Plasma surface interaction

Presented by K. Schmid

Material supplied by K.Krieger, M. Rubel, H.S. Bosch, R. Neu, J. Roth, J. Linke, AUG Team, JET TF-E Team, TEXTOR Team….

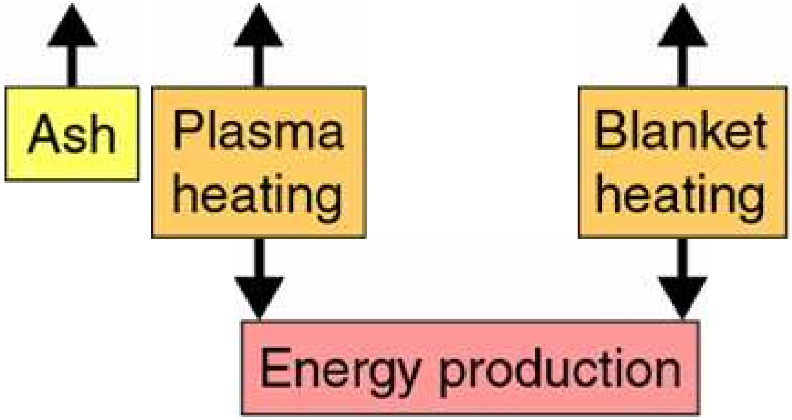
Outline

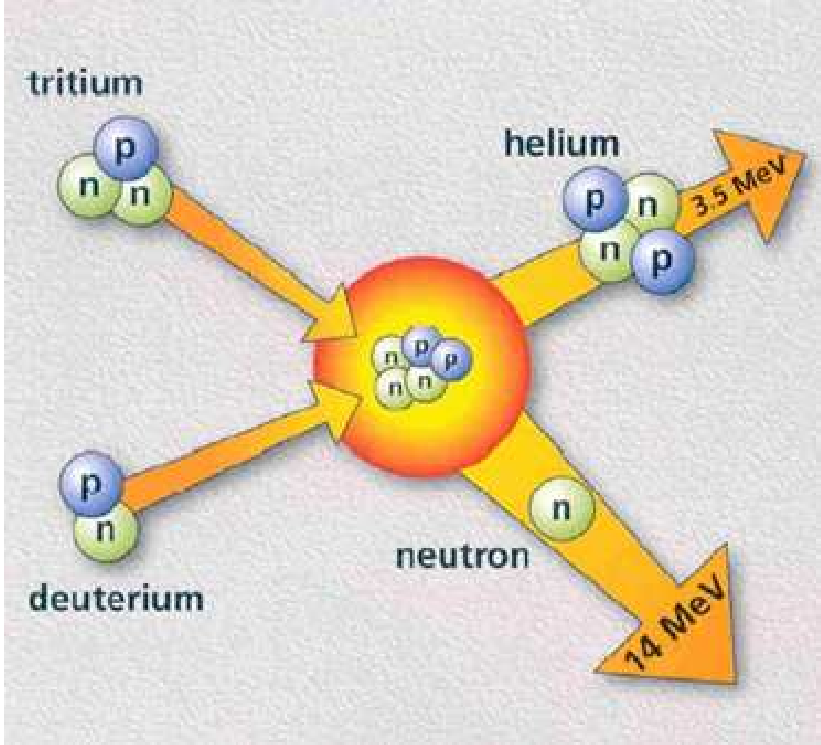
- ❖What is magnetic confinement fusion
- ❖Why do we need a wall in the first place
- ❖Power and particle fluxes to the wall
- ❖Fundamental processes during plasma wall interaction
- ❖Summary

What is magnetic confinement fusion

Most promising reaction (highest <σv>):

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





Reaction of 1g (0.2 mol) D-T mixture ⇒ $\approx 1.2\times10^{23}$ reactions → $E_\alpha = 67.5$ GJ, $E_n = 271.8$ GJ

- ➢Produced power must be exhausted and converted to electrical energy
- ➢Radioactive T must be contained such that it is available to the nuclear reaction

What is magnetic confinement fusion

❖ Required temperatures 10-20 keV to reach maximum in reaction cross section

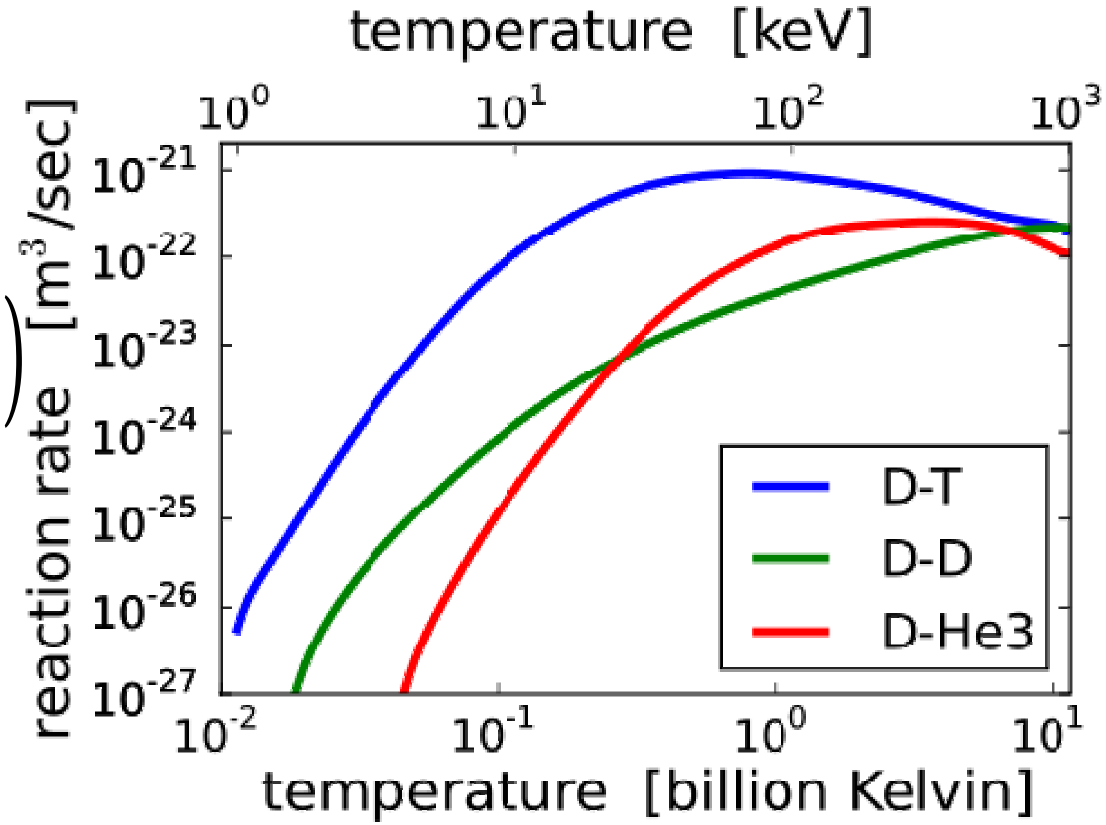
❖Lawson criterion

➢"Energy production > Energy loss"

$$f\, E_\alpha \geq \mathrm{P}_{Loss} = {3nK_BT}/{\tau_E} \qquad \left(eV/m^3 s\right)$$

$$f = \left(n/2\right)^2 \langle \sigma v \rangle \qquad \left(1/m^3 s\right)$$

$$n\tau_E \geq {3K_BT}/{\langle \sigma v \rangle E_\alpha}$$

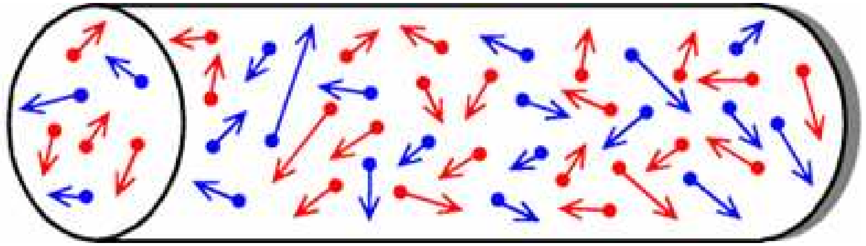


➢Must maintain high temperature, density and confine energy for ionized fuel species

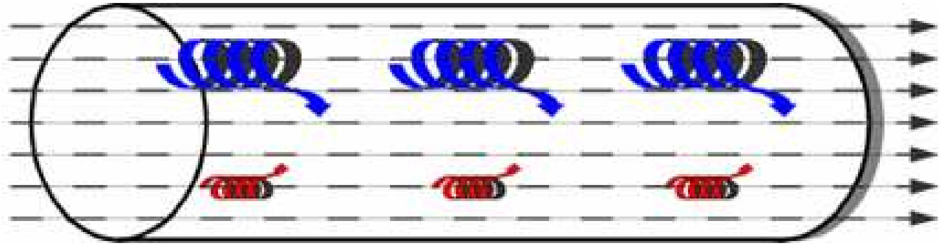
Confine in magnetic field

What is magnetic confinement fusion

without magnetic field



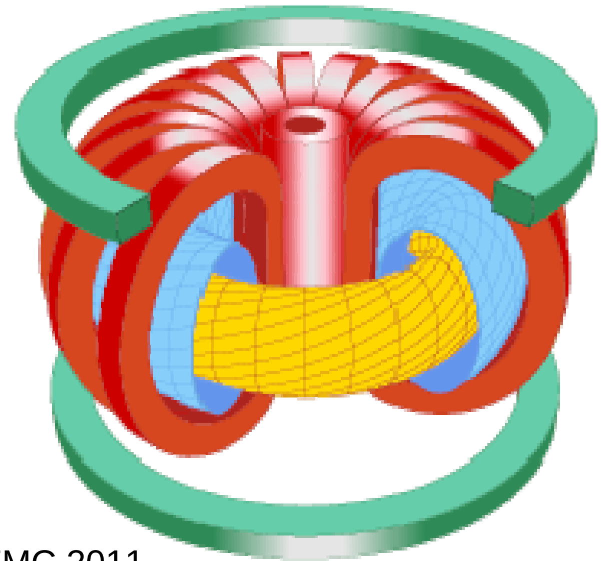
with magnetic field



mobility ⊥B ≪ mobility || B

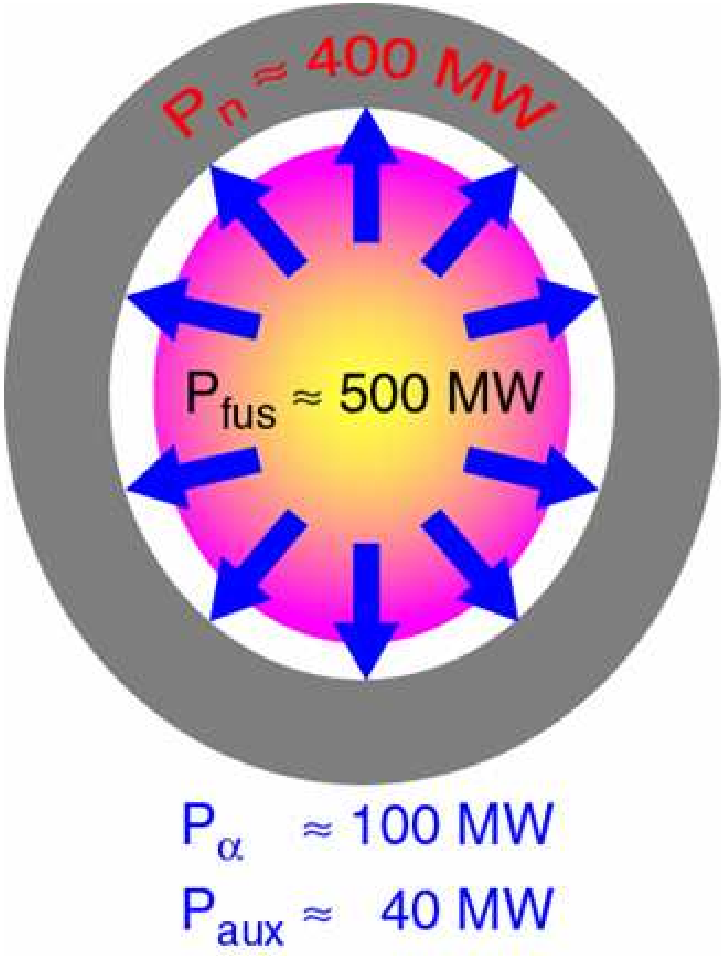
→ Loss at “ends”

→ Close field lines into a torus: “TOKAMAK” concept



Why do we need a wall in the first place

Example ITER



1. Vacuum conditions

Fusion plasma is hot and thin and
Cannot survive intense interaction.
with a surrounding atmosphere.

➩ We need a vacuum vessel.

2. Extraction of power

Both α-particle and neutron power fractions need to transfer energy to a thermodynamic cycle.

