Plasma-Surface Interactions

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…and in future: from this workshop
Outline

- Does nuclear fusion need a wall?
- What are power and particle fluxes to the wall?
- Which are the fundamental processes during PSI?
- What are ITER-specific PSI issues?
- How can we measure PSI in situ?
- Summary
Does nuclear fusion need a wall?
Fusion without a wall (?)

Example of a fusion reactor: the sun

Particles

Radiation

Gravity

Plasma pressure

No wall: No exhaust

We need a surface to extract power.

Plasma-Surface interactions tend to be difficult.

NYT, Nov 1882

A STORM OF ELECTRICITY

TELEGRAPH WIRES USELESS FOR SEVERAL HOURS.
ONE OF THE MOST SEVERE DISTURBANCES FOR MANY YEARS, EXTENDING EVEN TO EUROPE—TELEPHONE WIRES ALSO OBSTRUCTED—BUSINESS DELAYED A GOOD PART OF THE DAY.

Yesterday’s storm was accompanied by a more serious electrical disturbance than has been known for years. It very seriously affected the workings of the telegraph lines both on the land and in the sea, and for three hours—from 9 A.M. until noon—telegraph business east of the Mississippi and north of Washington was at a standstill.

images: nasa.gov
Fusion on earth: How?

Thermal plasma: \( \sim T^2 \)

Lawson-Criterion for positive power balance:
\[ n_e k_B T \tau_E > 5 \times 10^{21} \text{ keV m}^{-3} \text{ s} \]
(1 keV ~ 11.6 Mio °C)

typical: \( n_e \sim >10^{20} \text{ m}^{-3} \)
\( \tau_E \sim 1..10 \text{ s} \)

“Real” fusion fuel cycle:
\[ ^6\text{Li} + \text{D} = ^4\text{He} + 22.4 \text{ MeV} \]

\( T_{\text{bred}} / T_{\text{burned}} > 1 \)

~ 30 Million years of world energy demand available

Magnetic confinement fusion
Fusion on earth: **With a wall**

- Compatibility of tokamak/plasma physics with plasma-wall interaction:
  - Energy confinement
  - Particle confinement

- Exhaust of...
  - Heat => Electricity
  - Fusion products: neutrons, helium "ash"

- Blanket: Tritium breeding

- Tritium properties: Safety, breeding ratio

- Transient events: ELMs, Disruptions

- Accidents: Air ingress, LOCA

- Economic operation of power plant:
  - Steam cycle efficiency, Component lifetime, Complexity, Reliability, Costs, Maintainance
Extreme conditions (and physics) at the surface

from D. G. Whyte, MIT
Global picture

Plasma

fuel ions+atoms (charge exchange) + impurities

Material circulation

Erosion → Transport → Deposition → Re-erosion
“Clean” D+T plasma: limited impurities

Impurities are not all fully ionized

- Electronic transitions possible
- Power loss by radiation
“Clean” D+T plasma: limited impurities

Plasma is quasi-neutral

- Impurities dilute the plasma
- Each impurity of charge Z “displaces” Z-fuel ions

![Graph showing the relationship between impurity concentration and atomic number, with radiation and dilution lines.](image)
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.
Plasma divertors

**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**.
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
What are power and particle fluxes to the wall?
Edge plasma: particle flux to the wall

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

“cartoonic” simplification to catch essentials
“simple SOL”

Diffusion driven:
\[ v_{\perp} n = D_{\perp} \frac{\partial n}{\partial x} \]

\[ c_{s} = \sqrt{\frac{\gamma Z T_{e}}{m_{i}}} \], \( v_{\parallel} = 0.5 \, c_{s} \)

\[ \lambda = \frac{1}{n} \frac{\partial n}{\partial x} \]

\[ \frac{v_{\perp}}{v_{\parallel}} = \frac{\lambda}{L} \]

\[ D_{\perp} = 1 \, \text{m/s}^2 \]

\[ L = 10 \, \text{m} \]

\[ T_{e} = 50 \, \text{eV} \]

\[ \lambda = \sqrt{\frac{D_{\perp} L}{0.5 c_{s}}} = 0.03 \, \text{m} = O(0.01)\text{m} \]
Density $n$, flow velocity ($M = v/c_s$) and electrical potential $eV$ in edge plasma

