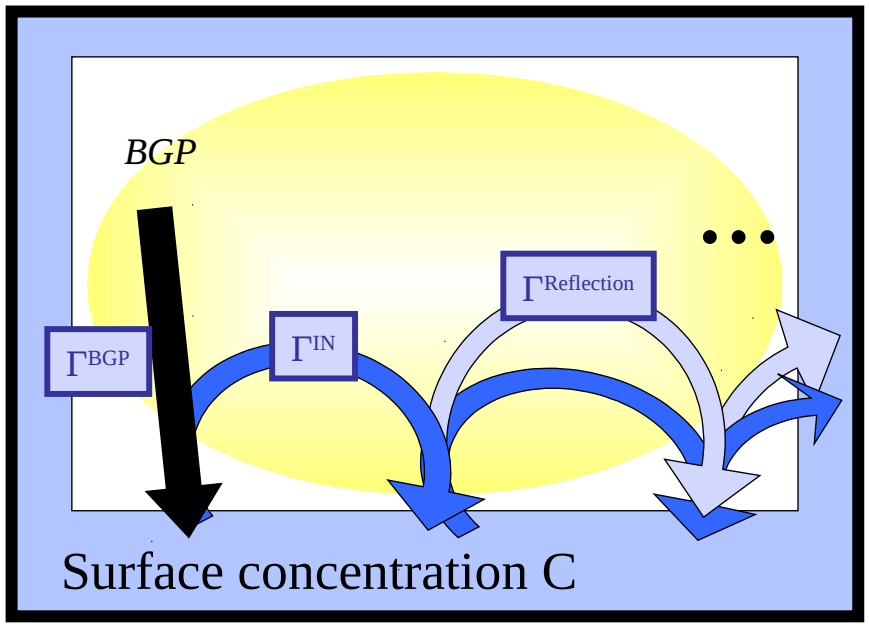
Large algebraic equation system …

BGP → Sputtering

Deposition
Reflection } closed system
Re-erosion } no material loss

Physical sputtering

Tokamak: CLOSED system



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$$\Gamma(\text{time, space, species, chargestate})$$
$$Y(\text{species, kinetic energy})$$

Large algebraic equation system …

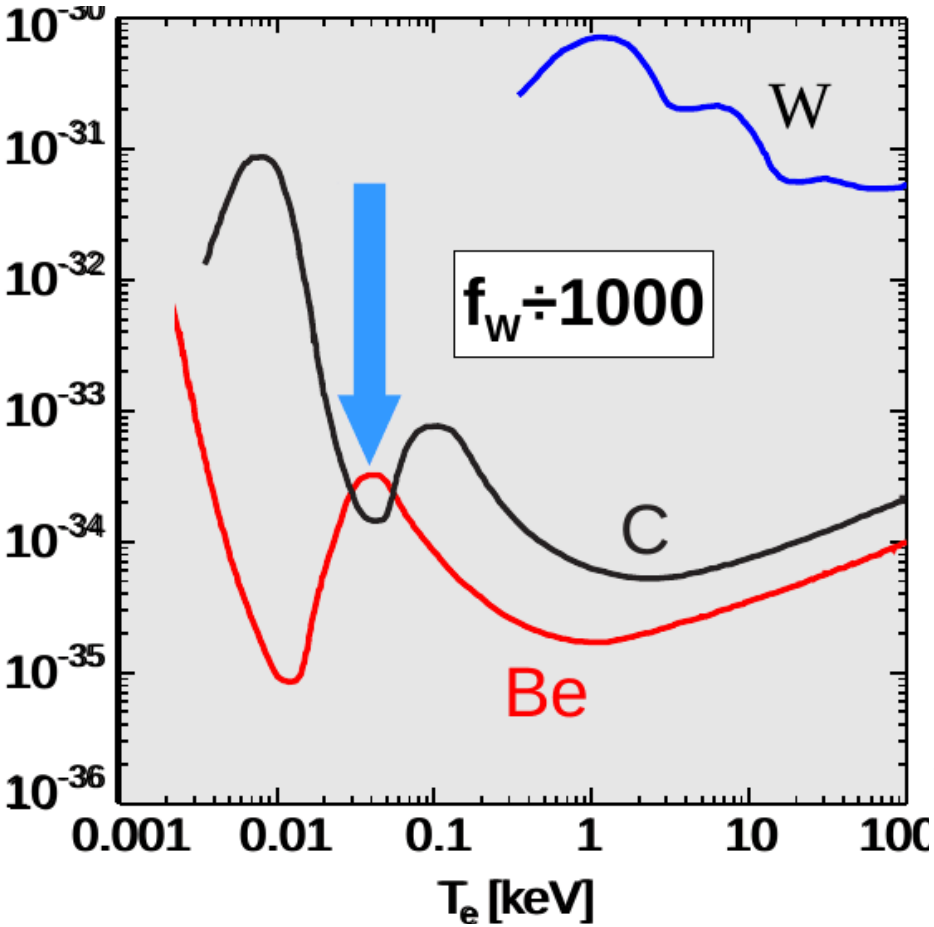
$$\frac{\partial C}{\partial t} = \Gamma^{IN} - \Gamma^{Sputtering} + \ldots$$

BGP → Sputtering
Deposition
Reflection — closed system
Re-erosion — no material loss

… coupled to a large differential equation system → challenging even without feedback to plasma (trace impurities??)
- Memory kernels (due to temperature)

Effects of eroded material as plasma impurity

Radiated power density per atom



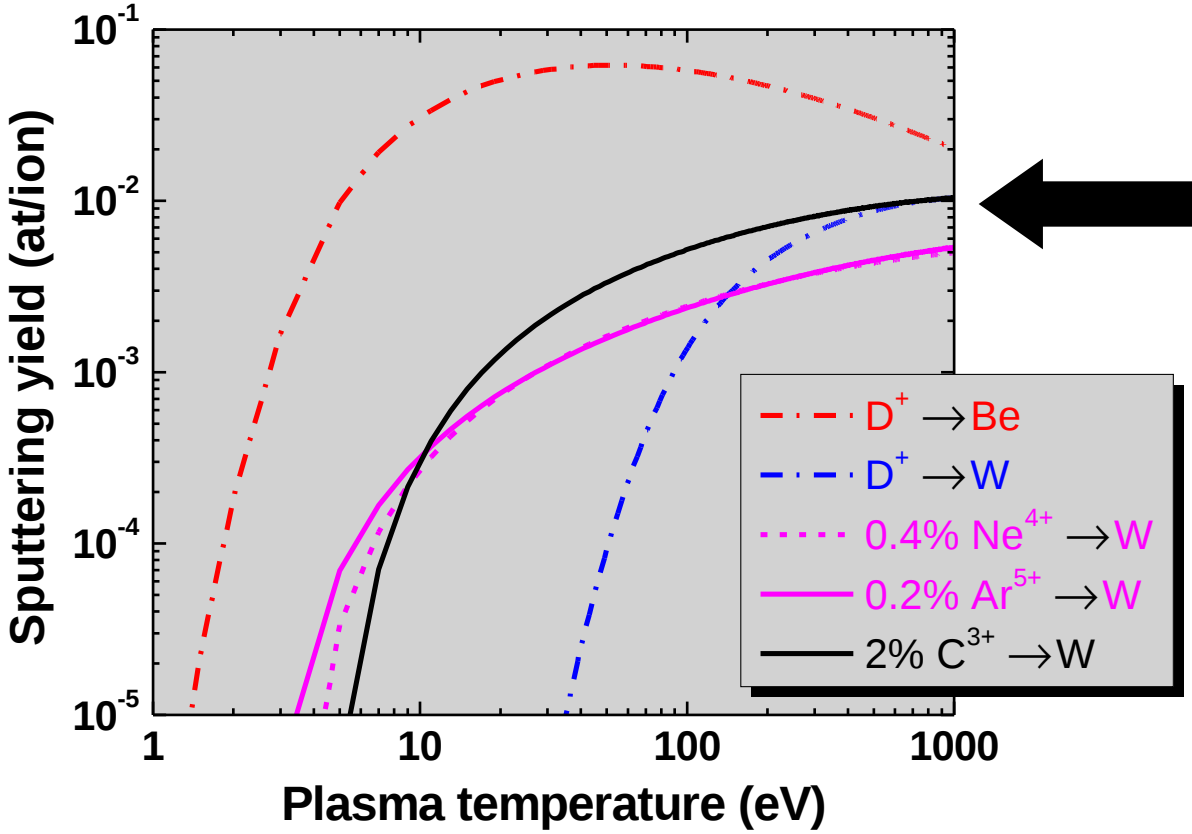
T. Pütterich, 2006

Concentration limit for sustained ignited plasma:

- Beryllium, Carbon≈ 10^{-2}
- Tungsten≈ 10^{-5}

However: Radiative divertor cooling in all metal devices requires impurity seeding...

Sputtering by seeded/intrinsic impurities



Sputtering yields for incident ions with Maxwellian energy distribution + sheath energy gain 3 Z k T_e

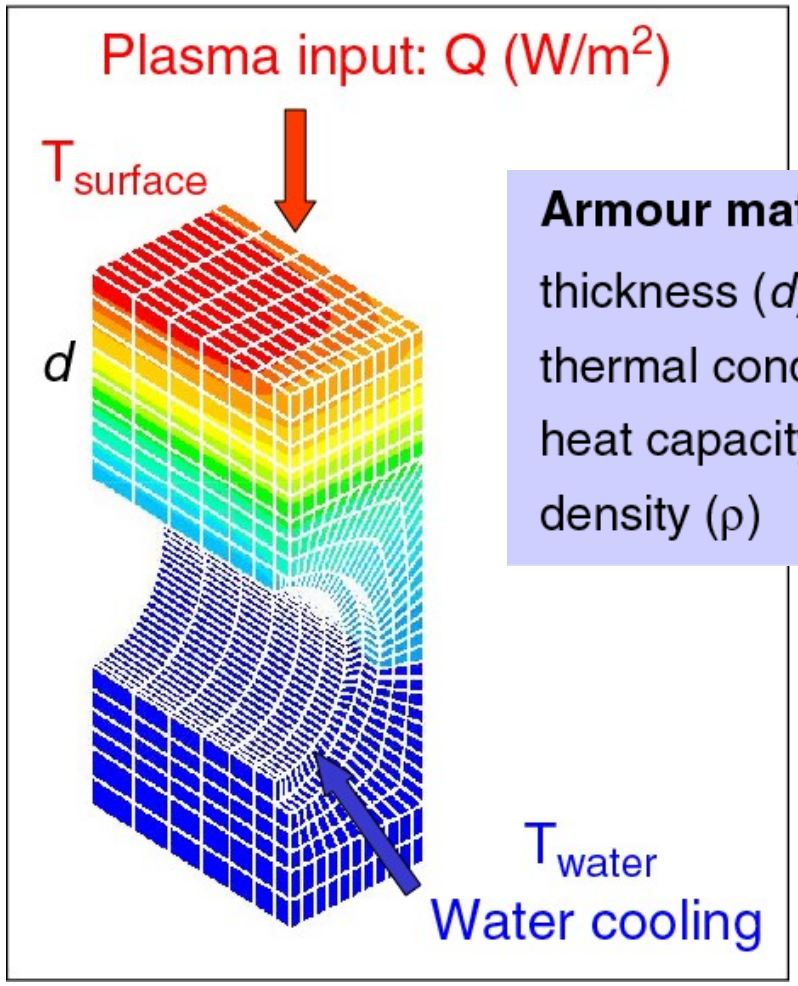
- **Impurity ions → sputtering threshold energy for W lower by factor ≈10**
- **Under divertor conditions W sputtering only by impurities**
- **Issue for developing radiatively cooled plasma scenarios**

Outline

Heat removal

Engineering concepts
Material mobilisation by transients
Degradation by neutrons

Heat removal - stationary



Armour material

thickness (d)

thermal conductivity (λ)

heat capacity (c)

density (ρ)

Steady state conditions:

