Plasma surface interaction

Presented by K. Schmid

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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 $<\sigma v>$):

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

- Ash
- Plasma heating
- Blanket heating
- Energy production

Reaction of 1g (0.2 mol) D-T mixture $\approx 1.2 \times 10^{23}$ reactions

$E_\alpha = 67.5 \text{ GJ}$
$E_n = 271.8 \text{ GJ}$

- 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"
  - \[ f \frac{E_\alpha}{P_{\text{loss}}} \geq \frac{3nK_B T}{\tau_E} \left( \frac{eV}{m^3 s} \right) \]
  - \[ f = \left( \frac{n}{2} \right)^2 \langle \sigma v \rangle \left( \frac{1}{m^3 s} \right) \]
  - \[ n \tau_E \geq \frac{3K_B T}{\langle \sigma v \rangle E_\alpha} \]

- 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 \( \perp B \ll \) mobility \( \parallel B \)  \( \rightarrow \) Loss at “ends”

\( \rightarrow \) Close field lines into a torus: “TOKAMAK” concept
Why do we need a wall in the first place

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 $\alpha$-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?

- 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

R. Neu, R. Parker, T. Pütterich
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.
Power and particle fluxes to the wall

**Divertor:**
A separate region in the vacuum vessel to which escaping ions are exhausted \( \parallel B \) by means of auxiliary magnetic coils.

The magnetic boundary between confined plasma and edge/divertor plasma is called **separatrix** \( \equiv \) LCFS.
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
K. Schmid, PWI Tutorial PFMC 2011
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

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

\[ \phi_{\perp}^{SOL} = -D_{\perp}^{SOL} \frac{\partial n}{\partial r} \bigg|_{LCFS} L_C W \left( s^{-1} \right) \]

Flux balance

\[ \phi_{\perp}^{SOL} = \phi_{\|}^{SOL} \Rightarrow \lambda_n = \sqrt{\frac{2D_{\perp}^{SOL} L_C}{c_s}} \approx O(0.01) m \]

\[ \phi_{\|}^{SOL} = 2W n(r_{LCFS}) c_s \lambda_n \approx O\left(10^{21} - 10^{23}\right) s^{-1} \]

Total flux entering the SOL from the bulk plasma is concentrated radially on length \( \lambda_n \) and toroidally on length \( W \sim 2\pi R \)

- Flux amplification
- Very high power flux densities MW/m²

For comparison:
- 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 $\Gamma = \text{density} \times \text{velocity}$
  - More electrons hit the wall than ions
  - Wall charges up, repelling electrons

- In equilibrium electrostatic potential $\Phi$ such that $\Gamma_e = \Gamma_i$

- For hydrogen plasmas $\Phi \sim 3T_e$
  - Positive ions of charge $q$ gain $3qT_e$ while traversing the sheath

  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

![Diagram showing power and particle fluxes to the wall, including first wall and divertor regions with corresponding energy distributions and fluxes.](Image)
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....
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
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 $E_{\text{CUT}} = 200\text{eV}$
  - Can be very well described theoretically by MD or MC codes

- Chemical erosion

Yield = # Sputtered / incident

<table>
<thead>
<tr>
<th>ENERGY (eV)</th>
<th>SPUTTERING YIELD (at/ion)</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>10</td>
<td>$10^{-3}$</td>
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<td>$10^{-1}$</td>
</tr>
<tr>
<td>10000</td>
<td>$10^{0}$</td>
</tr>
</tbody>
</table>

- Combination of sputtering theory, experimental data, and MD simulation

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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 compound leaving the solid
- Occurs only for certain target-projectile combinations

**CHEMICAL EROSION IN FUSION DEVICES:**

**FORMATION OF HYDROCARBONS:**
- \( \text{H} \quad \text{C} \quad \text{CH}_4 \ (+ \text{C}_x\text{H}_y) \)

**FORMATION OF CARBON OXIDES:**
- \( \text{O} \quad \text{C} \quad \text{CO} + \text{CO}_2 \)

**REACTIONS WITH SOME METALS:**
- \( \text{O} \quad \text{Me} \quad \text{Me} (\text{O}) \quad (\text{W} \text{ above } 1000 \, ^\circ\text{C}) \)
- \( \text{H} \quad \text{Me} (\text{O}) \quad \text{Me} (\text{OH}) \)
- \( \text{H} \quad \text{Me} (\text{OH}) \quad \text{Me} + \text{H}_2\text{O} \)
Chemical erosion decreases for high $\Gamma_D$ and vanishes at high $T_{\text{surf}}$. 

Graph showing chemical erosion yield vs. ion flux and temperature.
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
Material migration & mixing

Three elements have the potential for lots of mixed material issues

Be: primary wall, port limiter, baffle - 700 m²

W: upper vertical target, dome baffle, liner - 100 m²

CFC: lower vertical target - 50m²

likely to be replaced by tungsten for the D/T operation phase
Fundamental processes during plasma wall interaction

- Material migration & mixing

![Graph showing concentration at each wall index with different materials such as Be, C, and W.](image)
YES! Example: beryllium and tungsten can form alloys

Fundamental processes during plasma wall interaction

Material migration & mixing: Negative consequences of material mixing

melting point: 3695 K $\rightarrow$ 2370 K $\rightarrow$ 2520 K $\rightarrow$ $\sim$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 $\rightarrow$ Implanted H diffuses towards

- Bulk
- Surface

At the surface:
H recombines to $H_2$ and sublimes

In the bulk:
H is dissolved as an interstitial
H is trapped at defects

Retained amount is determined through 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

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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

Deposited layers may form ever growing inventory of buried fuel!

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Summary

- The wall of a magnetic fusion device is essential to its operation
  - Maintain clean vacuum
  - 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-deposition & 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
- Pristine first wall composition $C^0$
- D-plasma erodes first wall $Y^0$
- Impurities are re-deposited yielding wall composition $C^1$
- In reality this is not a stepwise but a continuous process
- Impurities are re-deposited yielding wall composition $C^2$
- D-plasma & impurities erode first wall $Y^2$
- Produces impurity influx $\Gamma^0$
- Produces impurity influx $\Gamma^1$
- Equilibrium

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

Potential radiation + explosion hazard!

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