From 1D fluid equations:

$$\frac{n}{n(0)} = \frac{1}{1 + M^2}$$

$$M = -2 \arctan M = (\frac{\pi}{2} - 1) \frac{z}{L}$$

$$V(z) = -\frac{kT_e}{e} \ln(1 + M(z)^2)$$

from A. Kirschner, FZJ
(Simplified) estimate of ion particle flux

\[ \lambda = O(0.01) \text{m} \]

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

\[ \Phi^{SOL} = 2Wn(r_{LCFS})c_s \lambda_n \approx O\left(10^{21} - 10^{23}\right) \text{s}^{-1} \]

Yearly fluence of D-T-He ions through sheath: 
4x10^{31} \text{ ions / m}^2

vs. Areal density of solid: 
6x10^{25} \text{ W atoms / m}^2

→ Flux amplification (~ x100!)
→ Very high power densities (~10 MW/m²)

For comparison:
Hot plate 0.05-0.1 MW/m²
Oxy-acetylene torch 100 MW/m²
Particle energies: sheath acceleration

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. $T_e = 20\,\text{eV}$
- $D^+ \rightarrow 60\,\text{eV}$
- $C^{+4} \rightarrow 240\,\text{eV}$
First wall: Particle fluxes and energies

**Divertor ion flux**

\[ \Gamma_{D^+} : 10^{24} \text{ m}^{-2} \text{ s}^{-1} \]
\[ T_e : <10 \text{ eV} \]

**First wall neutral flux**

\[ \Gamma_{\text{CX}} : 10^{20} \text{ m}^{-2} \text{ s}^{-1} \]
\[ \langle E_{\text{CX}} \rangle : 40-200 \text{ eV} \]

**First wall ion flux**

\[ \Gamma_{D^+} : 10^{22} \text{ m}^{-2} \text{ s}^{-1} \]
\[ T_e : 20-40 \text{ eV} \]
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
Transient flux excursions

Plasma instabilities can lead to transient heat load excursions
Which are the fundamental processes during PWI?
Fundamental PWI processes

- Rates for individual processes change as surface evolves (towards equilibrium? → later)
- Surface compounds (“mixed materials”) formed with different properties compared to pure elements
- Surface processes and plasma properties are interlinked: impurity fluxes, transport, temperatures, compositions, hydrogen isotope retention …

from D. G. Whyte, MIT
Fundamental PWI processes

Plasma-wall interactions comprise coupled processes spanning orders of magnitude in time and length scales

- Physical sputtering and implantation
- Chemical sputtering and reactions
- Radiation enhanced sublimation
- Photon induced desorption
- Evaporation and sublimation
- Altered thermomechanics
- Melting and splashing
- Arcing
- Neutron induced damage and transmutations
- Material mixing and migration
- Hydrogen isotope retention and release
- Heating and cooling, transport
Physical sputtering and implantation

Collision cascade

- Primary and secondary knock-on atoms
- Sputtering
- Energy loss: stopping
- Defects: point defects, vacancies, dislocations
  - \( \text{dpa} \): displacements per atom
- Projectile trapping

- Simulation: binary collision approximation
- Implantation profile measured by Elastic Recoil Detection Analysis (ERDA) reproduced
  - Limit (\( \rightarrow \) Molecular Dynamics simulations)
- Low kinetic energies (< 20 eV)
- Molecules

\[
3 \text{ keV D} \rightarrow \text{Be_{poly}}, \Gamma = 3 \times 10^{22} \text{ m}^{-2}
\]
Sputtering yield

\[ Y = \frac{\text{# eroded atoms}}{\text{# of projectiles}} \]

- Physical sputtering: threshold energy
- Maximum yield
- Carbon: chemical erosion: NO threshold hydrocarbon chemistry
Extreme power loads: Melting and splashing

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

**FOR CARBON:**
- Above a certain power load (threshold) emission of debris
  - BRITTLE DESTRUCTION
The plasma-material interface never comes to full equilibrium because the fusion environment perpetually evolves the surface and material properties.
What are ITER-specific PWI issues?
Neutron induced damage, transmutations

Production of lattice defects
- Reduced thermal conductivity

Transmutations
- Formation of new elements (alloys)
ITER: PWI with multi-element walls

Multi-element first wall:
ITER: Be – W
JET: ITER-like First Wall

W7-X: C – steel
DEMO: W-based alloys

Dynamic evolution of surface composition
• strongly alters physical and chemical first wall properties (erosion, melting, hydrogen inventory, …)
• influences plasma performance by impurity concentration and transport