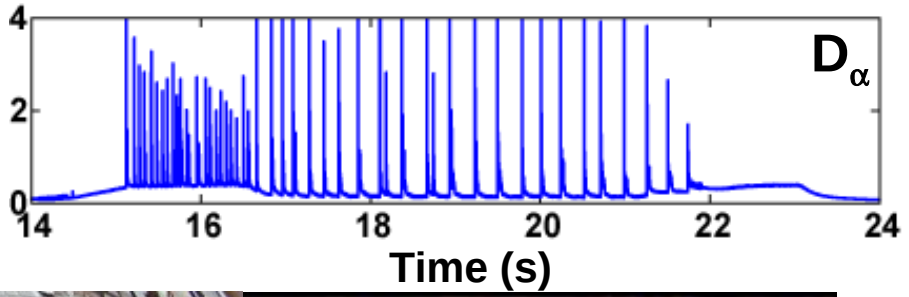
$\Delta T = T_{surface} - T_{water} = Q \times d / \lambda$

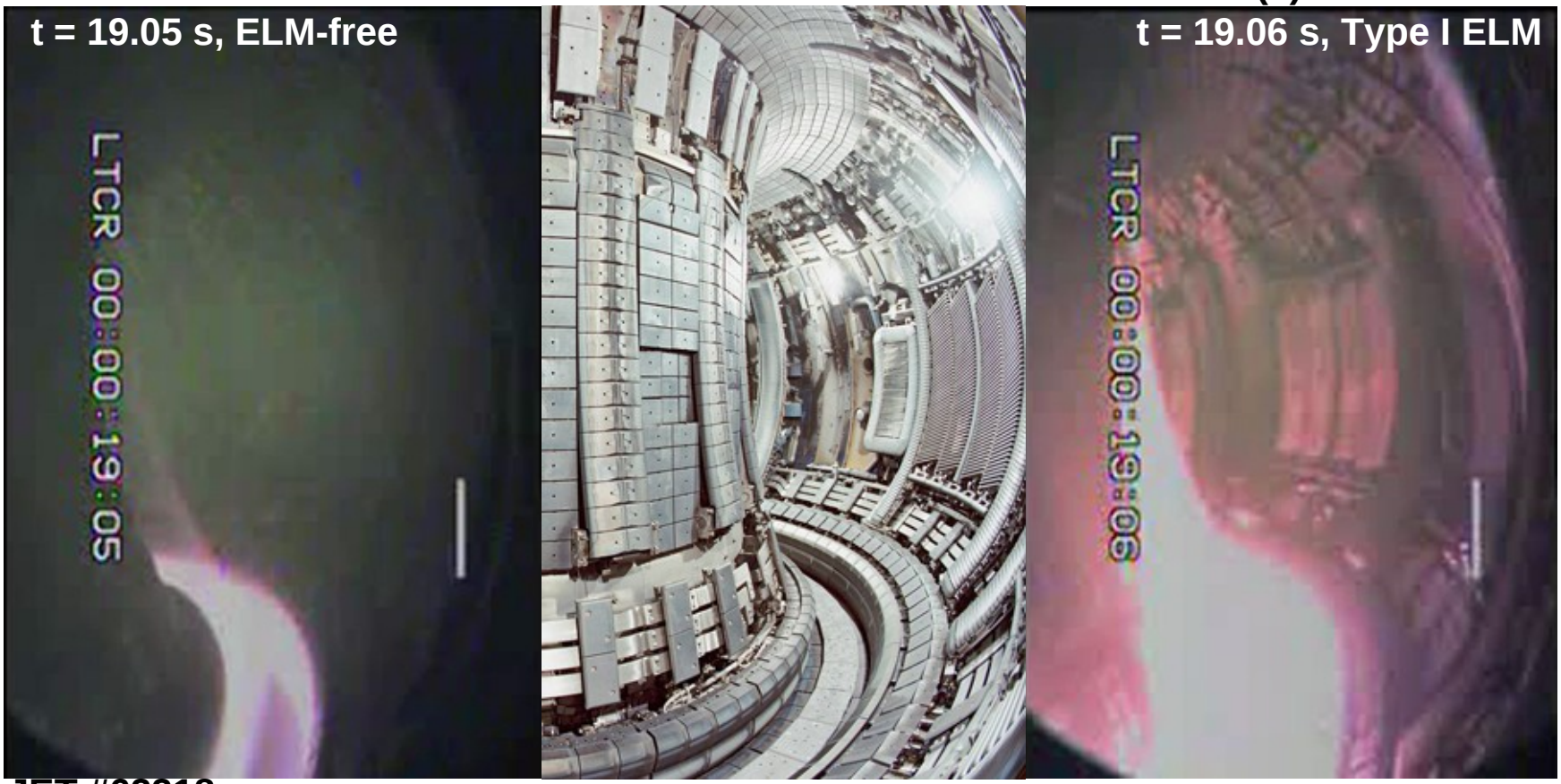
Typical parameters:

Q =10 MW/m^2, λ = 200W/mK, d = 0.02m, ΔT = 1000 ˚C

Transient flux excursions

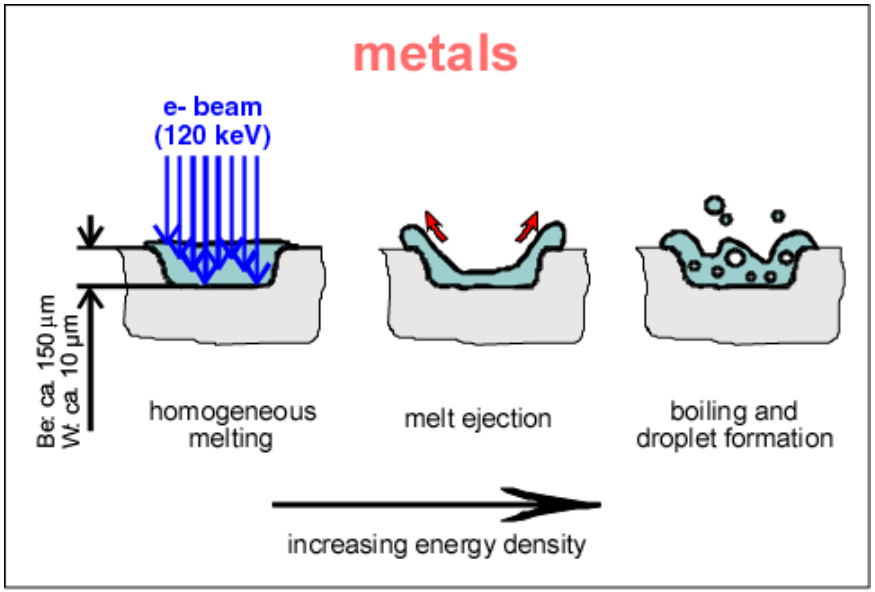
Plasma instabilities can lead to transient heat load excursions

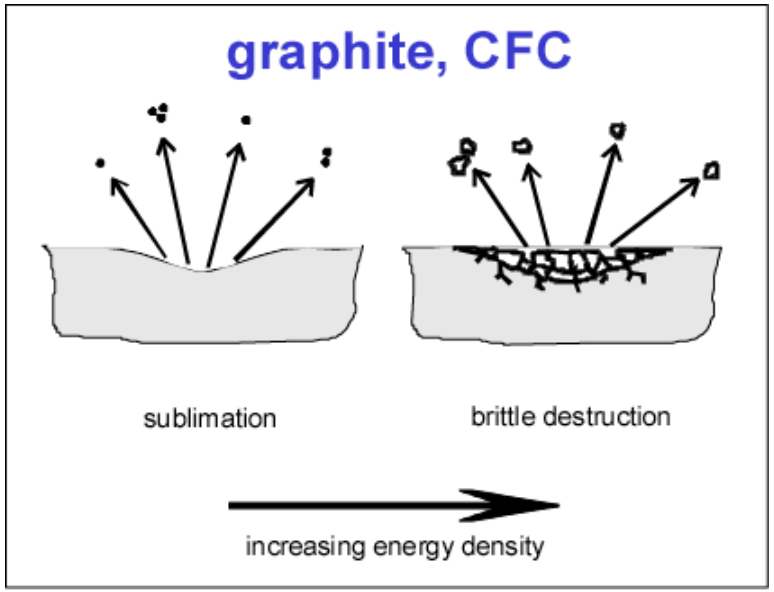




JET #62218

Material erosion under extreme power load





FOR METALS:

Splashing

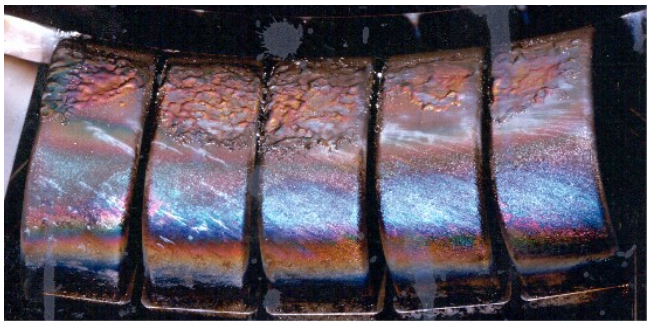
Formation of droplets

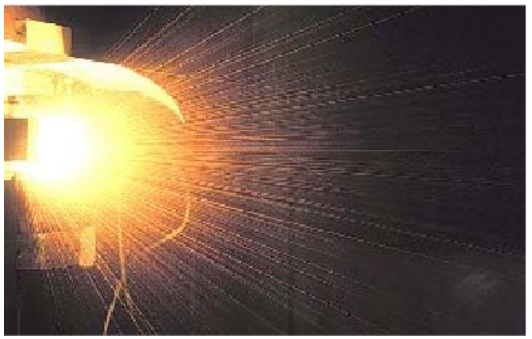
Formation of dust

FOR CARBON:

Above a certain power load (threshold) emission of debris

BRITTLE DESTRUCTION





Heat removal - transient

By MHD instabilities (disruptions, edge localised modes - ELMs) a fraction of the plasma stored energy is deposited in short pulses on plasma facing components

Size scaling! ⇒No problem for present fusion experiments BUT:

Example - ELMs in ITER

$W_{thermal}$	**350 MJ**
energy drop	**2-6 %**
per ELM	**≈ 15 MJ**
deposition time	**0.1 - 0.5 ms**
deposition area	**6 m²**
power density	**≈ 10 GW/m²**

Heat removal - transient

In transient events the energy must be absorbed by the target material. **Heat capacity** is essential (inertial cooling)

$$T(t) = P * (2/\pi\ \lambda\ \rho\ c)^{0.5} * t^{0.5}$$

temperature power conductivity density heat capacity time

t = 0.00025 s T_{max} = 6000 °C Penetration depth: 0.15 mm

Graphite$_{subl.\ thresh.}$ = *2200 °C*

Tungsten: T_m = 3410 °C, T_b = 5660 °C

Graphite target will sublimate quickly and undergo brittle destruction

Metals will melt ⟹ loss of melt layer by forces on induced currents

No material solution ⟹ Plasma physics must solve this problem!

Effects of neutrons on plasma facing armour

Heat conductivity	lattice defects
Swelling	void formation, gas bubbles
Ductility	neutron and helium induced hardening and embrittlement
Composition	transmutation products

Neutron damage investigations are difficult (100dpa(!))