➩ Their kinetic energy must be converted to heat by stopping in materials.

3. Magnetic coils are delicate structures

➩ Protection from energetic particles and radiation necessary.

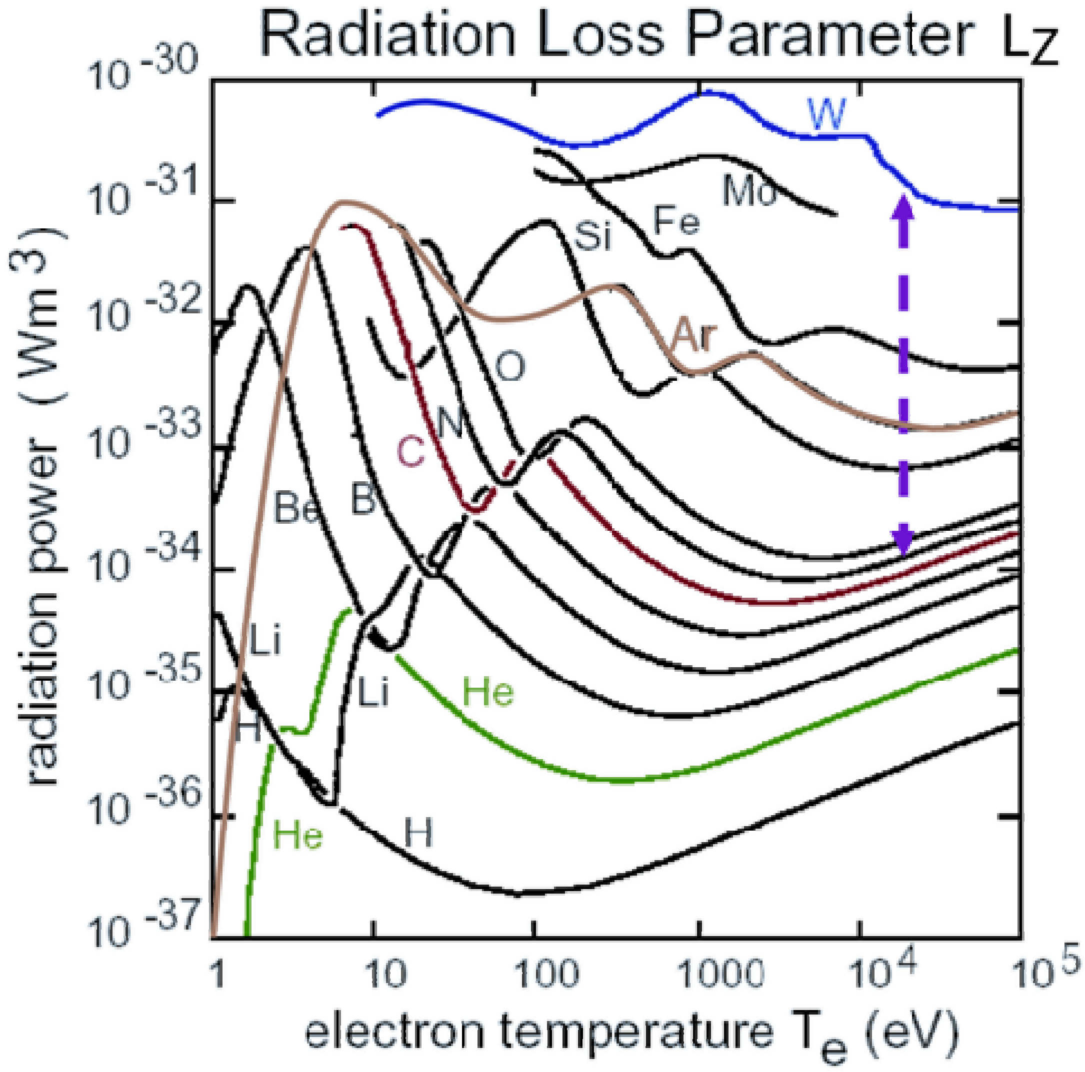
4. He ash removal by fuel circulation

➩ Material surface for neutralisation of escaping ions necessary.

Why do we need a wall in the first place

❖Plasma must be kept "clean" little to no impurities are allowed

But why?



R. Neu, R. Parker, T. Pütterich

❖Impurity are not all fully ionized

➢Electronic transitions possible

➢Power loss by radiation

❖Plasma is quasi neutral

➢Impurities dilute the plasma
→Each impurity of charge Z "displaces" Z-fuel ions

Power and particle fluxes to the wall

❖Where does the plasma hit the wall ?

- ➢Depends on the exact details of the magnetic field
- ➢Depends on the relative orientation and position of the wall relative to the field

❖Both are only known within certain tolerances

→ Without further effort the plasma would **concentrate** at some unknown wall location (and cut it open like turkey)

The plasma edge must be brought into contact with sections of the wall in a controlled fashion

❖Limiters

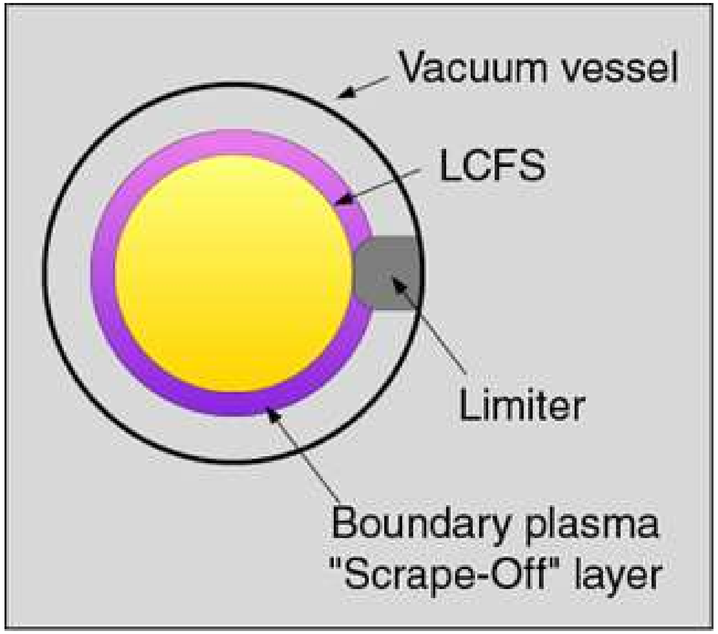
❖Divertors

Power and particle fluxes to the wall

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

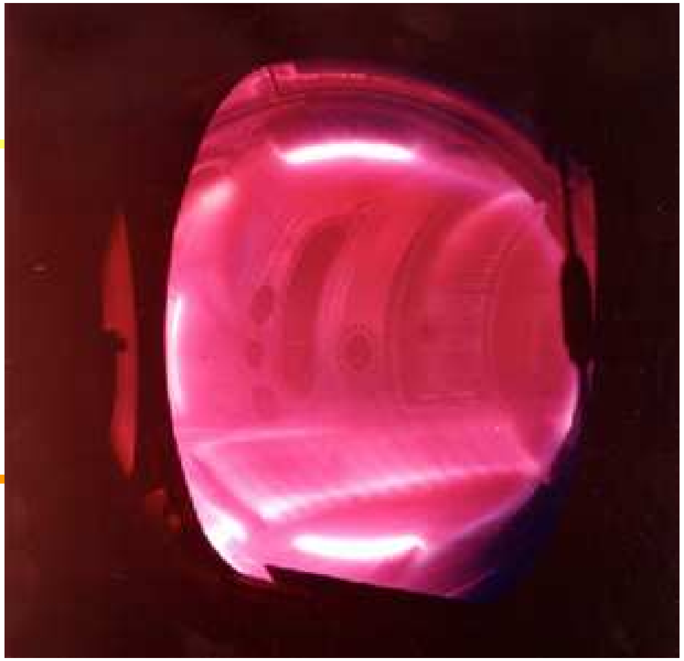
Last Closed Flux Surface (LCFS):
The magnetic surface that touches the innermost part of the limiter.

