Can we tend the fire?

Three lectures course on plasma surface interaction and edge physics

1 Introduction: WHAT happens in a fusion plasma near the walls

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Thanks to: V. Philipps, A. Kirschner, R. Janev
Mankind learning to tend a fire, again....

Fire from processes in atomic shell

Chemical process:
\[ C_xH_y + O_2 \rightarrow CO_2 + H_2O \]

100,000 years later....

Fire from processes in atomic nucleus

Nuclear process:
\[ d + t \rightarrow He + n \]
The Energy source of the sun and the stars in the universe is: **Nuclear Fusion**

The vision of nuclear fusion research: **A miniatur star in a solid container**

Fusion Reactor:  
T=100 Mill. degrees  
\[ d + t \rightarrow \text{He} + n \]

The Sun: T=15 Mill. degrees in the center  
\[ p + p \rightarrow d, \quad d + p \rightarrow \text{He}_3, \quad \text{He}_3 + \text{He}_3 \rightarrow \text{He}_4 + p + p, \]

Reaction time \(1/(n_p<\sigma v>_{\text{fus}}) = t_{\text{fus}} \approx 10^9 \text{ years}\)
What these lectures are NOT about:

From Robert Zemeckis movie: “Back to the future II”
The correct way: a magnetic bottle
Here: the JET Tokamak
≈ 2 meters
Euratom 26 Fusion Associations
Joint construction of JET (1978)
FZ Jülich: in *Germany* fusion research is organized in the Helmholtz Association

**Germany**
- Helmholtz Association
- DFG / Universities

**Europe**
- Trilateral Euregio Cluster (B, NL, Jül)
- EURATOM Association
- EFDA (JET, Technol.)
- F4E (ITER)

**World**
- IEA Implementing Agreement
- “Plasma-Wall Interaction” (J, USA, Canada)
- ITPA International Expert Groups
1854: Theory of Contraction (together with: Lord Kelvin)
The energy radiated by the sun is provided by contraction of the sun (and the stars), freeing the gravitational energy, i.e. accounted for in a purely mechanical concept
→ Age of the planet earth: ~ 10 Mill. Years (at highest)

Problem:
what is the source of energy of the sun?
how old is the sun?
how old is the earth at highest?
Ca. 1925: Sir Arthur Eddington:
Nuclear Fusion as energy source of the sun and the stars
($E=mc^2$)

Ca. 1935: Hans Bethe und Carl Friedrich von Weizsäcker:
final resolution of the nuclear fusion processes in the sun
(“Bethe-Weizsäcker cycle”)

(age of sun and earth: 4-5 billion years well possible)
1933: Oliphant und Rutherford fuse Deuteron atoms, discovery of tritium
Known in those days:
- Only magnetic fields can confine the flame (Lasers did not yet exist)
- It has to be a toroidal configuration (H. Poincare, ~1880)
- The B-field has to be helical

then: \(\rightarrow\) “only a stellarator is possible”

-1968: all expectations have been frustrated. All experiments have been gigantic (and costly) failures (Instabilities, sensitivity to small field errors,….)
The final end of nuclear fusion research?
No: a few small experiments in the USSR have shown surprising successes: Tokamaks
Progress in Tokamak research:

Compare: Moore’s Law microprocessors
Outline of course:

Introduction: Fusion Research & Plasma-Wall Interaction

I.) WHAT : basic plasma-wall interaction processes
II.) HOW : …can we make the application work? → ITER
III.) WHY : understanding the edge plasma, A&M processes
Early days of magnetic fusion (sometimes still today?):

Hope that a fusion plasma would not be strongly influenced by boundary:

“The edge region takes care of itself”.

Single goal: optimize fusion plasma performance

Now:
man made fusion plasmas are now powerful enough to be dangerous for the integrity of the container:

The edge region does NOT take care of itself.
It requires significant attention!

The ITER lifetime, performance and availability will not only be influenced, it will be controlled by the edge region
Role of Edge Plasma Science, cont.