- heavy ion bombardment as substitute for n-fluence
- licensing
- IFMIF as test facility

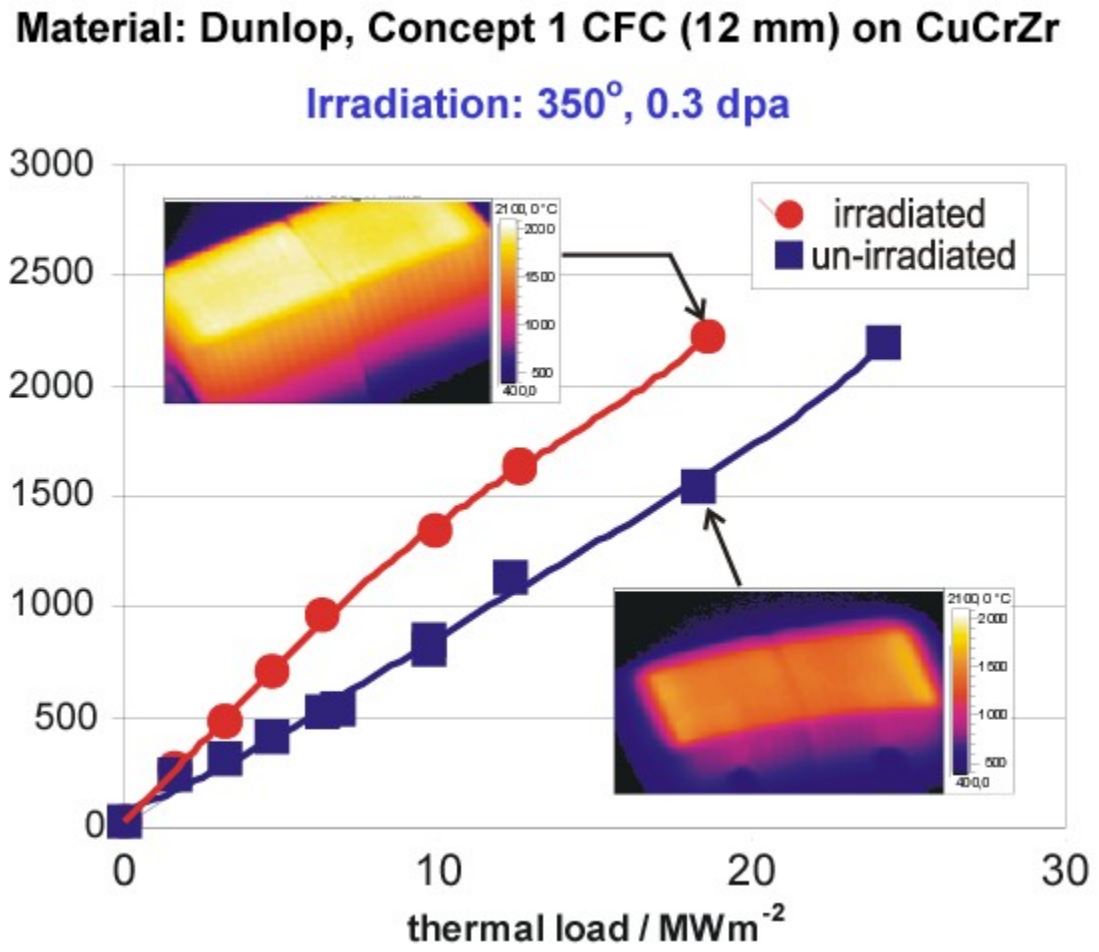
Effects of neutrons on plasma facing armour

Neutron damage simulation: Extreme multiscale problem

- 20 orders of magnitude in time,

- 10 orders in space

Example: degradation of heat conductivity



Outline

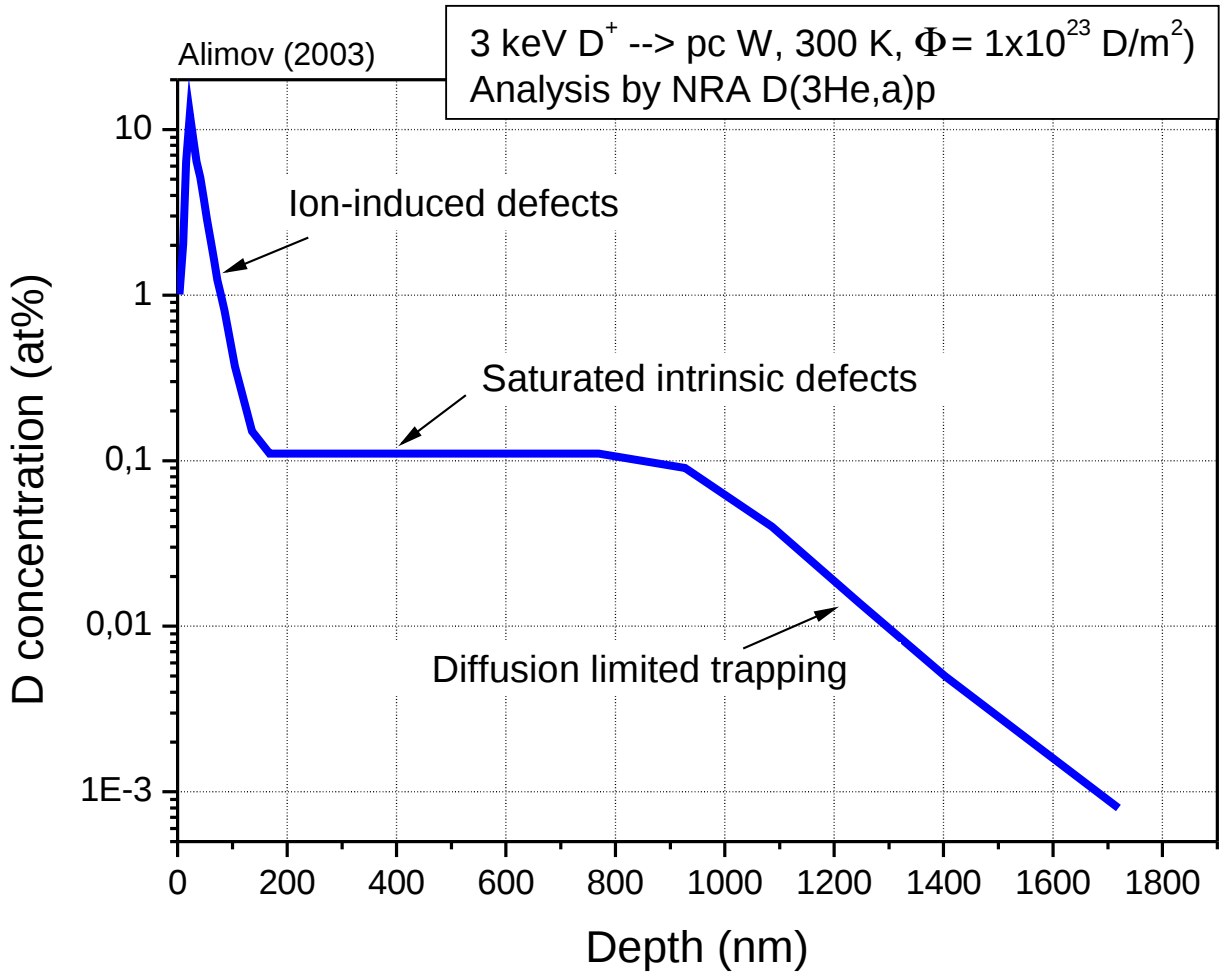
Radioactive inventory /
integrity of wall configuration

Formation of T inventories
Migration of wall material

Formation of T inventories

Inventory in **full metal** devices determined by

- Diffusion and
- Trapping in defects
- Interfaces



in addition: Thermal Desorption Spectroscopy (TDS) data

Formation of T inventories

Inventory in full metal devices determined by

- Diffusion and
- Trapping in defects
- Interfaces

- Analysis typically involves inversion of noisy ill-conditioned

nonlinear integral equations

$$Y\left(E;E_0\right)=\int dx\, c\left(x\right) s\left(E\left(c\left(x\right),x\right)\right)+b$$

Key factors:

- Temperature T(t)
- Impinging fluxes (interacting)
- surface properties (recombination)
- Material structure

Formation of T inventories

Diffusion: Experiments are challenging → strong support from simulations needed

Various levels of approximations:

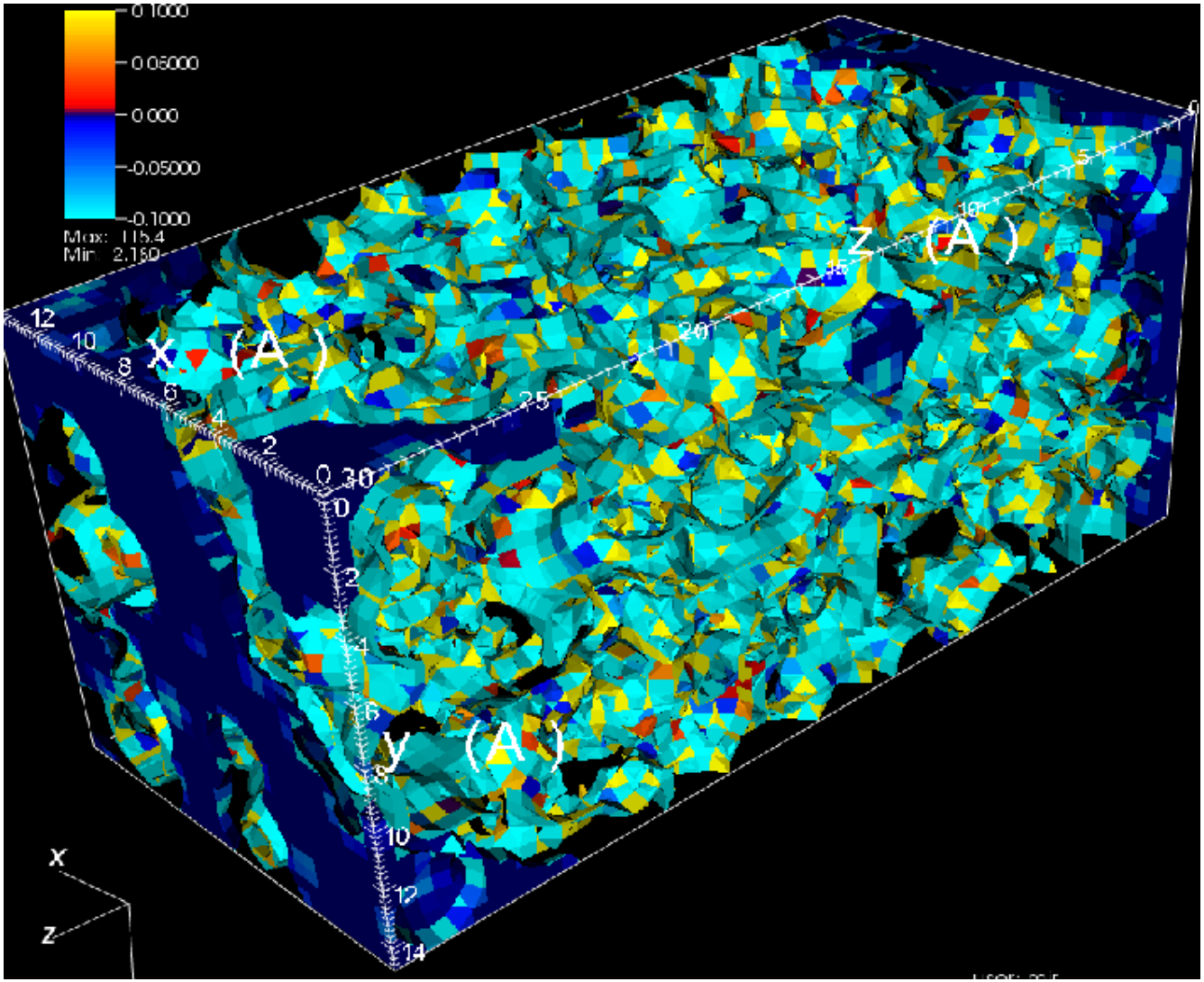
- **TSTs**
- Fokker-Planck-Eq
- Diffusion-Trapping models

MD-Approaches:

- TAD
- Parallel Replica
- Hyperdynamics

MC-Approaches:

- KMC

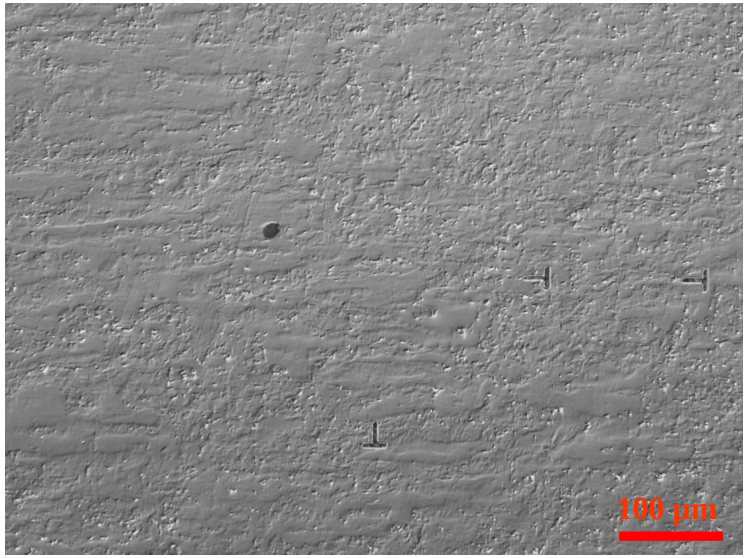


Tritium inventory: Blisters

- **Blister formation** (gas filled bubbles caused by D implantation):
  - Relatively **strong blistering** of **non-recrystallized** tungsten

optical micrograph (DIC)

initial sample surface



before implantation

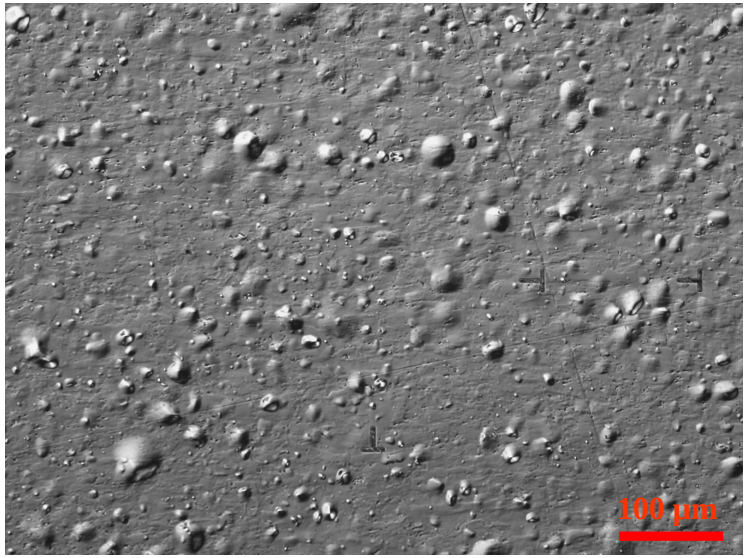
Non-recrystallized

Tritium inventory: Blisters

- **Blister formation** (gas filled bubbles caused by D implantation):
  - Relatively **strong blistering** of **non-recrystallized** tungsten
  - Blister **size** and **density** depends strongly on **implantation temperature**

optical micrograph (DIC)

many large blisters



$6 \cdot 10^{24}$ D/m^2
T_{sample} = 370 K

Non-recrystallized

Material migration

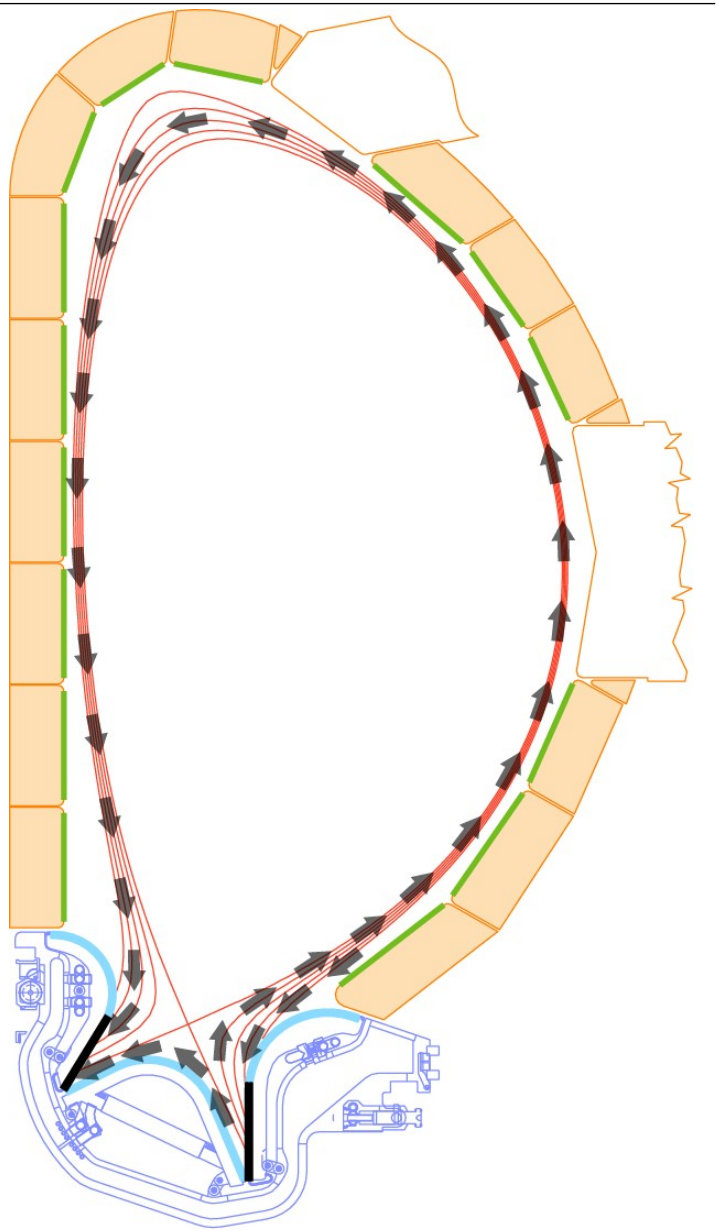
Plasma

Fuel ions + atoms (charge exchange) + impurity ions bombard 1st wall

Wall materials

Erosion → Transport → Deposition

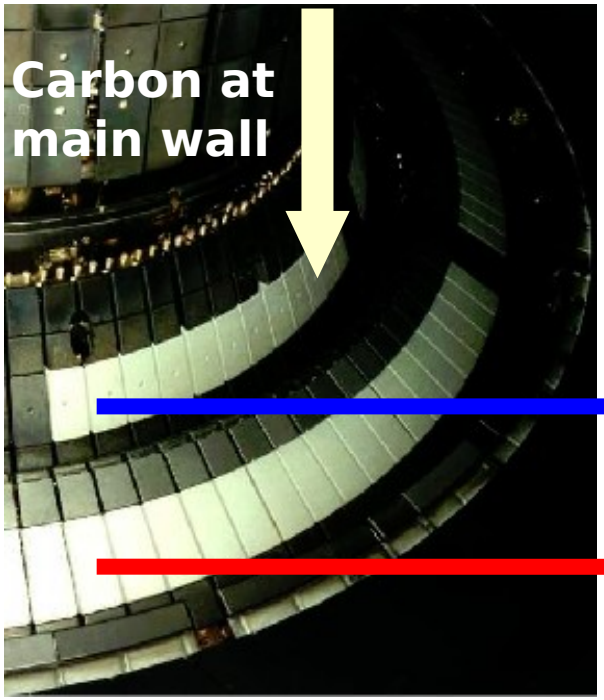
Re-erosion

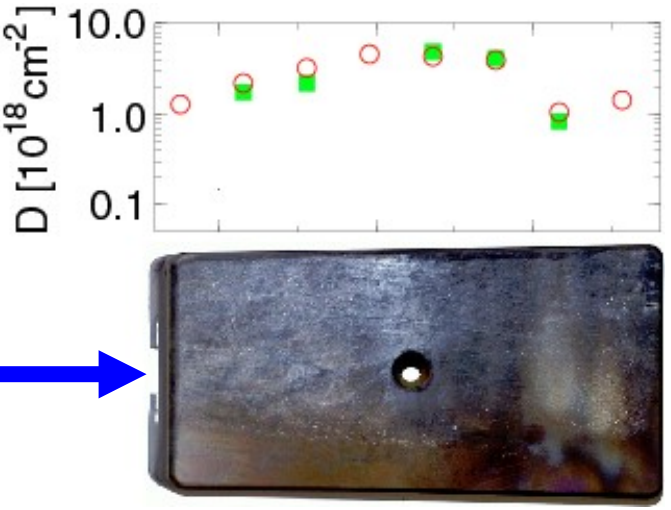


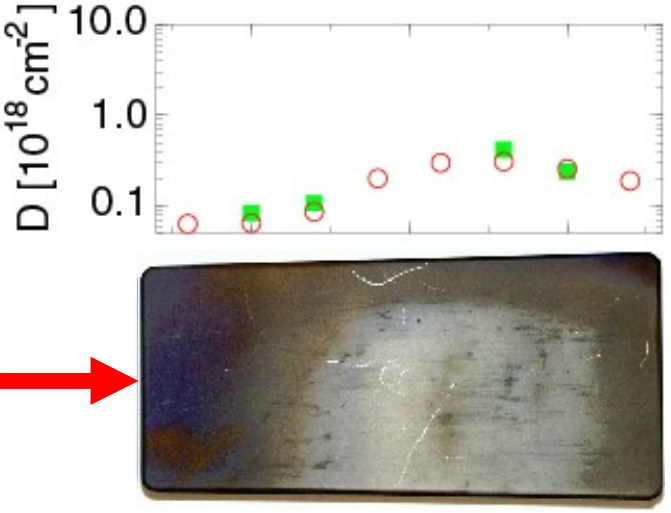
What are the consequences of material migration?

Layer deposition and material mixing!

Freshly installed tungsten divertor in ASDEX Upgrade

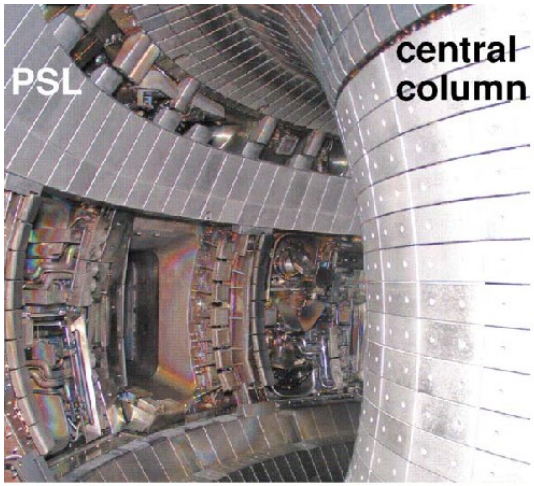


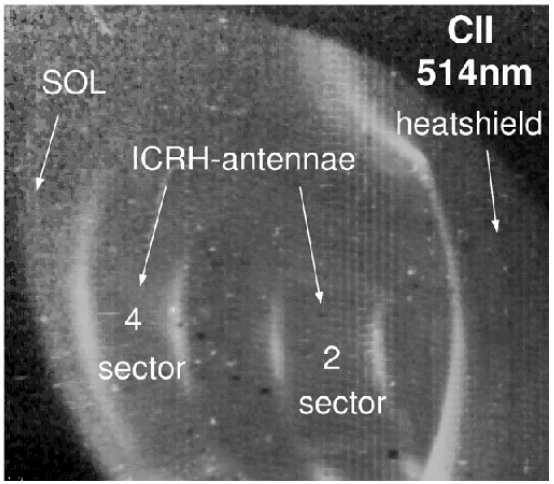




Deposited layers may form ever growing inventory of buried fuel!