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



Poloidal limiter

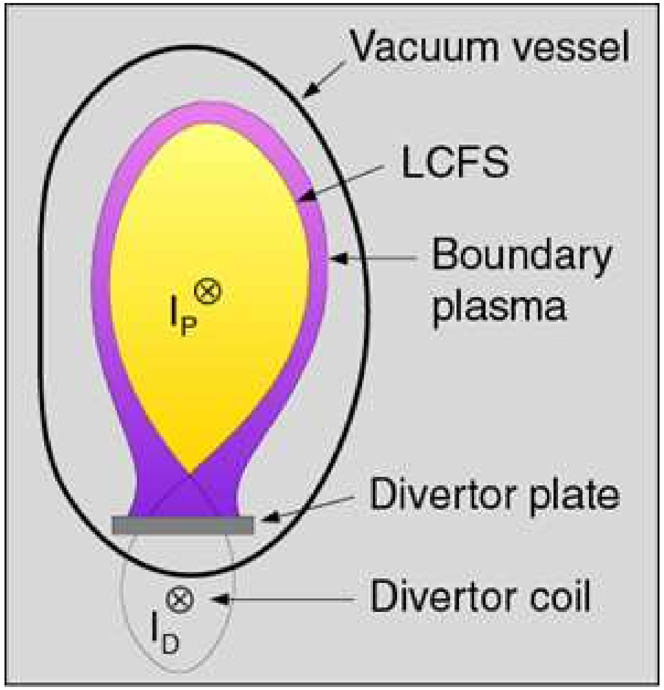
Toroidal limiter

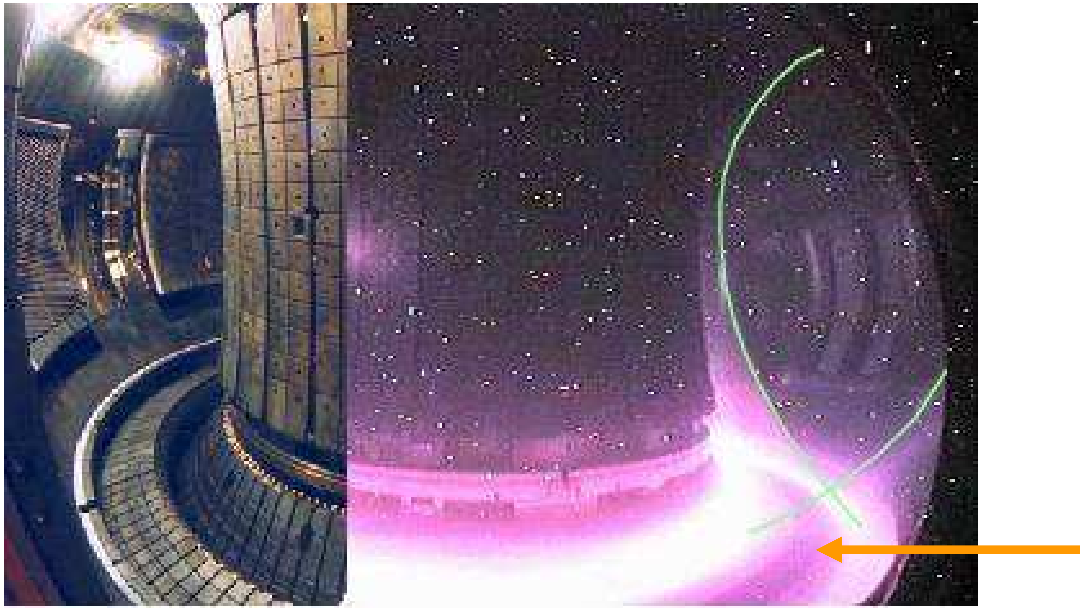


Power and particle fluxes to the wall

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





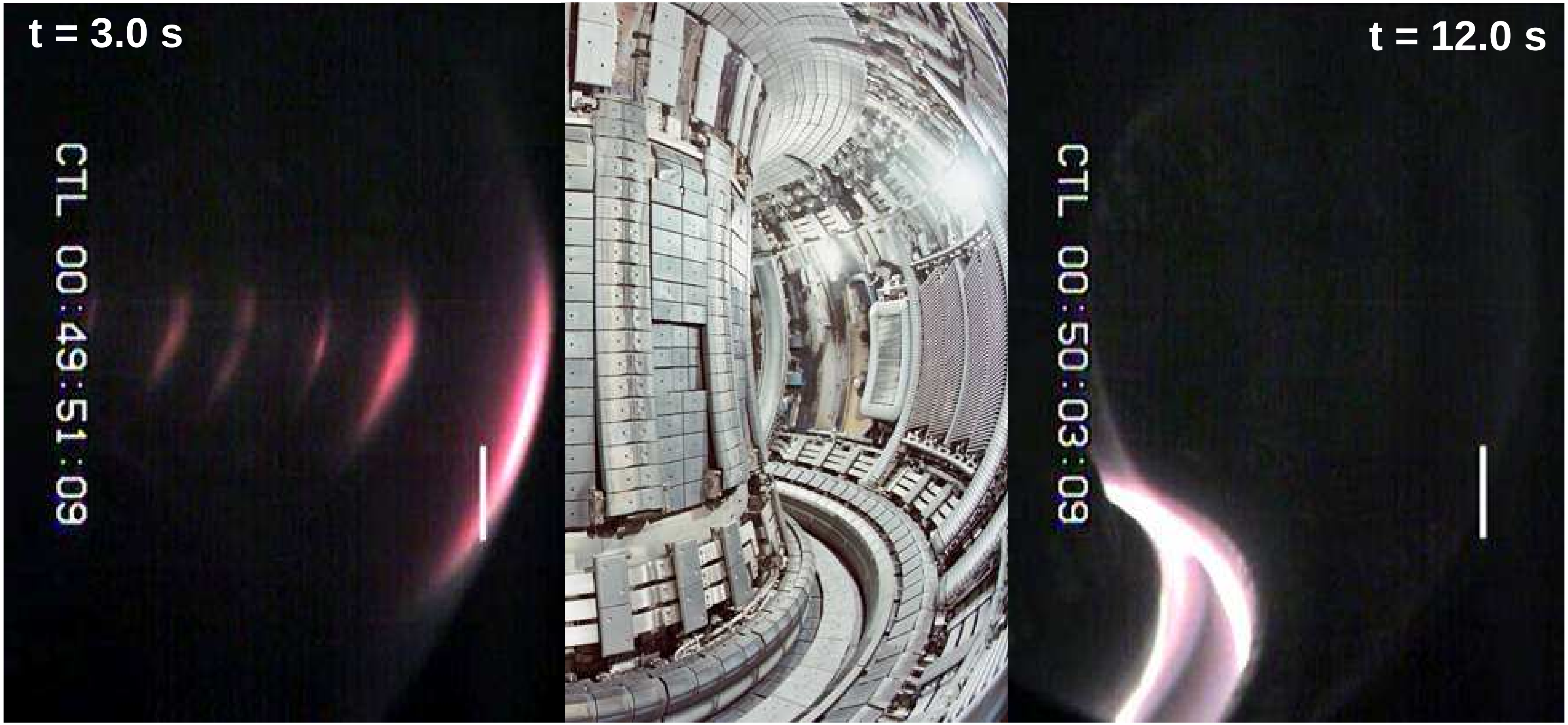
The divertor in ASDEX Upgrade

Power and particle fluxes to the wall

Divertor tokamaks need limiters for discharge ramp-up and shutdown

Example: JET

#62218: plasma visible light emission

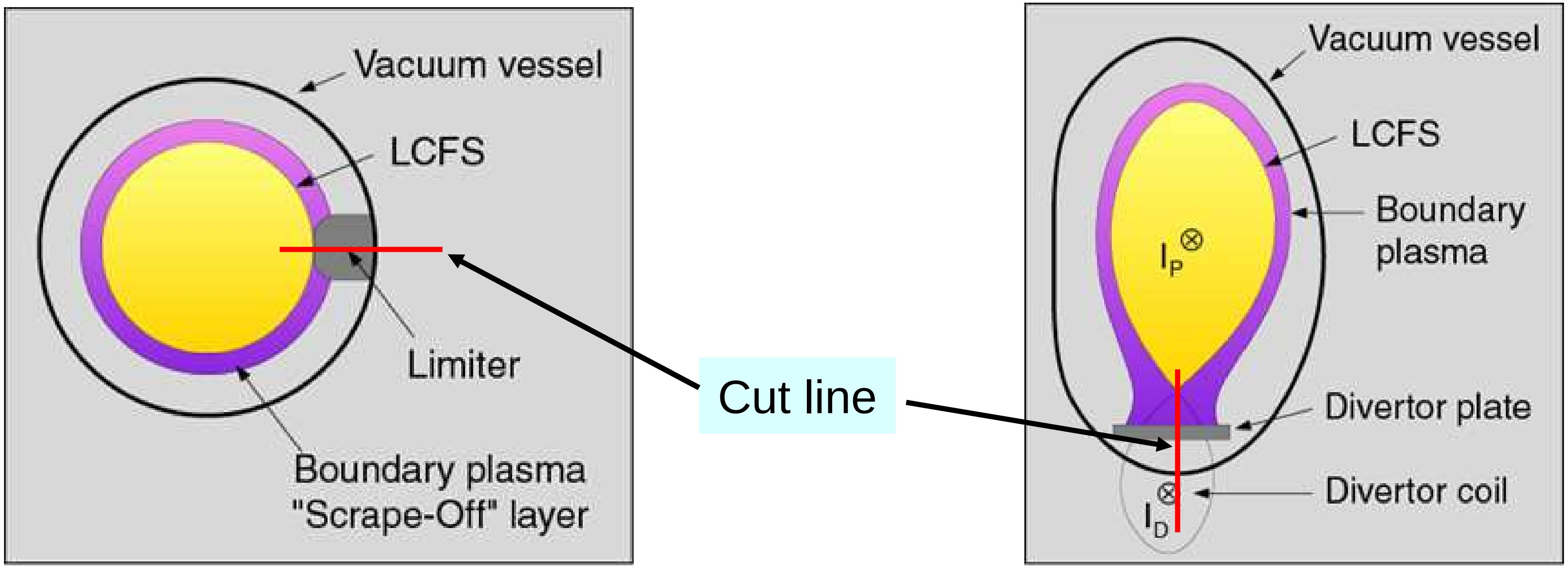


Limited **Diverted**

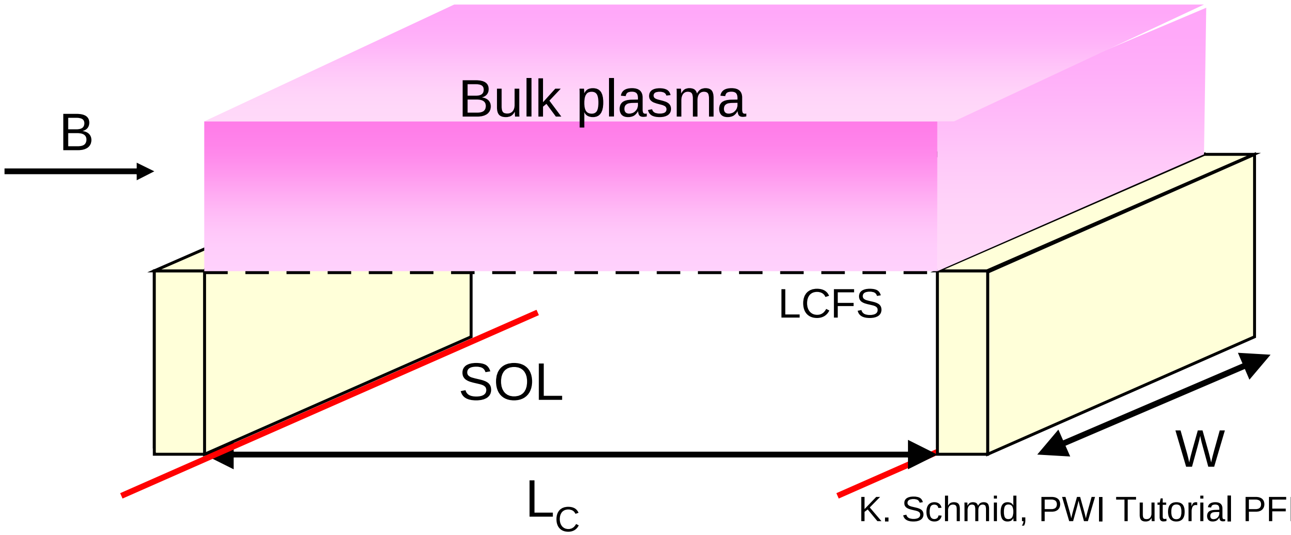
R.A. Pitts, EPS 2005

Power and particle fluxes to the wall

❖In both limiter and divertor plasmas wall elements are connected by field lines



❖In "field aligned" coordinates this can be drawn as a 2.5 dimensional problem



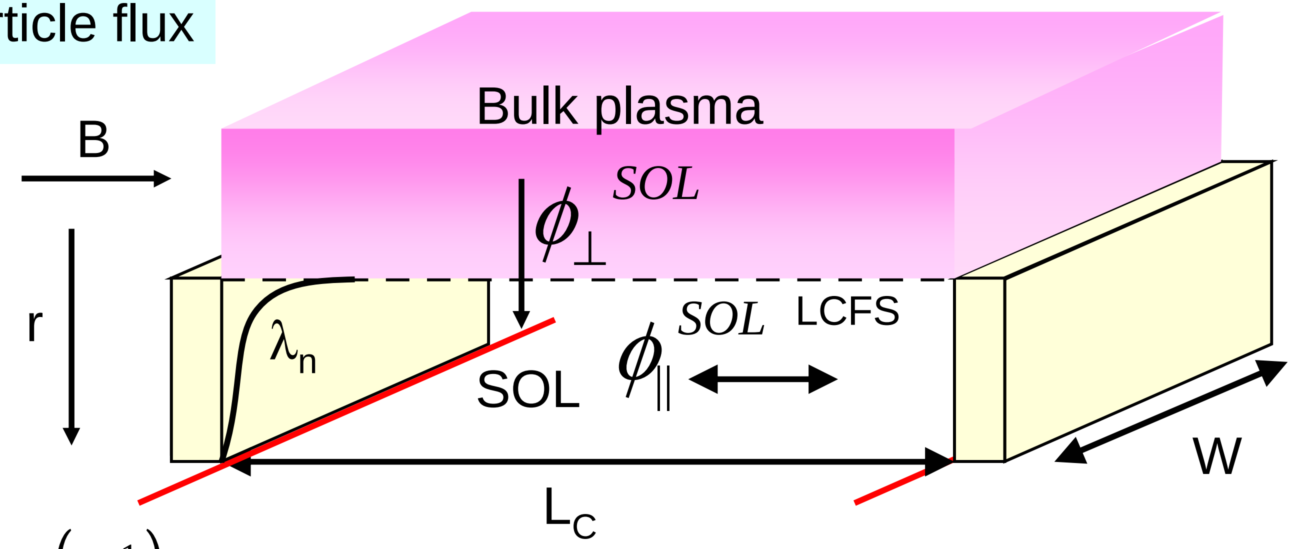
Power and particle fluxes to the wall

❖(Simplified) estimate of ion particle flux

$$\phi_{\parallel}^{SOL} = 2W \int_{r_{LCFS}}^{\infty} n(r) c_s dr \quad \left(\frac{1}{s}\right)$$

$$= 2W \int_{r_{LCFS}}^{\infty} n(r_{LCFS}) e^{-r/\lambda_n} c_s dr$$

$$\phi_{\perp}^{SOL} = -D_{\perp}^{SOL} \partial n / \partial r \Big|_{LCFS} L_C W \quad (s^{-1})$$



Flux balance $\phi_{\perp}^{SOL} = \phi_{\parallel}^{SOL} \Rightarrow \lambda_n = \sqrt{2D_{\perp}^{SOL} L_C / c_S} \approx O(0.01)\text{m}$

$$\phi_{\parallel}^{SOL} = 2Wn(r_{LCFS}) c_s \lambda_n \approx O(10^{21} - 10^{23})\, s^{-1}$$

❖Total flux entering the SOL from the bulk plasma is concentrated radially on length λ_n and toroidally on length W ~ 2πR

→Flux amplification

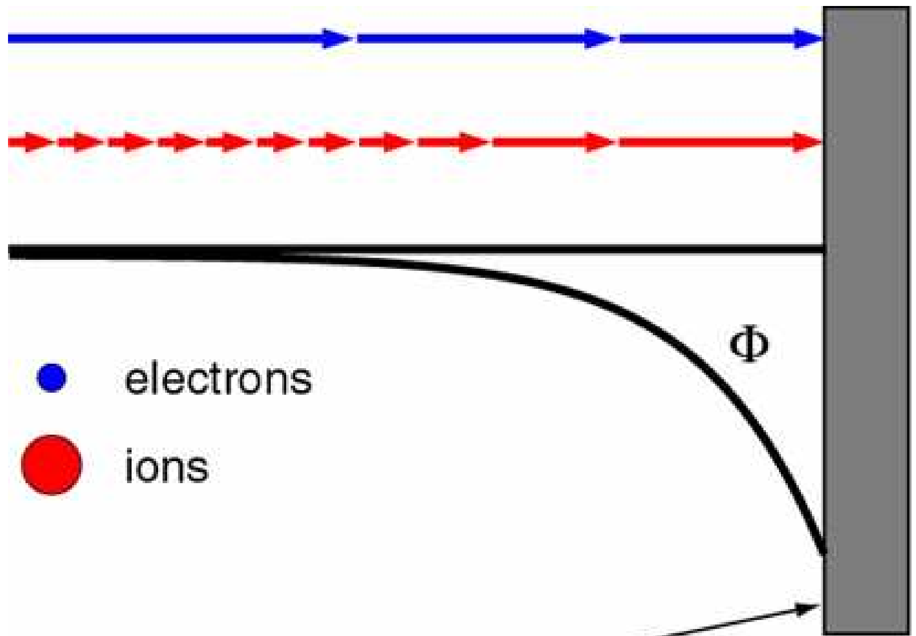
→Very high power flux densities MW/m²

<u>For comparison:</u>

Hot plate	0.05-0.1 MW/m²
Oxy-acetylene torch	100 MW/m²

Power and particle fluxes to the wall

❖Energies of ions hitting the wall



- Electrons much faster than ions
- Flux Γ = density x velocity

→More electrons hit the wall than ions
→Wall charges up, repelling electrons

❖In equilibrium electrostatic potential Φ such that $\Gamma^e = \Gamma^i$

➢For hydrogen plasmas $\Phi \sim 3Te$
→ Positive ions of charge q gain 3 q Te while traversing the sheath