The layman’s response to the idea:

“A miniature star (100 Mill degrees) in a solid container”:

THIS MUST BE IMPOSSIBLE!

It turned out unfortunately (early 1990th):

THE LAYMAN IS RIGHT!

Almost...
Physics of hot plasma core

Atomic/Molecular processes, Plasma material interaction

Ignition Condition for D/T Plasma

Fusion Triple Product $nT_E$ [$10^{20}$ m$^3$ KeV/s]

Plasma Temperature [KeV]

Q=1: Breakeven

Q=0: Quenching

Q=infinity: Ignition

\(\rho > 1\)

\(\rho > 5\)

\(\rho > 14\)

ITER
Can we hope that magnetic confinement core plasma physics progress will mitigate plasma-surface problems?

Candle, on earth:
- Convection, driven by buoyancy (i.e. gravity)
- Fresh air
- Used air

Candle, under microgravity:
- Only Diffusion (no convection)
- e.g.: parabola flight, \( g \approx 0 \)
- (only small, dim burn, at best)

Can we hope that magnetic confinement core plasma physics progress will mitigate plasma-surface problems?
Magnetic Fusion: how to produce convection? DIVERTOR

Increase convection → increase plasma surface interaction
L. Spitzer “A proposed stellarator”, US Fusionsprojekt: “Matterhorn”
AEC Report No. NYO-993 (PM-S-1) 1951

The “Divertor”

To remove wall
Released plasma
Impurities already
from the plasma
boundary,
by a “magnetic
exhaust”

Original report has
two figures!
JET (Joint European Torus):
Ø 8.5 m, 2.5 m high, 3.4 T, 7 MA, 1 min

Key area for plasma wall interaction
Extrapolation: present experiments $\Rightarrow$ ITER

Core:
plasma similarity:
present experiments
are “wind tunnel
experiments”
for ITER
Extrapolation of core plasma confinement to ITER

ITER reference scenario

World Wide Data Base (13 Devices)
Relative importance of plasma flow forces over chemistry and PWI

I Plasma Core

\[ \text{div}(n v_\parallel) + \text{div}(n v_\perp) = \text{ionization/recombination/charge exchange} \]

(Collisional + turbulent) cross field flow, \( D_\perp, V_\perp \)

(advanced plasma scenario development)

(empirical) ion transport scaling from spectroscopy on surface released impurities
(interpretation, line shape modelling):

- Spectroscopy : \( nZ^* \)
- CR Model : \( nZ^* \rightarrow nZ \)
- Transport Model : \( nZ \rightarrow D_\perp, V_\perp \)
Relative importance of plasma flow forces over chemistry and PWI

II: edge region  →  III: divertor

\[ \text{div}(\mathbf{v}_\parallel) + \text{div}(\mathbf{v}_\perp) = \text{ionization/recombination/charge exchange} \]

II: midplain  \quad \text{(parallel vs. (turbulent) cross field flow)}

III: target  \quad \text{(parallel vs. chemistry and PWI driven flow)}
Extrapolation: present experiments ⇒ ITER

Core:
plasma similarity: present experiments are “wind tunnel experiments” for ITER

Edge:
Computational plasma edge modelling (lecture III)
Edge/divertor science

- interdisciplinary
- already a highly integrated field
  - plasma physics
  - CFD
  - rarefied gas dynamics
  - opacity
  - plasma wall interaction
  - atomic physics
  - molecular physics
  - ....

fusion, technical-, astro plasmas
fluid-dynamics
aero-dynamics, vacuum
lighting, inertial fusion
Atomic & Surface data
(database: IAEA fusion data unit)

this lecture I
Plasma-wall interaction in fusion devices

**Impinging plasma and impurity particles**

- erosion of wall elements
  $\Rightarrow$ lifetime of wall elements is reduced
- eroded wall particles can penetrate into core plasma
  $\Rightarrow$ dilution and radiation cooling of core plasma
- re-deposition of eroded particles
  $\Rightarrow$ tritium retention in deposited layers
  (retained T has to be limited to 350g due to safety rule in ITER)

Erosion, transport and redeposition of impurities is a crucial (show stopping?) issue in fusion research
Control of plasma-wall interaction: the limiter concept

**Limiter:**
A material piece protruding from the main wall intercept the closed field lines to extract power and particles.