Carbon erosion and migration in ASDEX Upgrade





T. Pütterich et al., PPCF 45 (2003) 1873

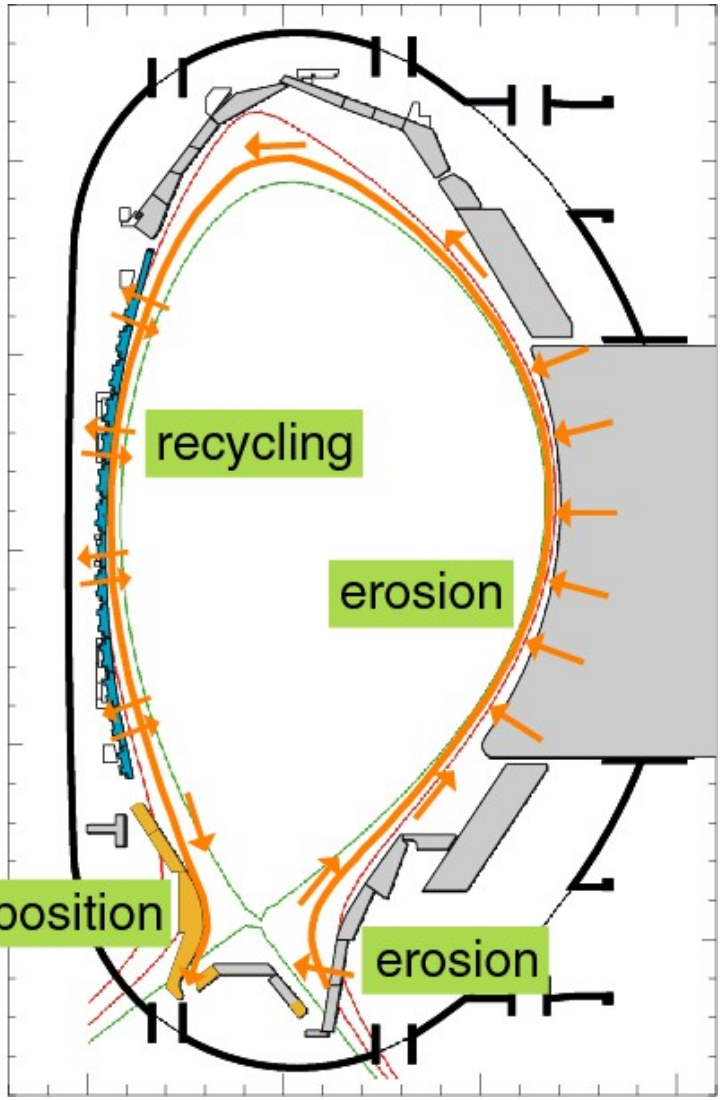
Primary source: Outboard limiters / Outer Divertor

↓

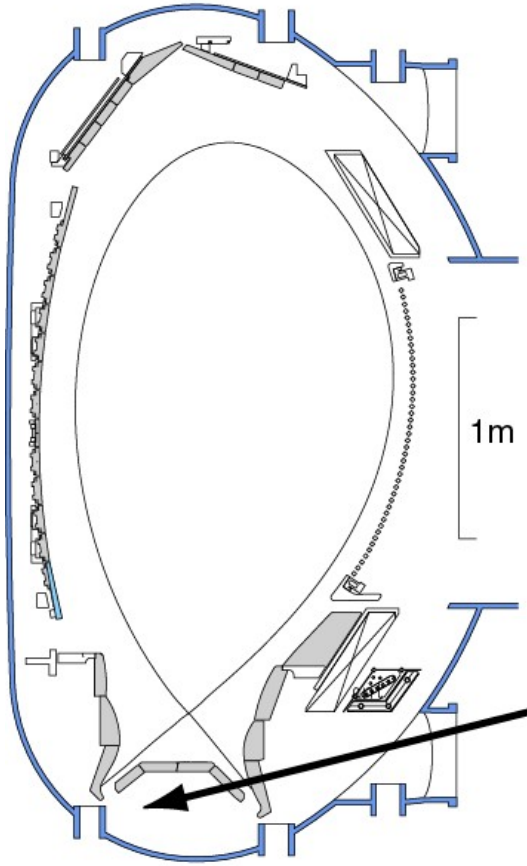
Transport to central column ⇒ Secondary source

↓

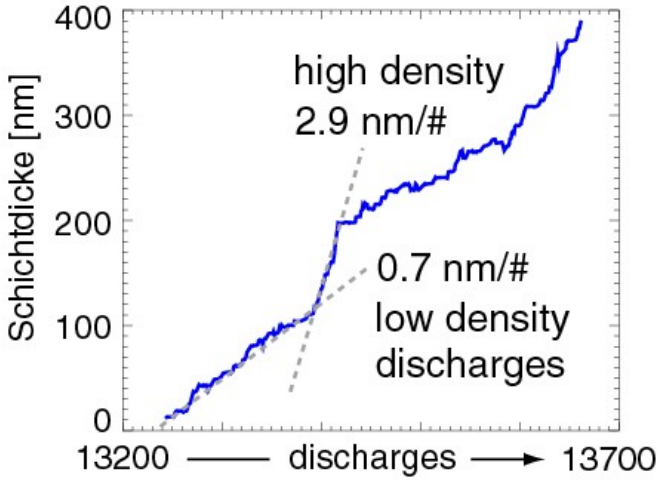
Finally deposition mainly in inner divertor



Carbon erosion and migration in ASDEX Upgrade



Growth of C-layers measured
by piezo quartz micro balance



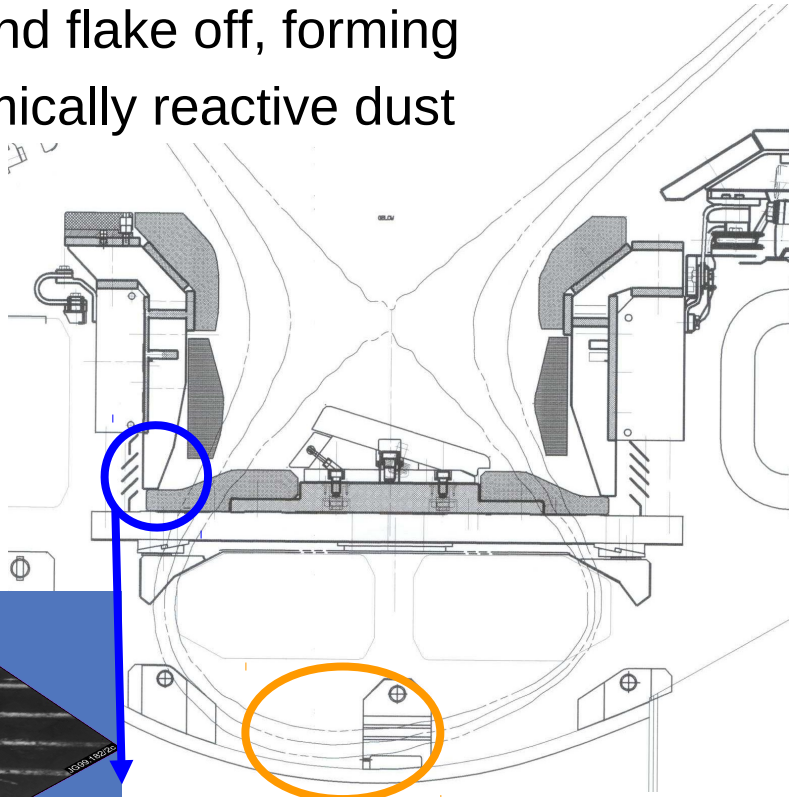
PROBLEM!

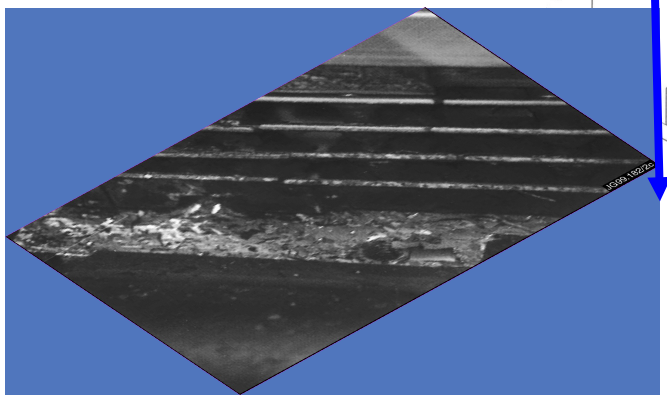
Carbon is continously eroded and re-deposited in divertor

ITER:
T inventory growth!

What happens if deposited layers become too thick?

Layers delaminate and flake off, forming radioactive and chemically reactive dust

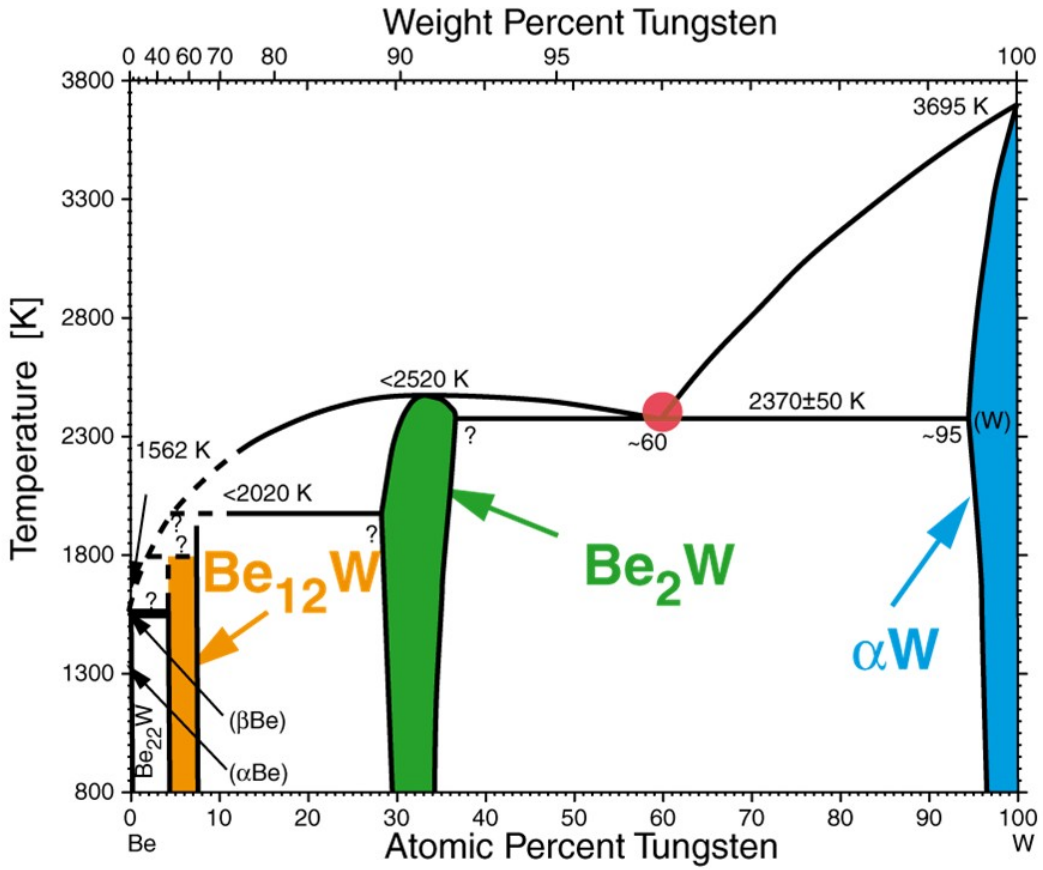




Potential radiation + explosion hazard!

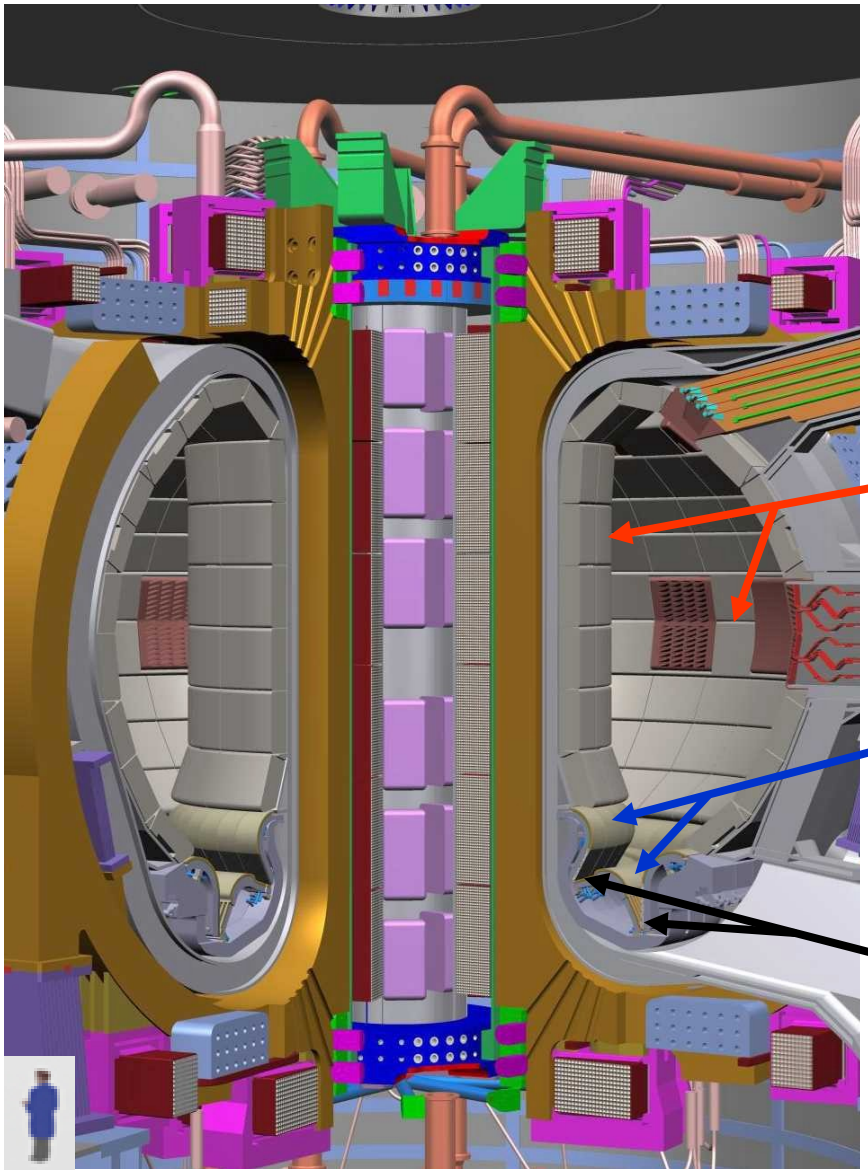
Negative consequences of material mixing?