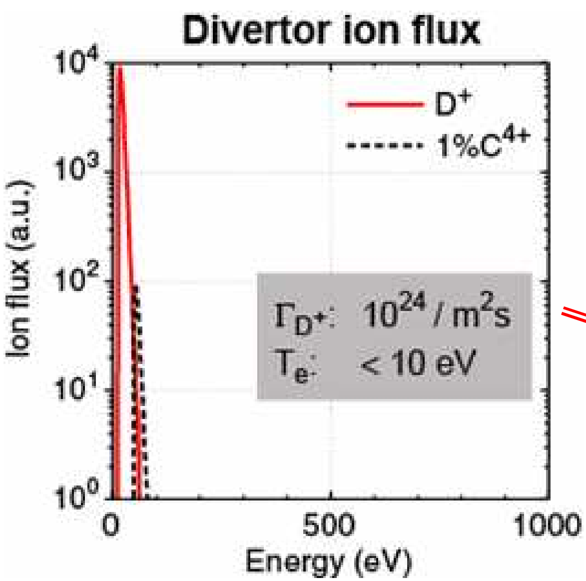
$$\text{e.g. } T_e = 20\,\text{eV}$$

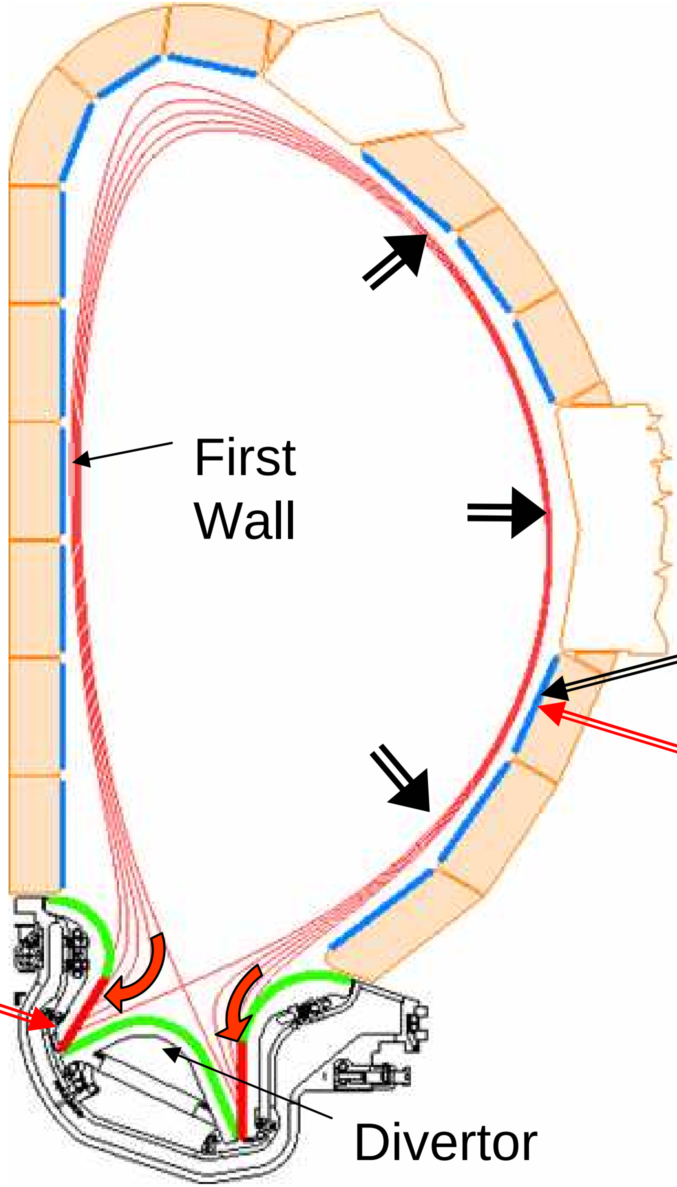
$$D^+ \rightarrow 60\text{eV}$$

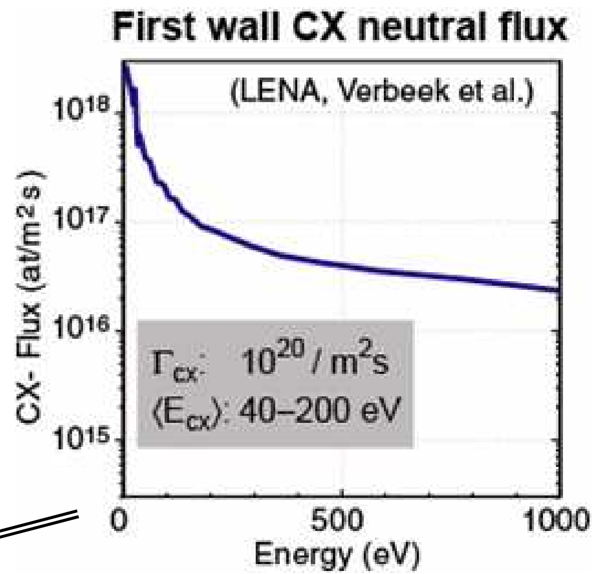
$$C^{+4} \rightarrow 240\text{eV}$$

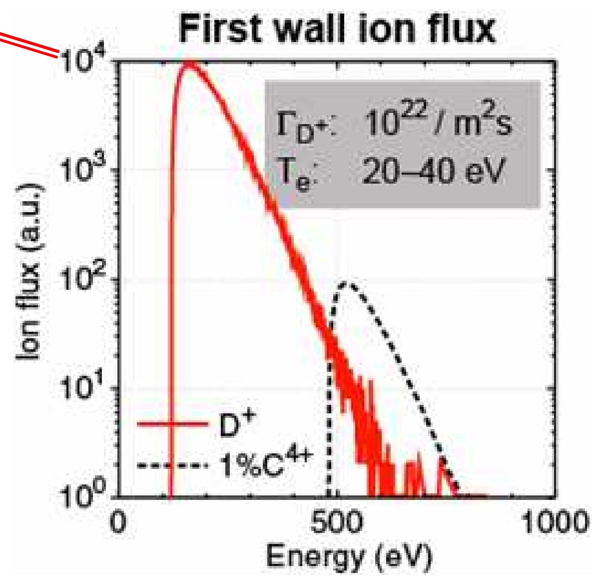
Power and particle fluxes to the wall

❖Energies of ions hitting the wall

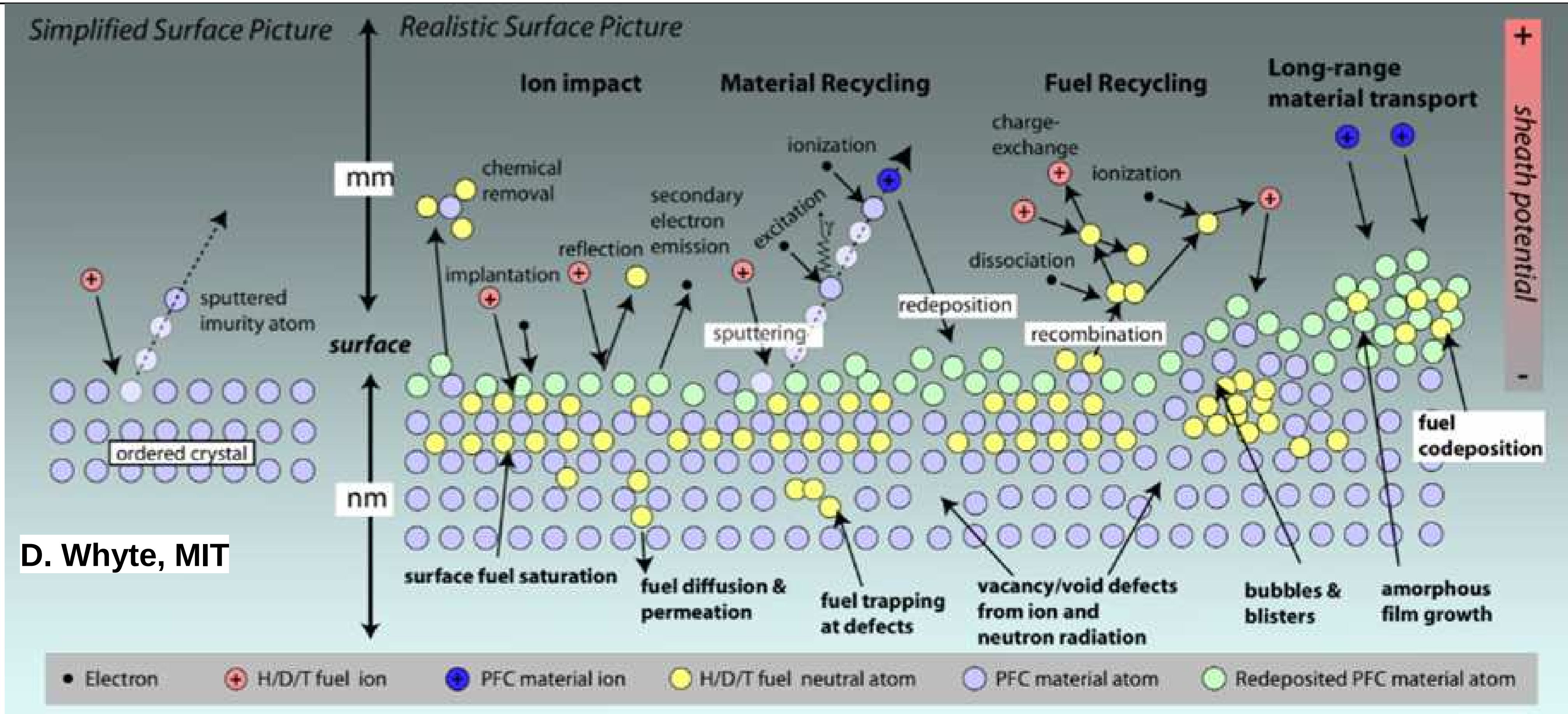








Fundamental processes during plasma wall interaction



- ❖Process rates are ever changing as surface evolves towards equilibrium
- ❖Material mixes are formed with very different properties compared to pure elements
- ❖Surface processes feedback to the plasma via impurity fluxes which change the plasma parameters which in turn change the process rates etc….