**Poloidal limiter**

**Toroidal belt pump limiter**

**TEXTOR**

**Poloidal limiters**
**Control of plasma-wall interaction: the divertor concept**

**Divertor:**
A separate chamber in the vacuum vessel to which particles and energy are directed
Next 2 slides: JUMPING AHEAD see again 3rd lecture
Consequences for ITER design (B2-EIRENE): shift towards higher divertor gas pressure to maintain a given peak heat flux (Kotov et al., CPP, July 2006)

ITER divertor engineering parameter: target heat flux vs. divertor gas pressure

1996 (ITER physics basis 1999)
2003, neutral - neutral collisions
...+ molecular kinetics ($D_2(v)$+D$^+$, MAR)
2005, + photon opacity

ITER design review 2007-2009: “Dome“ re-design now ongoing

$P_{PFR}$: average neutral pressure in Private Flux Region
Compare: re-entry problems e.g. Space shuttle

\[ \sim 10 \text{ MW/m}^2, \]

for some minutes

10 MW/m\(^2\) stationary: perhaps tolerable, but not trivial
Plasma - Wall Interactions

Main plasma

Boundary plasma

Scrape-off layer

Re-deposition and co-deposition

Solid Wall Material

Erosion

Retention

Recycling

Plasma impact $e^+, X_{e^+}, X_0$

Reflection

Retention
Basic Processes Induced in Materials by Plasma Particle Impact

Energy dissipation by elastic (with atoms) and inelastic (with electrons) collisions

(10^{-13} \text{ sec}, \text{ range } 10^{-7} \text{ m, } 200 \text{ eV D}^+)

Elastic collisions: Creation of vacancies and interstitials

elastic collisions

(energy transfer > threshold energy for damage)

Diffusion of vacancies and interstitials

voids, dislocations, swelling, radiation, embrittlement

Sputtering of surface atoms

(energy transfer > surface binding energy)

Transmutation

formation of nuclear reaction products
(including H isotopes and He)
The 14 MeV fusion neutrons heat an external material (for energy conversion) and they breed Tritium in the blanket.

Unfortunately:

14 MeV fusion neutrons also produce volumetric radiation damage, and change and deteriorate the material properties

<table>
<thead>
<tr>
<th>heat conductivity</th>
<th>lattice defects</th>
<th>scattering of phonons</th>
</tr>
</thead>
<tbody>
<tr>
<td>swelling</td>
<td>void formation, gas bubbles</td>
<td>agglomeration of vacancies and helium</td>
</tr>
<tr>
<td>ductility</td>
<td>neutron and helium induced embrittlement</td>
<td>densification of dislocation network, agglomeration of helium bubbles on grain boundaries</td>
</tr>
<tr>
<td>composition</td>
<td>transmutation products</td>
<td></td>
</tr>
</tbody>
</table>

→ Science of irradiated materials (not further discussed here)
Basic PSI Processes

I.) Sublimation
II.) Physical sputtering
III.) Chemical erosion
IV.) Radiation Enhanced Sublimation (RES)
V.) Backscattering

*Only briefly discussed here:*

VI.) Retention (hydrogen isotopes)
VII.) Desorption/Adsorption
VIII.) Blistering
IX.) Secondary electron emission
I.) Sublimation
Heat diffusion time

\[ t = \frac{d^2}{2D} \]

D: diffusivity

\[ D = \frac{\lambda}{\rho \, c} \]

conductivity density heat capacity

\[ \sim 4 \text{ s} \quad \sim 5 \times 10^{-5} \text{ m}^2/\text{s} \]

In steady state

\[ T_s - T_w = \Delta T = Q \times \frac{d}{\lambda} \]

Q=10 MW/m\(^2\), \( \lambda=200\text{[W/(m K)]} \), \( d=0.02\text{m} \)

\[ \rightarrow \Delta T = 1000 \text{ °C} \]
In transient events, like disruptions or ELMs, part of the plasma stored energy is deposited in very short pulses to the walls.