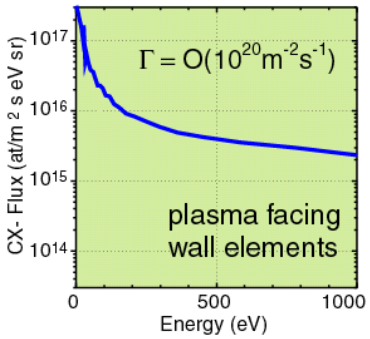
YES! Example: beryllium and tungsten can form alloys

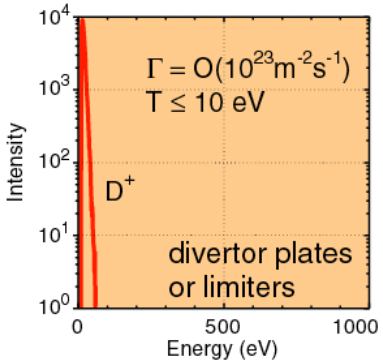


melting point: 3695 K → 2370 K → 2520 K → ~1570 K
with increasing Be content

Summary: the initial ITER 1st wall configuration







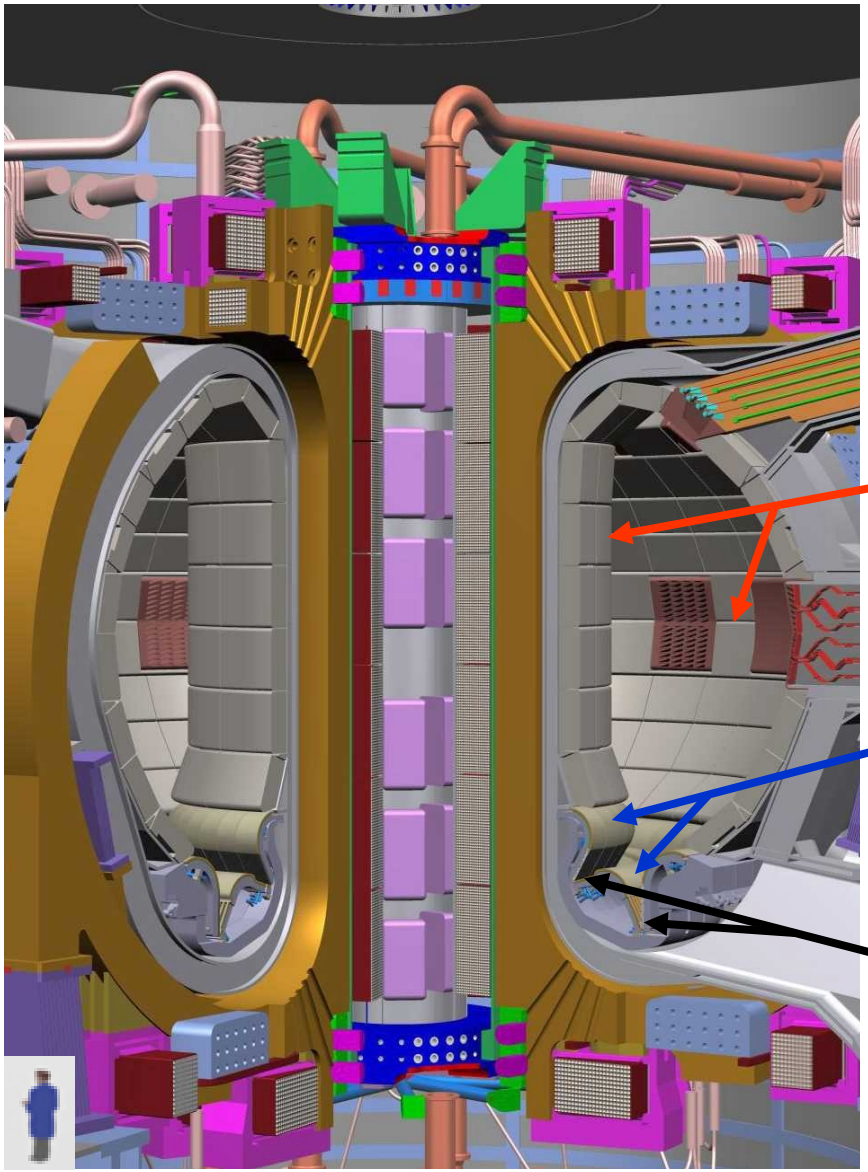
Be: primary wall, port limiter, baffle - 700 m^2

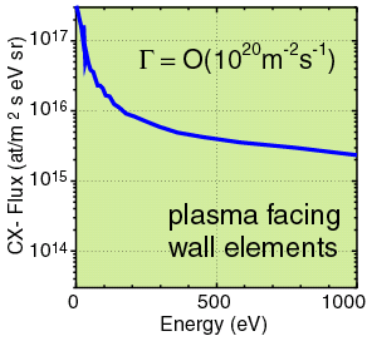
W: upper vertical target, dome baffle, liner - 100 m^2

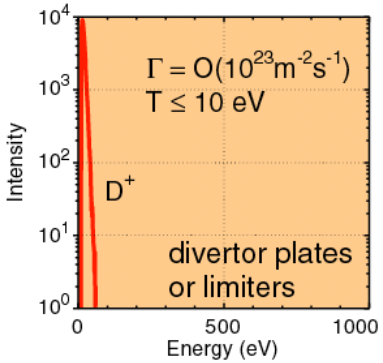
CFC: lower vertical target - 50m^2

First wall design of DEMO: u.i.

Summary: the final ITER 1st wall configuration







Be: primary wall, port limiter, baffle - 700 m^2

W: upper vertical target, dome baffle, liner - 100 m^2

~~**CFC:** lower vertical target - 50m^2~~

Replaced by tungsten

First wall design of DEMO: u.i.

Thank you
for your attention

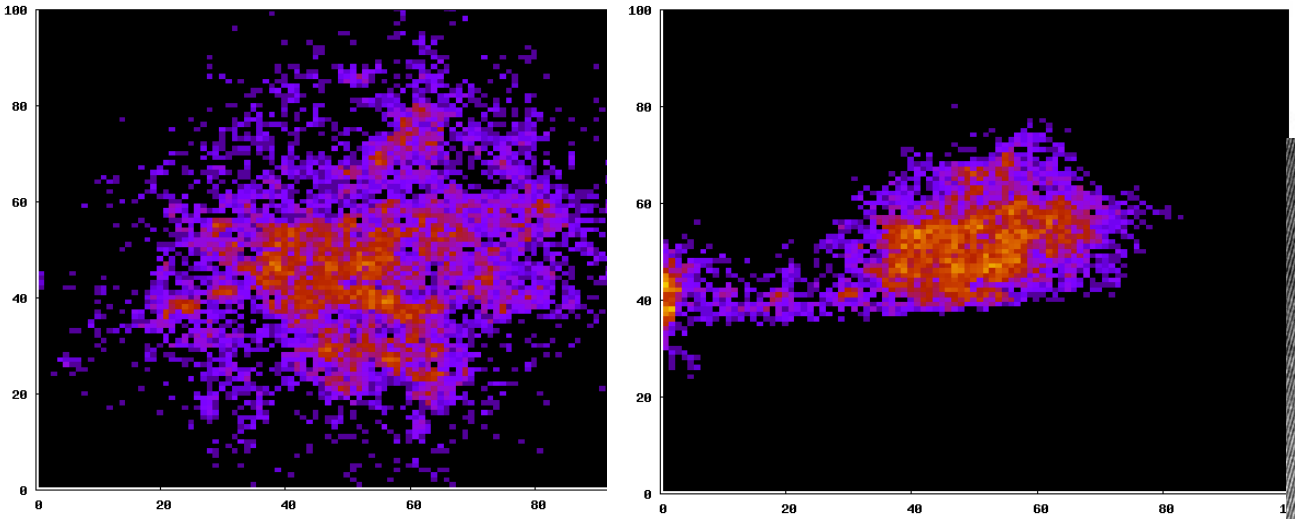
Questions?

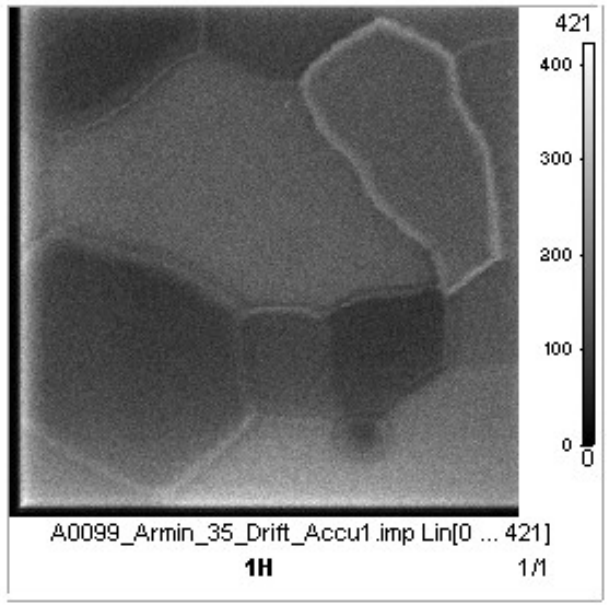
Hydrogen transport in tungsten

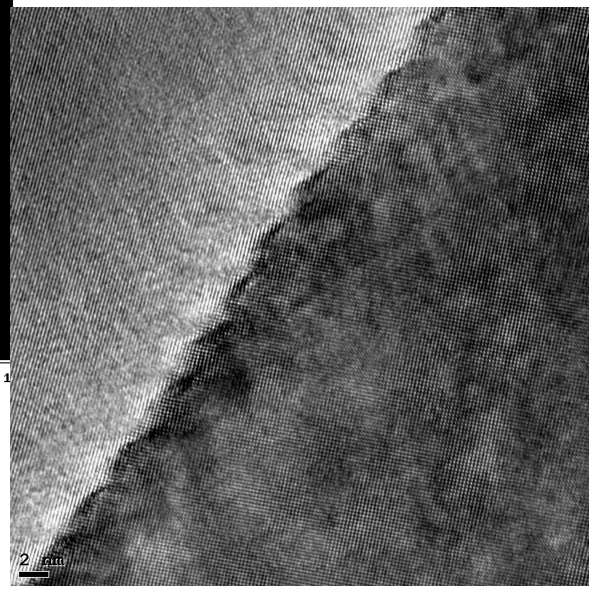
Example: Grain boundary diffusion of H

Well known in other materials (SS,Ni[1])

- May dramatically alter diffusion properties:
- Transport in **large** asymmetric random networks
- Percolation theory on sparse 10^7 x 10^7 matrices