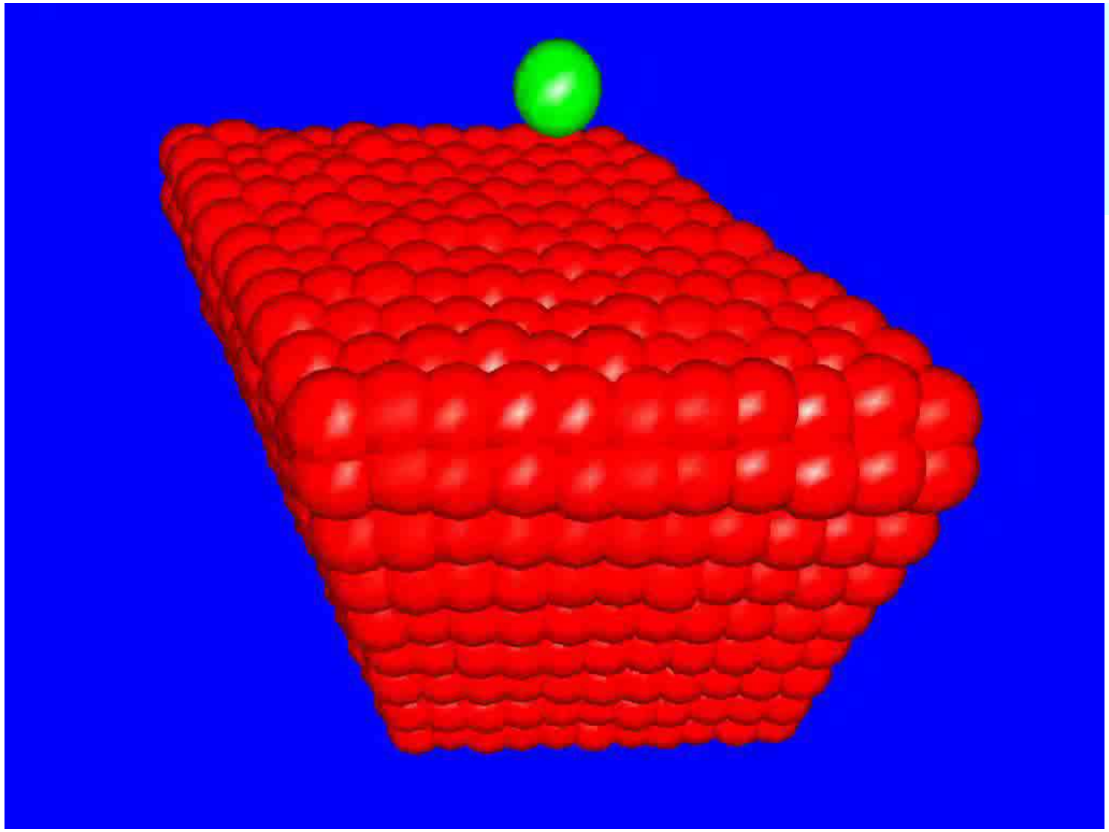
Fundamental processes during plasma wall interaction

Plasma wall interaction contains coupled processes spanning orders of magnitude in length and time scale

- Physical Sputtering
- Chemical Erosion
- Radiation Enhanced Sublimation
- Photon Induced Desorption
- Evaporation & Sublimation
- Brittle destruction
- Melting & Splashing
- Arcing
- Neutron Induced Damage
- Material migration & mixing
- Hydrogen retention and release

Fundamental processes during plasma wall interaction

❖Physical sputtering



Molecular Dynamics simulation of 50eV He → Be

❖Energetic particle impact involves a complex collision cascade during which:

- The projectile may be reflected back out of the surface
- The projectile may remain in the surface (=implantation)
- Surface atoms may be ejected out from the surface (= physical sputtering)
- The surface may be left with crystal damage.

Energetic particle impact is a stochastic process and is therefore described by giving average yields for the different processes

Fundamental processes during plasma wall interaction

❖Physical sputtering

➢Physical sputtering has a cut off energy

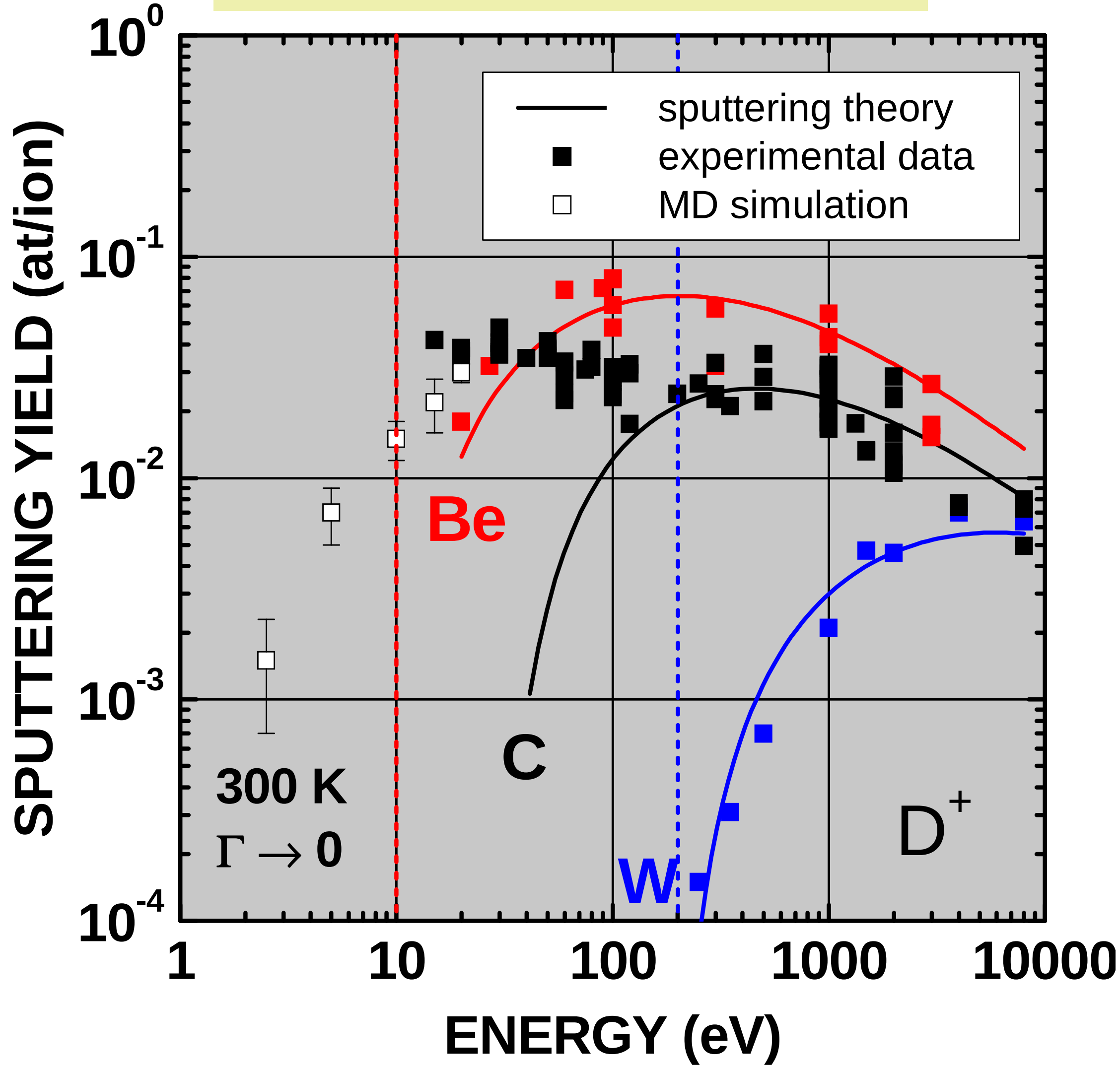
e.g. D→W E_{CUT} = 200eV

➢Can be very well described theoretically by MD or MC codes

…Except for C

Chemical erosion

Yield = # Sputtered / incident



Fundamental processes during plasma wall interaction

❖Chemical erosion

- Chemical erosion originates from the formation and release of volatile molecules in the interaction of incident plasma particles and target atoms.

- In fusion application the formation of hydrocarbons in the interaction of hydrogen atoms with carbon surfaces is the dominant example of chemical erosion

- As chemical reactions are involved, chemical erosion shows a strong temperature dependence in contrast to physical sputtering.

- Chemical erosion is due to interaction of thermal atoms and does not require a threshold energy.

Fundamental processes during plasma wall interaction

❖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	$CO + CO_2$

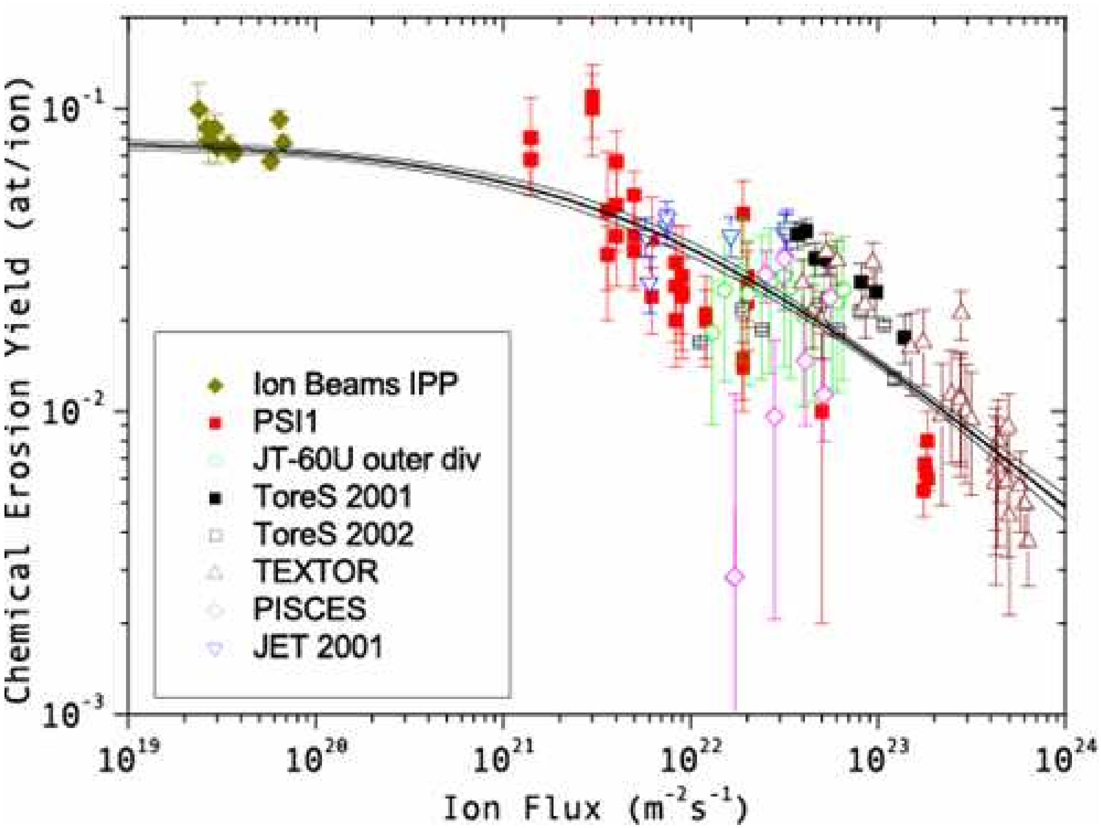
REACTIONS WITH SOME METALS:

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

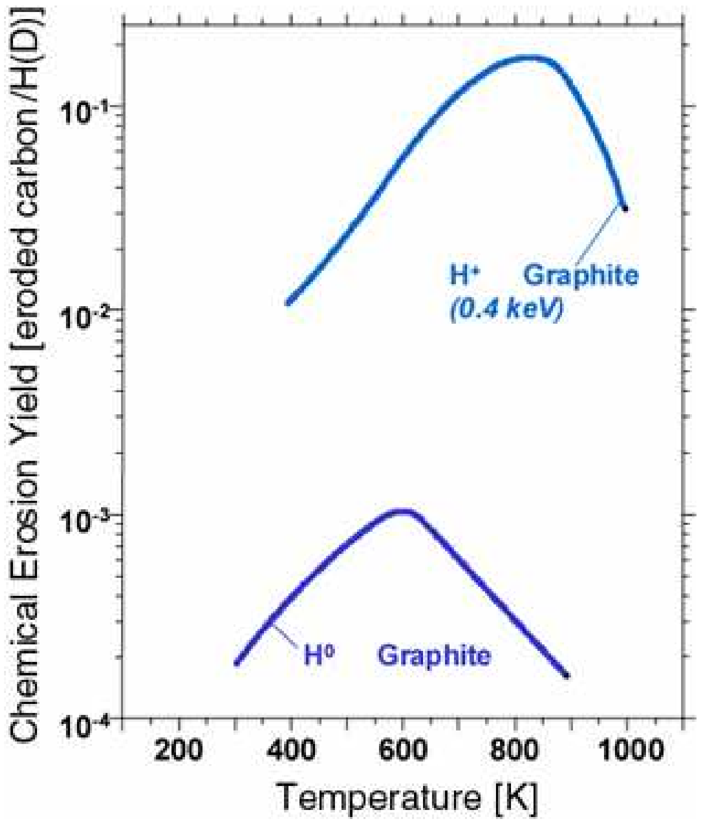
Fundamental processes during plasma wall interaction