**example: type I Elms in ITER:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$W_{\text{thermal}}$ (Plasma)</td>
<td>350 MJ</td>
</tr>
<tr>
<td>Energy loss during ELM</td>
<td>2-6 %</td>
</tr>
<tr>
<td>Energy per ELM</td>
<td>$\sim$ 20 MJ ($\sim$30 hand grenades at 150g TNT each)</td>
</tr>
<tr>
<td>Deposition time</td>
<td>$\sim$ 0.2 ms</td>
</tr>
<tr>
<td>Deposition area</td>
<td>$\sim$ 10 m²</td>
</tr>
<tr>
<td>Power density</td>
<td>10 GW/m²</td>
</tr>
</tbody>
</table>
In transient events the energy must be absorbed by the heat capacity (inertial cooling)

\[ T(t) = P \star \left( \frac{2}{\pi} \lambda \rho c \right)^{0.5} t^{0.5} \]

- temperature
- power
- conductivity
- density
- heat capacity

\[ t = 0.25 \text{ ms} \rightarrow \quad T_{\text{Smax}} = 6000 \text{ C} \quad \text{Penetration depth: 0.15 mm} \]

Sublimation threshold: 2200 C

Graphite Target will sublimate quickly

With duration of 0.2 ms and area 10 m\(^2\) the maximal energy per ELM in ITER must be limited to < 1-2 % of stored energy to avoid material loss by sublimation.

Metals will melt leading to loss of melt layer by MHD effects in melt layer.

Type I ELM operation critical for ITER.
Material Behaviour under Extreme Power Loads

FOR METALS:
- Splashing
- Formation of droplets
- Formation of dust

FOR CARBON:
Above a certain power load (threshold) emission of debris occurs = BRITTLE DESTRUCTION

Effects of interaction

- Metals: e-beam (120 keV) with homogeneous melting, melt ejection, boiling and droplet formation, increasing energy density
- Graphite, CFC: sublimation, brittle destruction, increasing energy density
MELTING observed commonly in present machines

Beryllium antenna screen at JET

$$T_m(\text{Be}) = 1278 \, ^\circ\text{C}$$

Limiter from FTU TZM coated with 2 mm VPS Tungsten

TEXTOR: Melting of 170 mm B4C coating on copper
The TEXTOR PWI Test Facility with air lock
a tool (user facility) for PWI research

Air locks for PWI components

- < 15 cm diameter (enlargement foreseen)
- external heating (up to 1800K) or cooling (down to RT)
- radial movement (+- 5 cm around LCFS)
- rotatable
- electrical biasing of limiters
- exchange time for samples <½ day
- local gas injection systems

Comprehensive diagnostics

- overview spectroscopy (UV-VIS-IR)
- 2D imaging (Dα, CII etc.),
- high resolution spectroscopy
- laser-induced fluorescence
- 2D thermography, thermocouples
- colorimetry
- laser desorption/ablation
- edge diagnostics for ne, Te (Langmuir probes and atomic beams)

Presently used in cooperation with Japan (TEXTOR-IEA), VR, IPPWL, Slovenia, Universities,....
Inside the TEXTOR Tokamak @ FZ-Jülich
Focus on Plasma Surface interaction research
Plasma parameters at the TEXTOR PWI Test Facility:

Exceeds ITER particle and heat fluxes

parallel particle fluxes: up to $4 \times 10^{24}/\text{m}^2\ \text{s}$

particle fluencies: up to $2 \times 10^{26}/\text{m}^2$ per day
(150 s plasma per TEXTOR operation day)

parallel power fluxes: up to 200 MW/m²

⇒ Melting of bulk W limiters in $\approx 4\ \text{sec}$
II.) Physical sputtering
II.) Physical sputtering