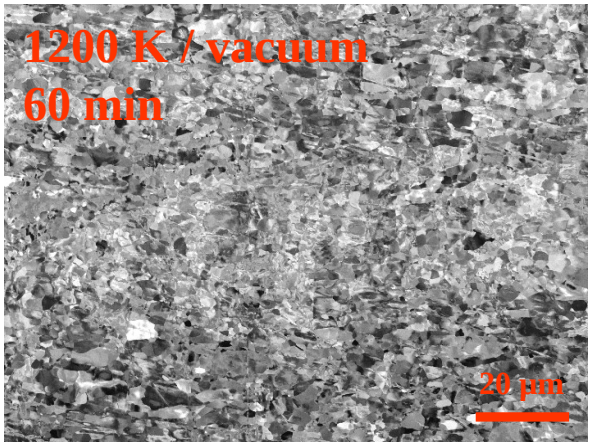


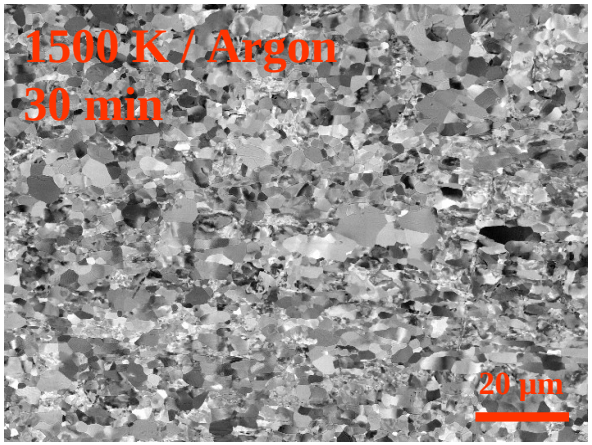


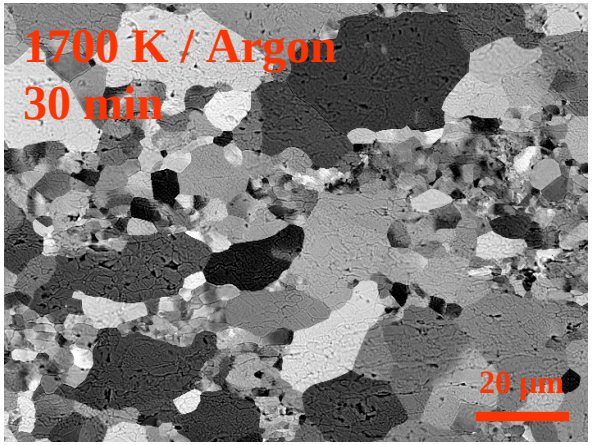
GB may enhance or suppress diffusion

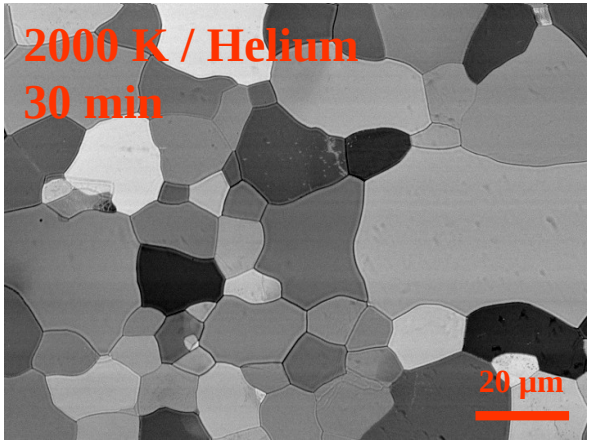
1) A.M. Brass, Acta mater. 44 (1996), 3823

Tungsten...
Description requires structural *and* material parameters





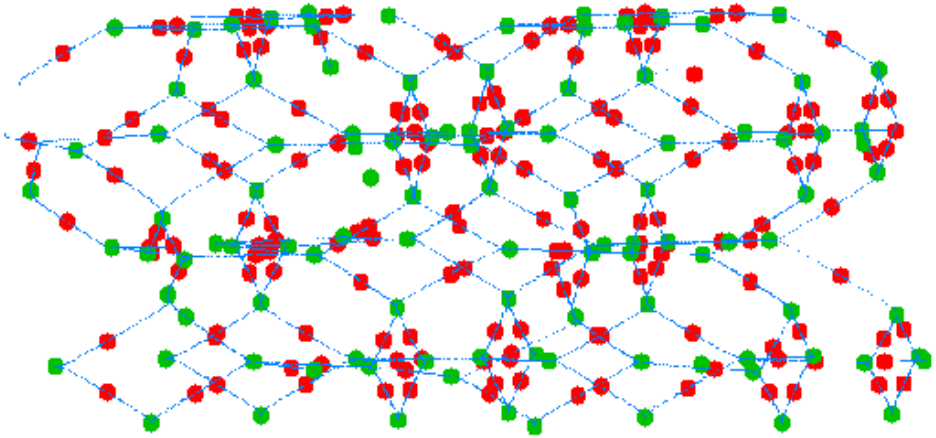




courtesy A. Manhard

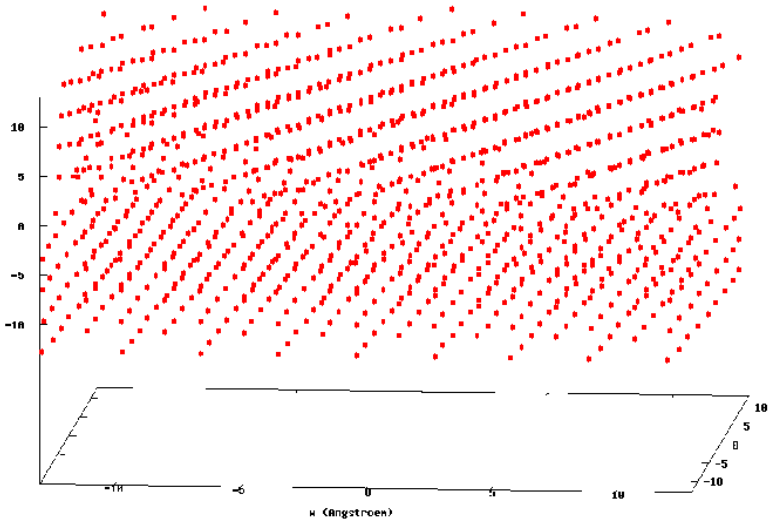
Hydrogen transport in tungsten

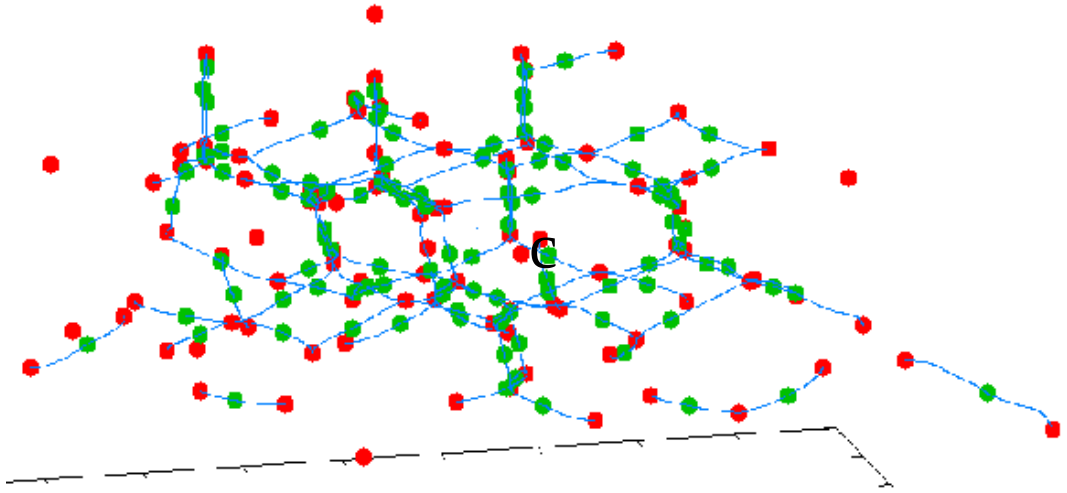
Computation of transport network:



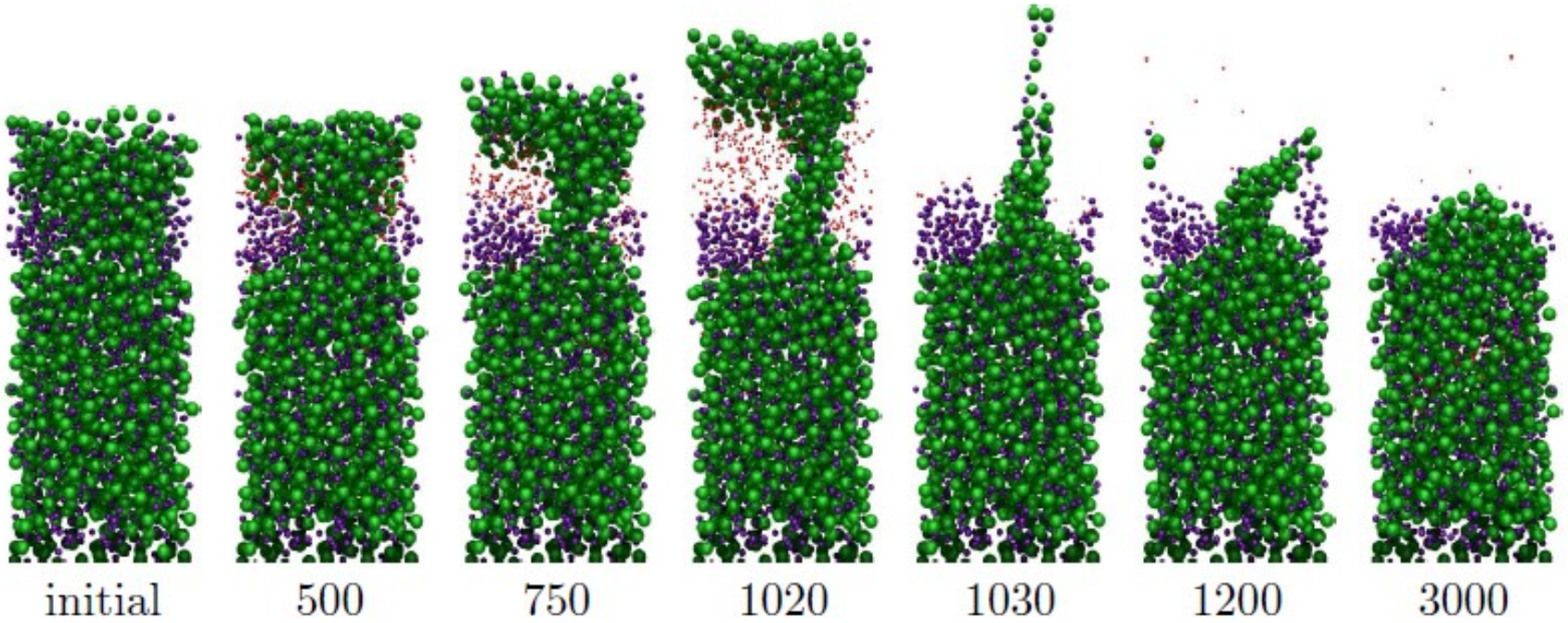
- Challenge: Locate **all** Sps (NEB, DIMER methods fail)