❖Chemical erosion

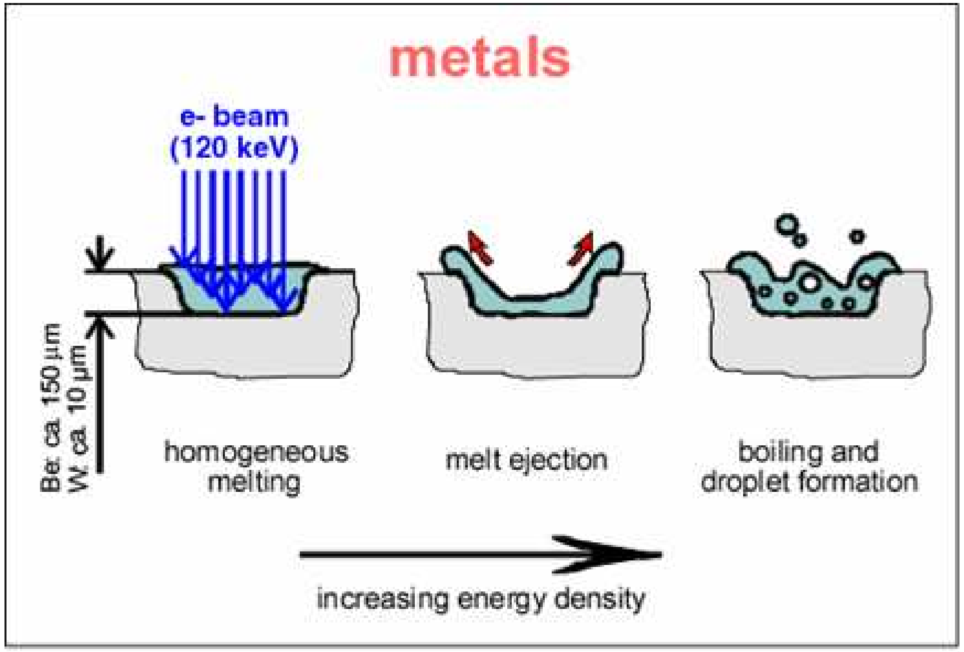
chemical erosion decreases for high Γ_D

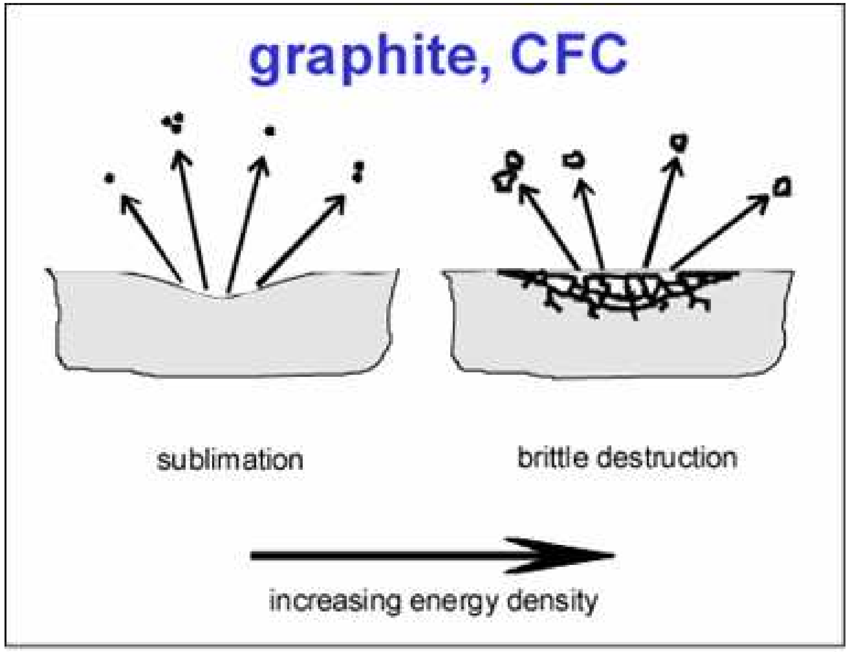


chemical erosion vanishes at high T_{surf}



Fundamental processes during plasma wall interaction





FOR METALS:

Splashing

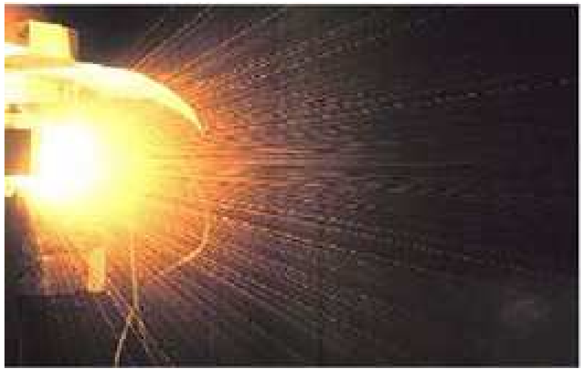
Formation of droplets

Formation of dust

FOR CARBON:

Above a certain power load (threshold) emission of debris

⇒ *BRITTLE DESTRUCTION*



Fundamental processes during plasma wall interaction

❖In a burning D-T plasma a high flux of high energy (max 14MeV) hit the wall

→ Produce collision cascades throughout the first wall material (not just the surface)

❖In the cascade atoms are displaced from their equilibrium position

→ Measure "damage" in DPA Displacements per atom

❖The actual conversion from DPA to real defect types is not straight forward and depends on the element and n-spectrum

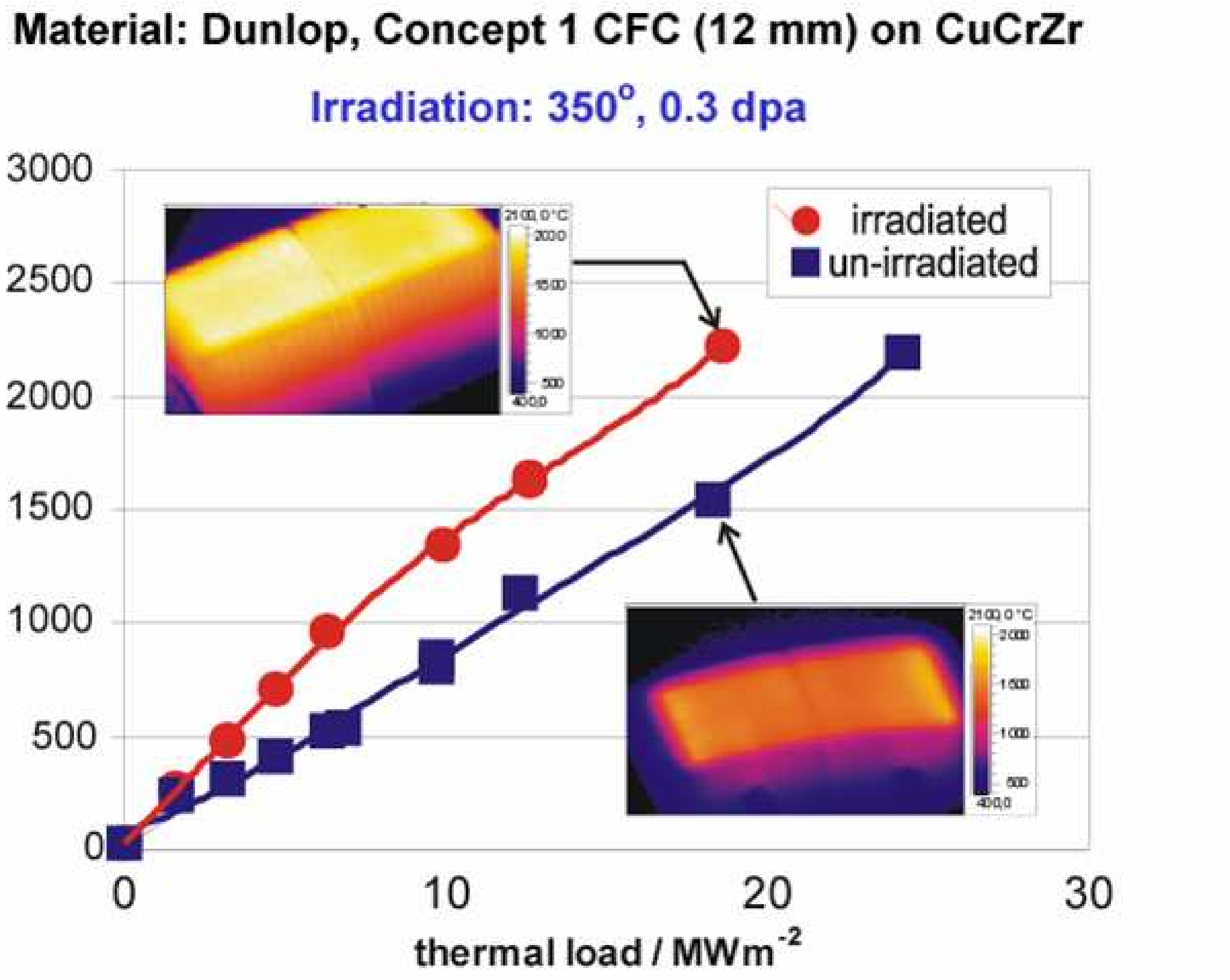
- Point defects
- Dislocations
- Vacancy clusters
- …

❖This radiation damage affects the thermomechanical stability

Fundamental processes during plasma wall interaction

❖Effect of n-damage

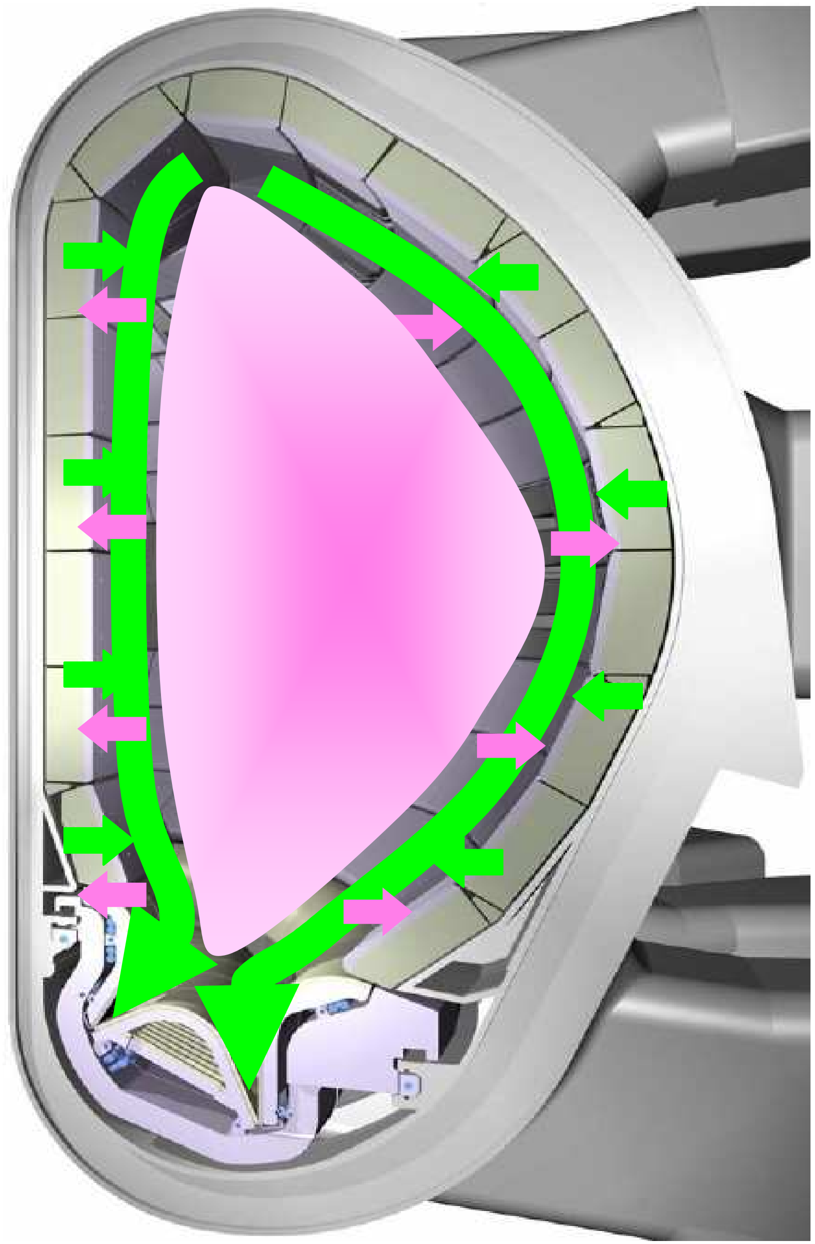
Example: degradation of heat conductivity