Mechanism: energy transfer from projectile to solid atom at surface

Impinging projectile ion initiates collision cascade inside the solid ⇒ energy transfer to surface solid atom which is released
II.) Physical sputtering

*Collision cascades: different regimes*

**Single collision regime**: light ions at low energies, atomic motion stopped after few collisions, binary collision approximation (BCA) valid

**Linear cascade regime**: collisions only between fast particles and atoms at rest, BCA

**Thermal spike regime**: dense cascade, collisions between fast particles important
II.) Physical sputtering

Simulation of collision cascades: example “linear cascade” regime

Monte Carlo simulation, Binary Collision Approximation

5 typical cascades of 3 keV Ar$^+$ ions into graphite

- Ion trajectory
- Vacancies
- Interstitials
- Phonons
II.) Physical sputtering

*In general: definition of erosion yield $Y$*

**Erosion yield $Y$:**

average number of eroded target atoms per incident projectile

**Impinging flux of projectiles:**

$$\Gamma_{in} = \frac{\text{number of incoming projectiles}}{\text{area} \times \text{time}}$$

**Emitting flux of eroded particles:**

$$\Gamma_{ero} = \frac{\text{number of eroded particles}}{\text{area} \times \text{time}}$$

**Erosion yield $Y$:**

$$Y = \frac{\Gamma_{ero}}{\Gamma_{in}}$$
II.) Physical sputtering

Main features of physical sputtering

- Occurs for all combinations of projectile – substrate
- Existence of threshold energy $E_{th}$. If $E_{in} < E_{th}$: $Y_{sputter} = 0$
- Sputter yield $Y_{sputter}$ depends on energy and angle of incoming projectile
- Sputter yield $Y_{sputter}$ depends on projectile – material combination. Maximal energy transfer factor $\gamma = 4 \frac{M_1 M_2}{(M_1 + M_2)^2}$
- No significant dependence of $Y_{sputter}$ on surface temperature
- Sputtered species: atoms or small clusters of substrate particles
II.) Physical sputtering

Typical dependence of sputter yield $Y$ on incident energy of projectile $E_{\text{in}}$:

$E_{\text{in}} < E_{\text{th}}$: $Y = 0$. Increasing $E_{\text{in}} \Rightarrow Y$ increases until maximum. Further increase of $E_{\text{in}} \Rightarrow Y$ decreases (collision cascade penetrates deeper into solid).

$H$ on $Fe$ (normal incidence)

$E_{\text{th}} \sim 8 \text{ eV}$
II.) Physical sputtering

Typical dependence of sputter yield $Y$ on incident angle of projectile $\alpha$

$Y$ first increases with increasing $\alpha$ (with grazing incidence more energy is deposited near surface). After reaching maximum $\Rightarrow Y$ decreases (reflection).

H on Fe ($E_{in} = 200$ eV)
II.) Physical sputtering

Energy distribution of sputtered particles

In many cases:

sputtered particles have Thompson distributed energy

\[ N(E) \propto \frac{E}{(E + E_S)^3} \]

\( E_S \): sublimation energy

Most probable energy \( E = E_S/2 \)

Deviations from Thompson distribution for light ion bombardment and/or non-normal incidence
II.) Physical sputtering

Angle distribution of sputtered particles

In many cases: **sputtered particles have cosine distribution**

Deviations: for light ions and non-normal incidence
Physical sputtering: deuterium impact on different first wall materials

- Maxwellian energy distribution shifted by the sheath potential (3 kT_e): $E_{in} \sim 6-7$ kT_e
- Largest physical sputter yields and low threshold for Be
- Small yields and large threshold for high Z materials

Threshold for D impact

<table>
<thead>
<tr>
<th></th>
<th>Be</th>
<th>C</th>
<th>W</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>3 eV</td>
<td>8 eV</td>
<td>80 eV</td>
</tr>
</tbody>
</table>
Total erosion Yield of Graphite, Be and W by D impact

For beryllium and tungsten theoretical and experimental curves overlap.