- MD relaxation of GB sample





Molecular dynamics: High flux simulations

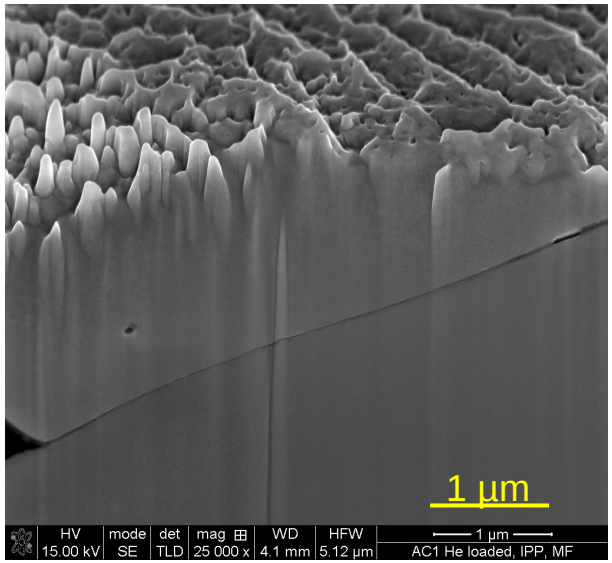


Blister formation: Supersaturation at C-rich site
Gas pressure: 2GPa
Depth: 2 nm

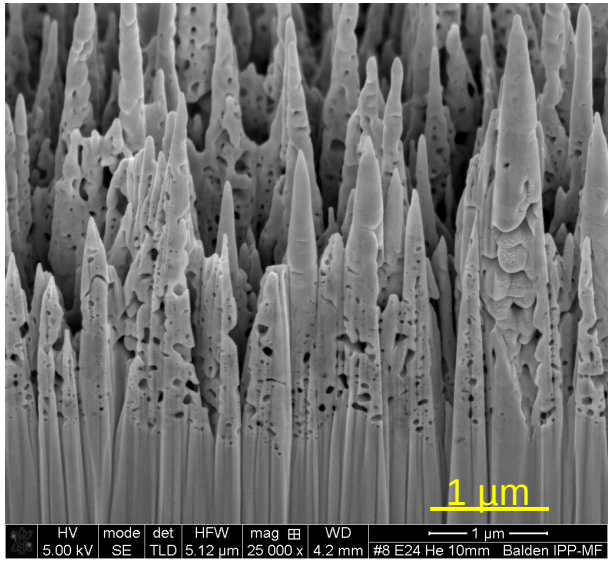
Results: influence of surface temperature on erosion (1)

high fluence $1 \cdot 10^{25}$ He/m²

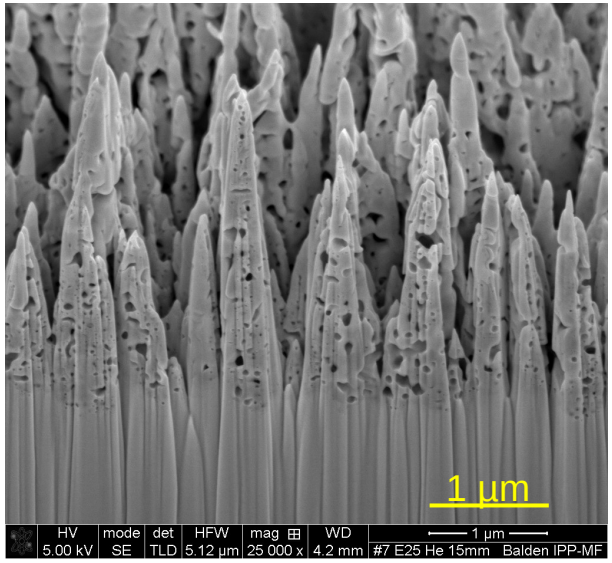
Tsurf=200°C



Tsurf=1000°C



Tsurf=1450°C



note: 70 nm penetration depth, calculated erosion: 5 µm

FIB: M.Balden

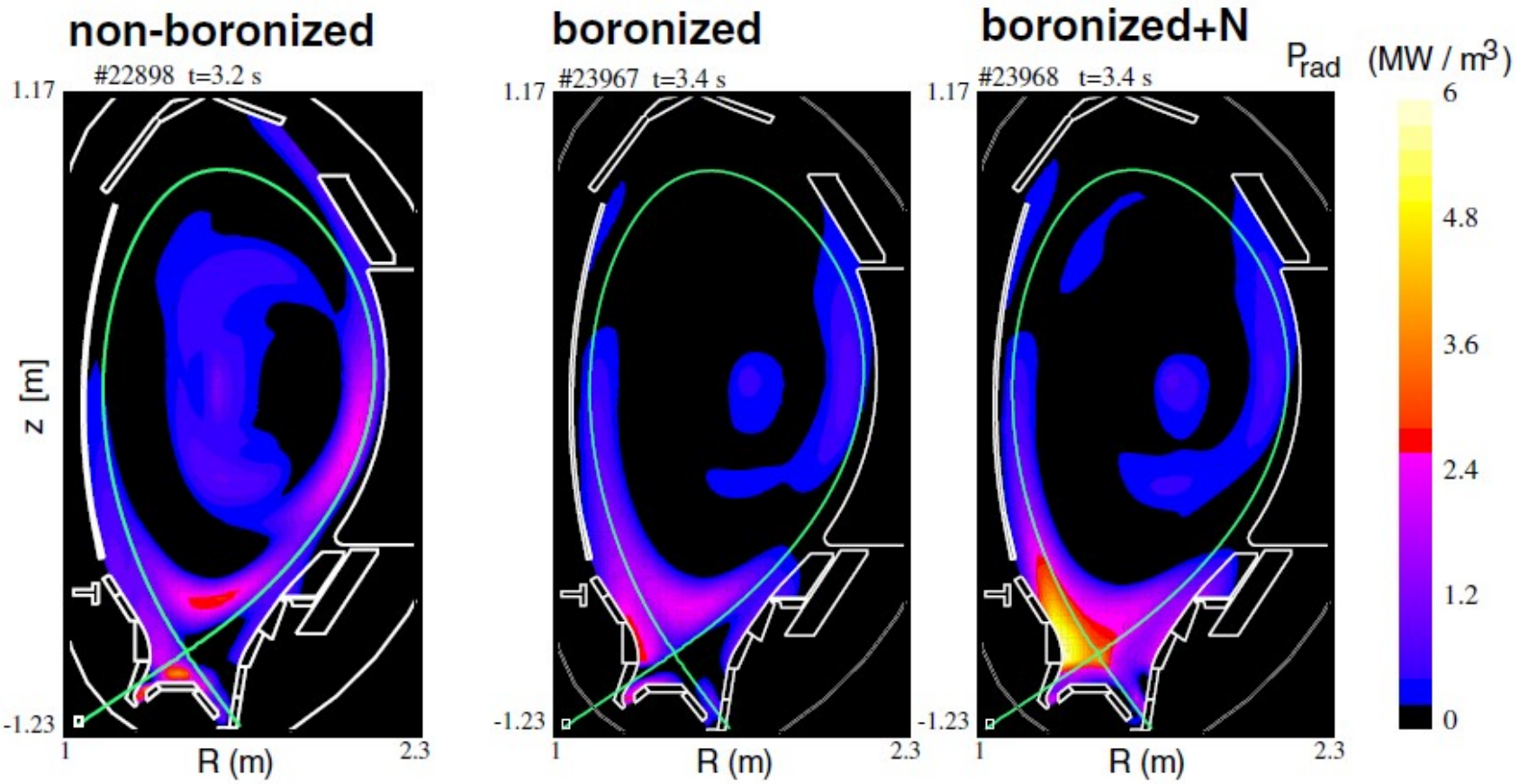
Low temperature: no bubble formation was observed
Tsurf ≥ 1000°C: strong bubble formation dominates erosion pattern

Further investigation: confirmation of results, determination of “bubble start temperature”

Motivation for N_2-seeding

AUG with W wall: Radiation profiles (bolometry)

[A. Kallenbach et al., Nucl. Fusion **49** (2009) 045007]

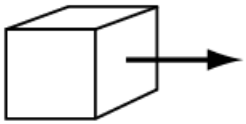


Total radiated power:

4.5 MW	3.4 MW	4.5 MW

Sheath potential

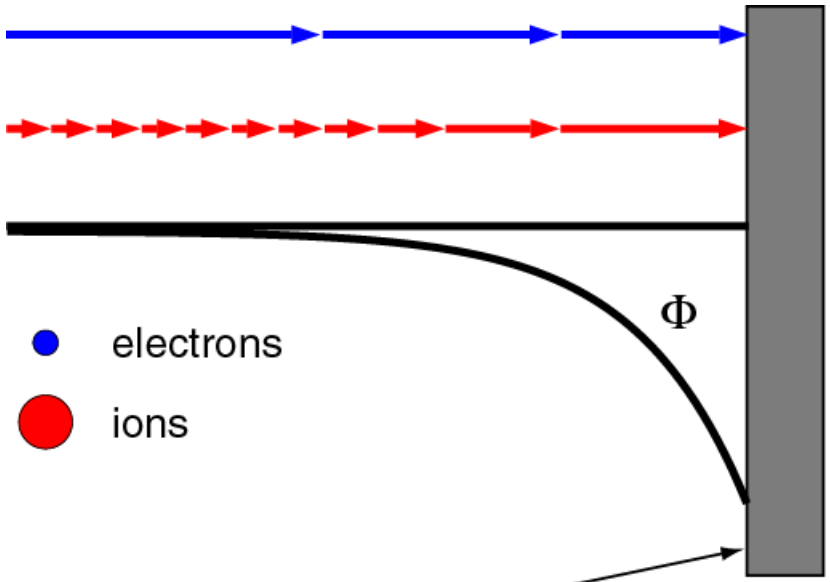
Plasma in local thermodynamic equilibrium



$$\Gamma_x = \int_0^{\infty} f_{Maxw}(\vec{v})\, v_x\, dv_x \int_{-\infty}^{+\infty} dv_y \int_{-\infty}^{+\infty} dv_z$$

$$= \frac{1}{4} n \bar{v}$$

$$\bar{v} = \left(\frac{8kT}{\pi m} \right)^{1/2}$$



$\bar{v}_e \gg \bar{v}_i$ but plasma must remain neutral: $\Gamma_w^e = \Gamma_w^i$

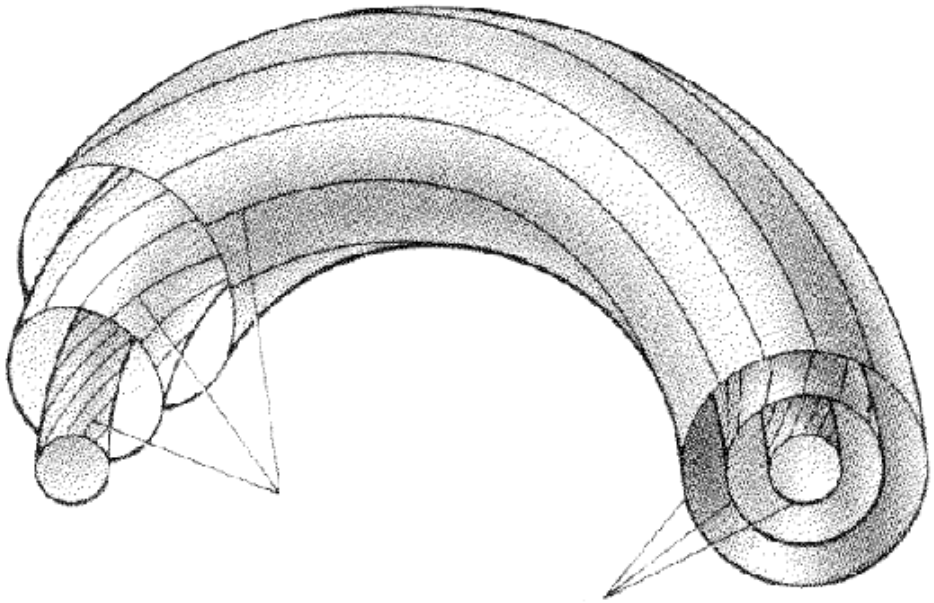
- formation of potential to repel electrons
- $\Gamma_w^e = \frac{1}{4} n_w \bar{v}_e = \frac{1}{4} n \exp(e\Phi / kT_e) \bar{v}_e$
- $\frac{e\Phi}{kT_e} = \frac{1}{2} \ln \left[\left(2\pi \frac{m_e}{m_i} \right) \left(1 + \frac{T_i}{T_e} \right) \right] \approx -3$

Ions: energy gain $3ZkT_e$

Plasma confinement by magnetic field

Field lines intersecting material surface

- ↬ fast plasma loss
- ↬ toroidal geometry



Plasma parameters:

Sound velocity: ~10 000 m/s:

C_s= 9.79*10**5*sqrt(((1+2/n)*Z*T_e[eV]/(m_i/m_p))) [cm/s]
(NRL Plasma formulary, p. 29)

D_perp ~1m/s