Fundamental processes during plasma wall interaction

❖ **Material migration & mixing**

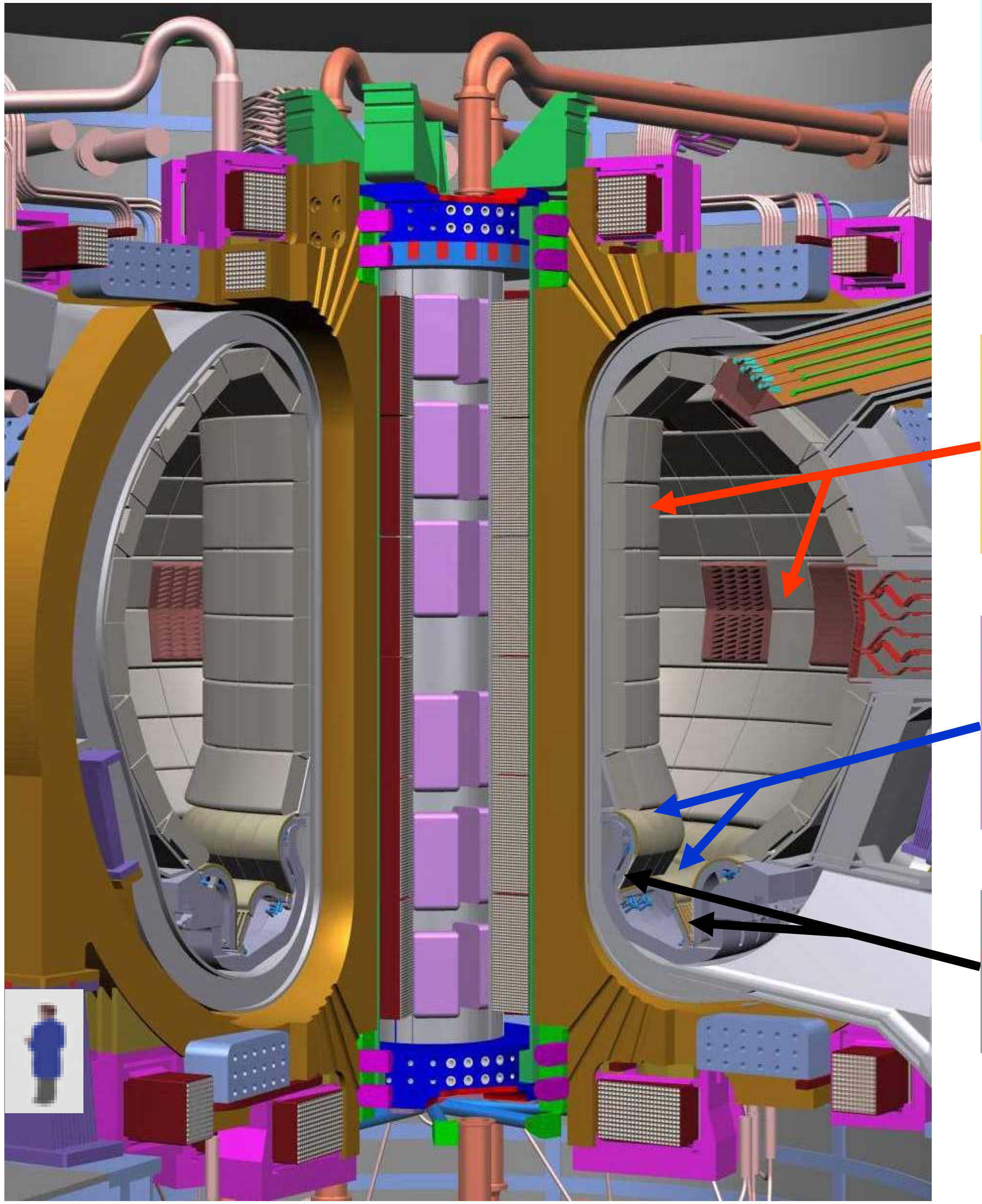
- ➢ H-Plasma erodes wall
- ➢ Impurities are released into the plasma
- ➢ Impurities are transported along the plasma flow (mainly to divertor)
- ➢ Particle re-deposited somewhere (potentially far) away from the origin
- ➢ Formation of mixed materials
- ➢ Re-erosion of deposited material
- ➢ ……Equilibrium surface condition



Fundamental processes during plasma wall interaction

❖ Material migration & mixing

❖Three elements have the potential for lots of mixed material issues



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

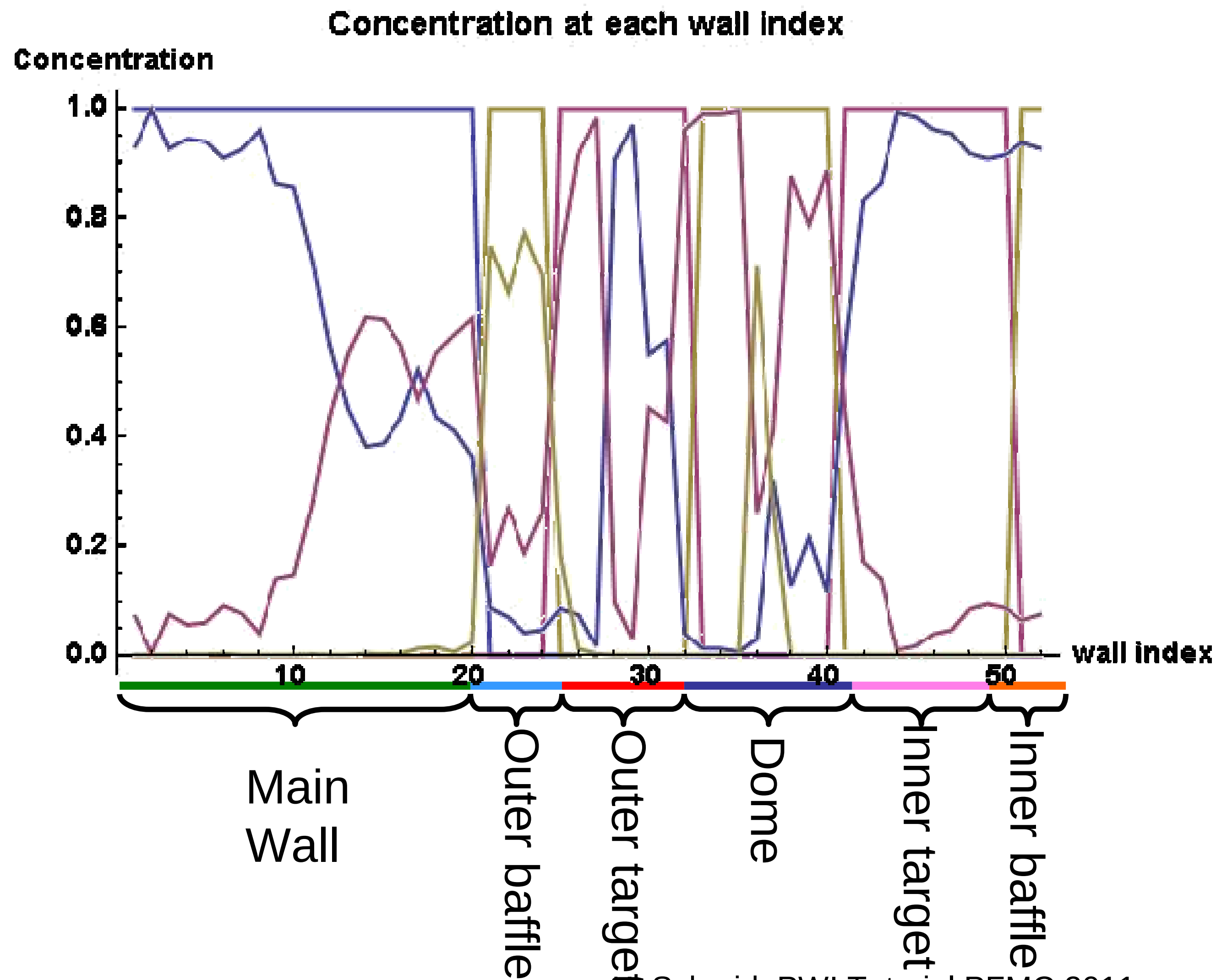
W: upper vertical target, dome baffle, liner - 100 m^2

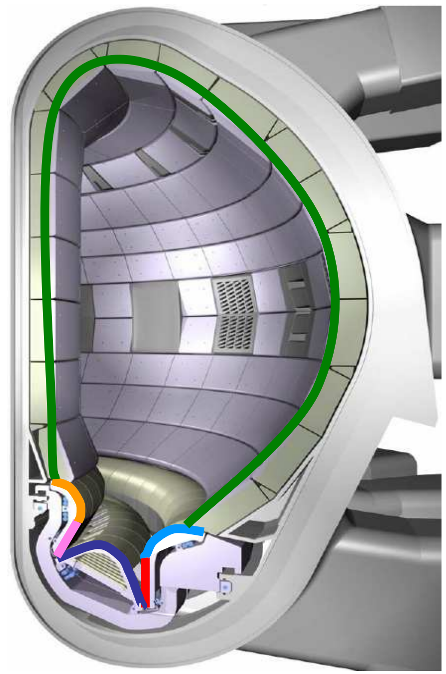
CFC: lower vertical target - 50m^2

likely to be replaced by tungsten for the D/T operation phase

Fundamental processes during plasma wall interaction

❖ Material migration & mixing



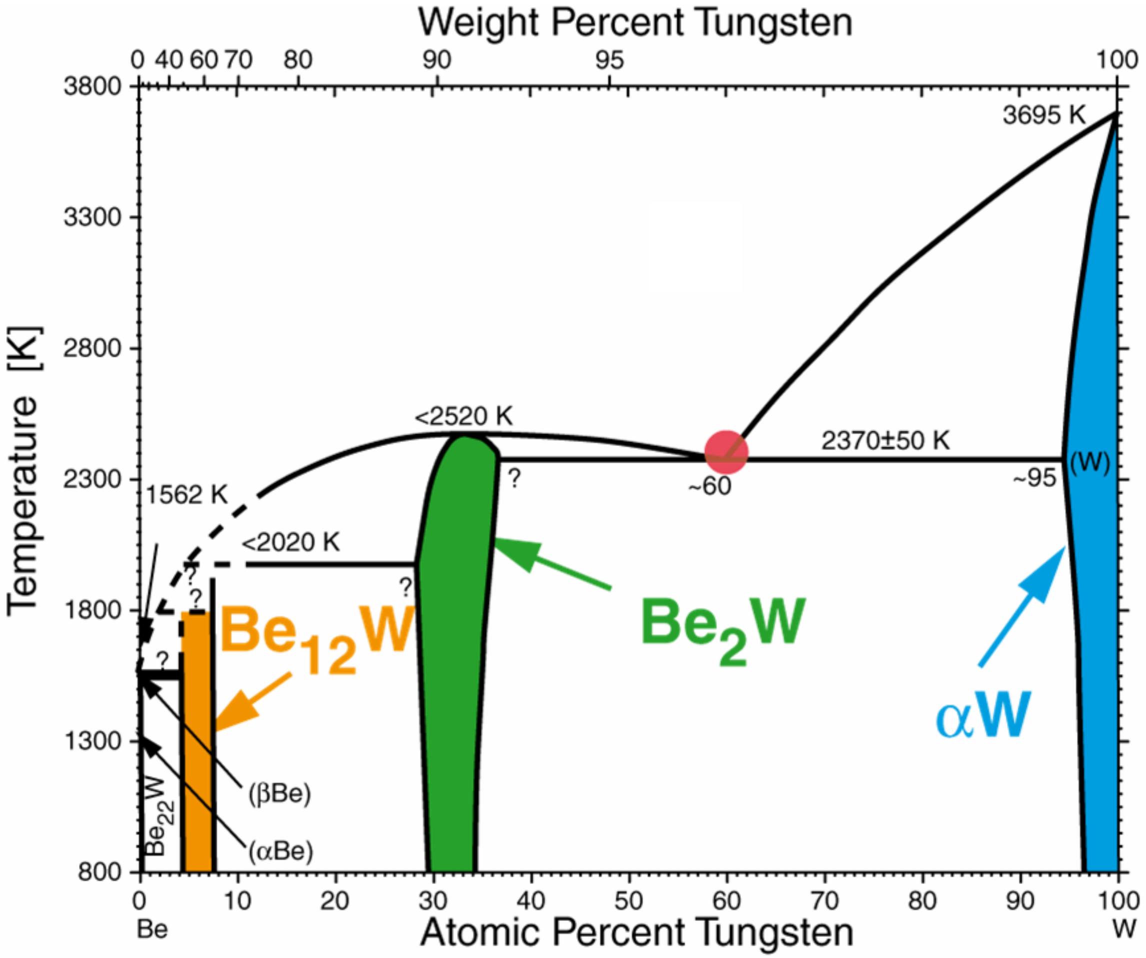


K. Schmid, PWI Tutorial PFMC 2011

Fundamental processes during plasma wall interaction

❖ Material migration & mixing: 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

Fundamental processes during plasma wall interaction

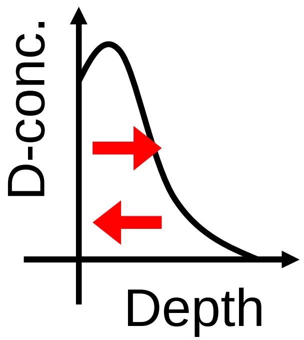
❖Hydrogen retention & release

❖First wall is bombarded with a huge flux of energetic hydrogen (H, D, T)

→ Retention due to implantation

H from plasma is implanted → Implanted H diffuses towards

- Bulk
- Surface



<u>At the surface</u>

H recombines to H_2 and sublimates

<u>In the bulk</u>

H is dissolved as an interstitial

H is **trapped at defects**

Retained amount is determined through out diffusion and trapping in the bulk

- Can be limited by diffusion or recombination rate

- Depends on intrinsic, neutron and ion induced defects
- Trap filling is diffusion limited