Carbon shows additional erosion, not dependent on impact energy.

CHEMICAL EROSION
III.) Chemical erosion
III.) Chemical erosion

Mechanism: formation of molecules from projectiles and solid atoms

Impinging deuterium penetrates into graphite and forms hydrocarbon molecule after thermalisation $\Rightarrow$ molecule “diffuses” through porosity to surface of the solid and desorbs
III.) Chemical erosion

Main features of chemical erosion

• Occurs only for special combinations of projectile – substrate (most important: hydrogen on graphite, oxygen on graphite)

• No (or very low) threshold energy

• Strong dependence of erosion yield $Y_{chem}$ on surface temperature $T_{surf}$

• Dependence of erosion yield $Y_{chem}$ on hydrogen content in solid

• Synergetic effects caused by energetic ions

• Sputtered species: molecules formed from projectile and substrate atoms
III.) Chemical erosion

Fusion research: Importance of chemical erosion of carbon-based materials

Main disadvantage of carbon-based materials:
- chemical erosion due to hydrogen & its isotopes even at lowest plasma $T_e$
- in a fusion reactor: tritium (T) as fuel $\Rightarrow$ erosion of $C_xT_y$ molecules
  $\Rightarrow$ re-deposition of $C_xT_y$ molecules leads to formation of T-containing layers. Amount of permitted radioactive T limited to 350g in ITER
  $\Rightarrow$ removal of T-containing layers necessary after having reached 350g

Advantages of carbon-based materials:
- no melting even under extremely high power loads (in ITER: 10 MW/m²)
- high sublimation temperature ($\sim$3800°C)
  $\Rightarrow$ therefore carbon-based materials are foreseen to use at areas of high power loads in ITER (divertor plates)
III.) Chemical erosion of carbon-based materials

**Dependence of chemical erosion yield on surface temperature** \( T_{surf} \)

- **Maximum erosion yield @ ~950K**
- **Erosion yield decreases with elevated** \( T_{surf} \)

![Graph showing the dependence of methane yield on surface temperature](image-url)
III.) Chemical erosion of carbon-based materials

*Flux dependence of chemical erosion yield*

Chemical erosion yield decreases with increasing deuterium flux.
III.) Chemical erosion of carbon-based materials

Chemical erosion yield in dependence on properties of carbon material

Soft (hydrogen-rich) carbon layers suffer from an enhanced chemical erosion

D° on a-C:H
more soft
hard
×1000

a-C:H
amorphous hydrocarbon layer

H° on graphite
H° on diamond films

Temperature [K]

Total Erosion Yield [C/H° or C/D°]
III.) Chemical erosion of carbon-based materials

**Energy and angle distribution of eroded particles**

Chemically eroded particles have **Maxwell distributed energy**

\[ E \sim kT_{\text{surf}} \sim 0.05 \text{ eV} @\text{RT} \]

**Angle distribution** of chemically eroded molecules:

as for physical sputtering: good choice **cosine** distribution
IV.) Radiation Enhanced Sublimation (RES)
IV.) Radiation Enhanced Sublimation (RES)

Erosion yield from beam experiments in dependence on surface temperatures

5 keV Ar⁺ on graphite

For carbon-based materials:
- increasing erosion yield at surface temperatures larger than ~1000K

⇒ radiation enhanced sublimation
Mechanism of RES

- During diffusion of C interstitials to surface: probability of recombination with vacancies or stable defects ($\Rightarrow$ annihilation of interstitial)
- Density of vacancies increases with increasing ion flux $\Rightarrow$ flux dependence of RES
- So far RES not clearly seen in tokamak experiments (not yet clarified)
V.) Backscattering
V.) Backscattering

Reflection of impinging particles at the surface

Reflection coefficient \( R \):

\[
R = \frac{\text{amount of reflected particles}}{\text{amount of incoming particles}}
\]

Deposition = 1 - \( R \)

- In most cases: reflected particles are neutrals
- Reflection coefficient depends on:
  - mass of projectile and target
  - energy and angle of incident particles
V.) Backscattering

Dependency of reflection coefficient on incident energy

Monte Carlo simulation (BCA): C on C, $\alpha_{\text{in}} = 60^\circ$

At low energies: BCA not valid \(\Rightarrow\)
Molecular Dynamic calculations yield $R \neq 0$
V.) Backscattering

Dependency of reflection coefficient on incident angle

Monte Carlo simulation (BCA): C on C, $E_{in} = 100 \text{ eV}$
V.) Backscattering

Energy and angle distribution of reflected particles

Reasonable assumptions:

Energy: exponential decrease for reflected particles if incoming particle energy is Maxwell-distributed

Angle: cosine distribution for reflected particles if isotropic bombardment
further important Plasma-Wall Interaction Processes
VI.) Retention

Hydrogen retention in graphite and co-deposited layers

Four retention mechanisms have been identified:
- **Build-up of a saturated surface layer** during hydrogen implantation
- **Chemisorption** on grain boundaries and inner porosity surfaces
- **Intergranular diffusion and trapping** at temperatures > 1000K
- **Co-deposition** of hydrogen with carbon

Based on experimental data:
- **Co-deposition is expected to be most important mechanism** for long-term tritium retention in ITER

**Licensing:** in-vessel tritium inventory in ITER limited to 350g
V.) Retention

Hydrogen retention via co-deposition

physical & chemical erosion yields: 1 - 3 %

re-deposited carbon can be re-eroded much stronger (10 - 20%)

build-up of hydrogen containing layers

shadowed areas
**Plasma-Wall Interaction Processes**

**VII.) Adsorption/Desorption**

*Definition of the processes*

**Adsorption:** binding of particles or molecules to a solid surface
(adsorption from residual gas $\text{O}_2$, $\text{H}_2\text{O}$, $\text{CO}$ …or from impurities segregated at surface at elevated temperatures)

- physisorption: binding due to van der Waals forces ($E_B < \sim 0.5 \text{eV}$)
- chemisorption: binding via exchange/sharing of electrons ($E_B \sim \text{eV}$)

**Desorption:** adsorbed species leave the surface and return into gas phase

$\Rightarrow$ impurity release process

Ion-induced desorption most important desorption process for fusion.
VIII.) Blistering

*Trapping of gas atoms in bubbles of high pressure*

**Example: blistering in tungsten**

![Image of blistering in tungsten](image)

*Pressure in bubble too high ⇒ repetitive exfoliation of micron-thick flakes*
Plasma-Wall Interaction Processes

IX.) Secondary Electron Emission

Mechanisms of secondary electron emission

- reflection of electrons which impinge the surface, mostly elastic scattering
- true electron-induced secondary electron emission from the solid
- ion-induced electron emission

Why important in fusion research?

Secondary electron emission coefficient influences the sheath potential in front of target surface exposed to plasma (later in these lectures …)
Detailed book-keeping of PWI processes (and local transport)

The Impurity Transport Code ERO: see also: lecture III

radial direction

background plasma

incoming flux \((D^+, C^{4+}, O^{5+})\)

reflected and eroded particles

reflected and eroded particles

deposition

re-deposition

B

E

deposition

\(C^0\)

\(CD_4\)

\(C^{x+}\)

\(CD_y^{0,+}\)

toroidal direction

limiter-surface
Plasma wall interaction is unavoidable and necessary for particle and energy exhaust

WHAT happens:

Low Z materials are favourable since higher concentrations can be tolerated in the plasma due to lower radiation losses but the erosion of low Z materials is stronger. A compromise between impurity release and acceptable impurity concentration must be found, which is connected by impurity transport.

Graphite has large advantages for off-normal heat loads in ELMS and disruptions, since it does not melt, but the disadvantage of high erosion and which can lead to large fuel retention by co-deposition

High Z metals have much lower erosion and show much lower hydrogen retention but metal walls can suffer from melt layer loss in off normal heat loads.

Next lecture: HOW can we make ITER work despite these issues