- In particular the filling of n generated defects throughout the bulk is a concern

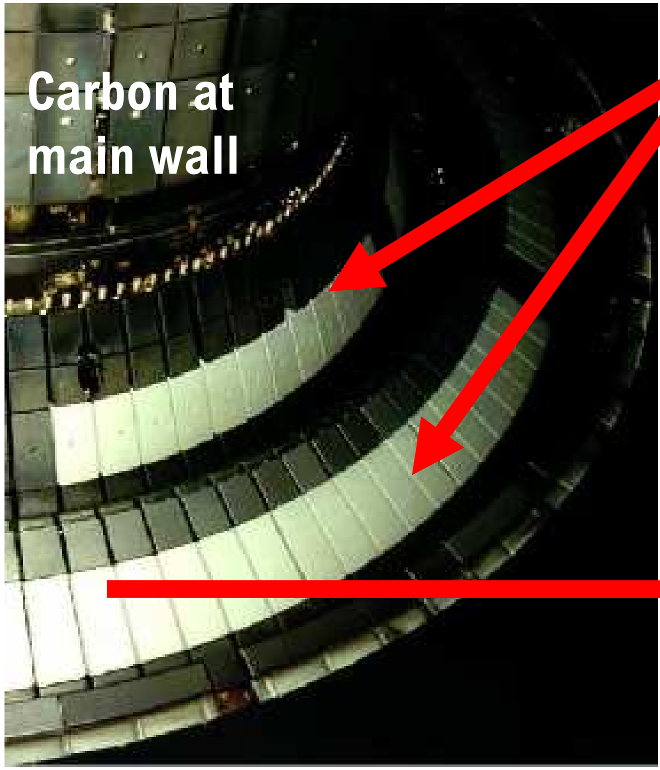
Fundamental processes during plasma wall interaction

❖Hydrogen retention & release

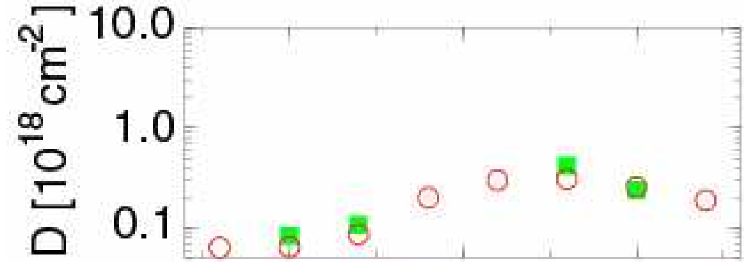
❖First wall is bombarded by large hydrogen and impurity (e.g. C) fluxes

→ Retention due to co-deposition (Simultaneous deposition of H + Impurities)

❖Hydrogen is retained in a deposited layer of impurities



Freshly installed tungsten divertor in ASDEX Upgrade



Deposited layers may form ever growing inventory of buried fuel!

Summary

❖The wall of a magnetic fusion device is essential to its operation

➢Maintain clean vaccum
➢Power and particle exhaust

❖The wall is exposed to high particle and power fluxes leading to large number of coupled processes that span many length and time scales

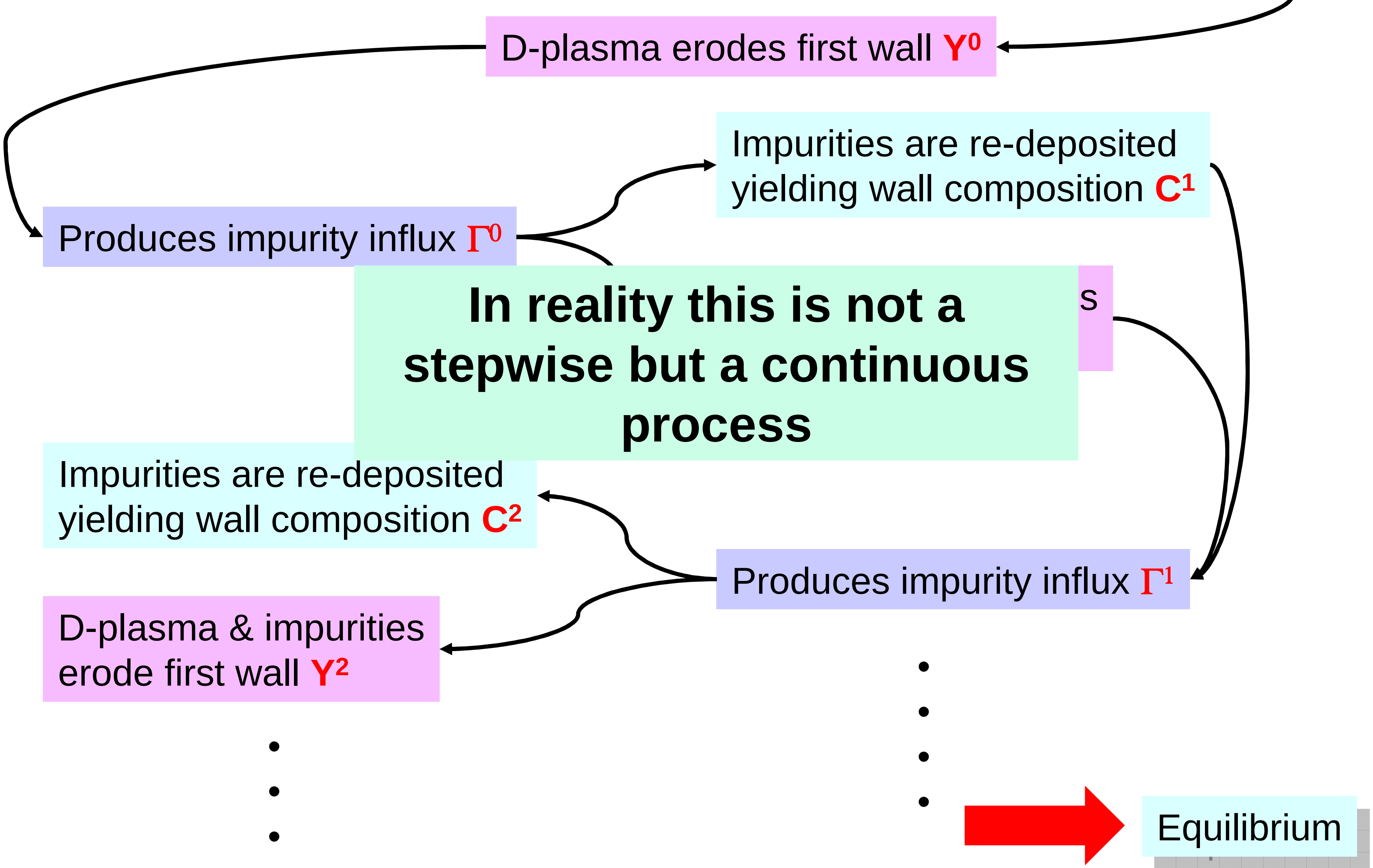
➢Erosion, material migration, re-depostion & co-deposition
➢Mixed material formation
➢H-retention

❖For burning D-T plasmas the additional fast n load on the wall will result in additional challenges due to radiation damage throughout the bulk.

❖Plasma wall interaction is one the key challenges on the way of a working fusion power plant

Fundamental processes during plasma wall interaction

❖ **Material migration & mixing**



Fundamental processes during plasma wall interaction

❖Retention of hydrogen due to plasma wall interaction is far from thermodynamic equilibrium

➢Due to high particle energies the surface can be oversaturated by D way beyond solubility limits

➢At ambient temperatures return to thermodynamic equilibrium is usually kinetically hindered

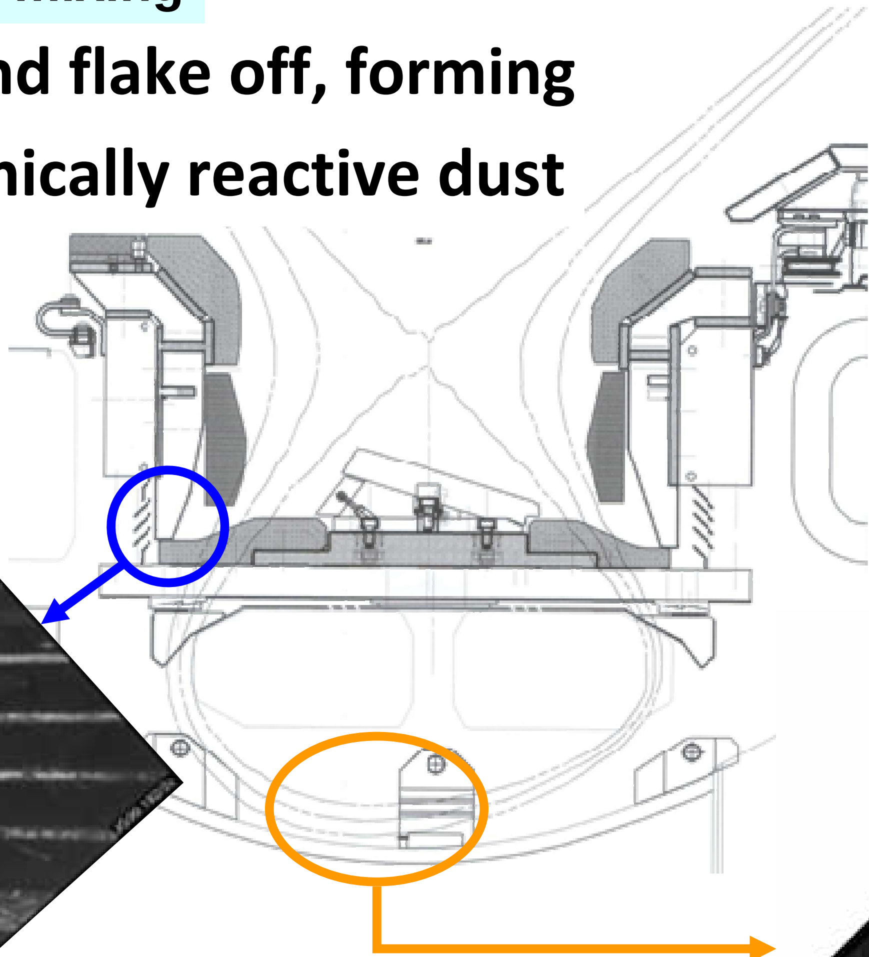
❖Activation barriers for diffusion and detrapping are too high
❖Large amounts of H, D, T can be retained after exposure to plasma

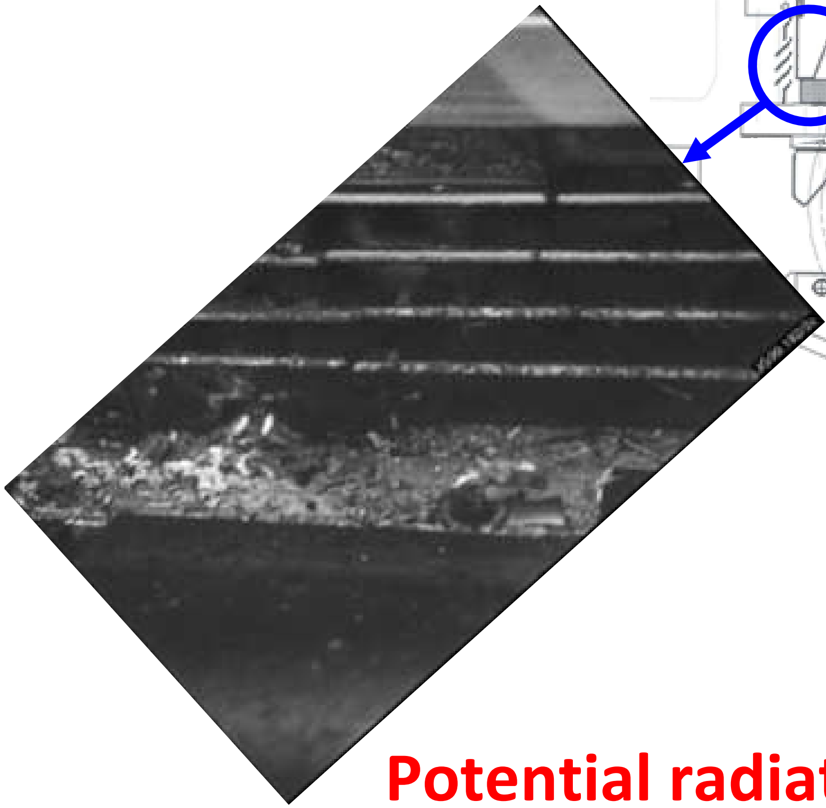
→Radioactive inventory
→Loss of fuel species

Fundamental processes during plasma wall interaction

❖ **Material migration & mixing**

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





Potential radiation + explosion hazard!