→ Integrated modeling of plasma scenarios including dynamic wall evolution

Two ingredients required:
• Model of background plasma, providing particle and energy fluxes to/from the wall (fusion device!)
• Model of physical and chemical surface processes (laboratory!)
Atomistic reaction data: System Be – W

Lab experiment (UHV): 2.5 nm Be on W_{poly}
- Alloy formation and decomposition
- Quantitative XPS measurements

Forward calculation: reaction front model
- Be diffusion in Be_2W
- Be_2W → 2 Be + W
- Be + O → BeO
- etc.
- Coupling of rate equations:

$[C]^z = [A]^x [B]^y k \exp\left(-\frac{E_a}{k_B T}\right)$
Background plasma and impurity transport

JET #78647
EDGE2D/EIRENE

- L-mode
- Standard calculation grid
- Verified by experiment

Wall elements and transport

- Materials: Be und W
- DIVIMP redistribution matrix
- Dynamic surface temperature

⇒ Solve rate equation system for each wall element
Surface composition at strike point during discharge

Composition at divertor strike point and sublimation flux

- Periodic: Deposition and erosion at inner strike point
- Be flux into plasma from outer strike point

⇒ Dynamic composition based on a static plasma scenario!
Hydrogen isotope retention and release

Simulation of collision cascade with Monte Carlo codes (TRIM)

Result: Depth profile

3 keV D → Be\text{poly}, Γ = 3 \times 10^{22} \text{ m}^{-2}

Si-ERDA data
Monte Carlo simulation

D concentration vs. depth [nm]
Thermal release

Elementary steps

- diffusion of H in the solid
- trapping and release of H from binding sites (defects)
- recombination and desorption of H\(_2\) from the surface
Thermal release

Described by Diffusion-Trapping Model

Local elementary reactions (trapping / release of H)
- thermally activated processes
  with:
  \( n_i \): number density of each species
  \( k \): reaction rate constant
  \( E_a \): activation energy

Diffusion:
- driven by concentration gradient
  (1st Fick's law)

Local concentration change:
Diffusion described by continuity equation
(2nd Fick's law)
Particle flux at desorption

Partial differential equation:

considers both diffusion and elementary reactions

\[
\frac{\partial n_i}{\partial t} = -D_i \text{ div (grad } n_i) + \sum R_{\text{source}} + \sum R_{\text{sink}}
\]

Example:

\(n_i\): concentration of mobile (dissolved) \(H_{\text{mobile}}\)

\(R\): rates for trapping and release at traps \(\Box_{\text{trap}}\)

PDE describes H diffusion and the reaction: \(H_{\text{trap}} \rightleftharpoons H_{\text{mobile}} + \Box_{\text{trap}}\)

⇒ Consider arbitrary elementary reactions

Description of the thermal release by a system of coupled differential equations
Tritium inventory in Be
Tritium in Be: saturation

D retention demonstrates saturation. For 1 keV D ion irradiation, the saturation is observed at a fluence of $10^{22}$ D/m².

For D is trapped in the implantation zone with negligible diffusion into the bulk.

When the irradiation temperature increases, the D retention decreases.

Experiment: Desorption von D₂ from Be

Determination of parameters by forward calculation

- Different single processes
- Numerical solution of PQE with boundary conditions (implantation profile, desorption of D₂ molecules from surface)
- Comparison to experiment

![Graph showing desorption flux vs. temperature for different implantation energies and fluences.]

Single processes

- Diffusion of D
- Diffusion of D\(^{\text{trap}}\)
- Release
- Self release

<table>
<thead>
<tr>
<th>Single process</th>
<th>(E_a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion of D</td>
<td>0.3 eV</td>
</tr>
<tr>
<td>Diffusion of D(^{\text{trap}})</td>
<td>1.2 eV</td>
</tr>
<tr>
<td>Release</td>
<td>1.85 eV</td>
</tr>
<tr>
<td>Self release</td>
<td>0.3 eV</td>
</tr>
</tbody>
</table>
Hydrogen isotope retention and release

Full and detailed detailed description of H isotope retention and release

- Investigation of single steps in the relevant
  - Fluence ranges
  - Temperature ranges
  - Particle energy ranges

Global modeling with respect to the various regions of a fusion device
Can we measure PSI *in situ*?
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
Joint European Torus (JET)

Divertor experiment in Culham, GB; worldwide largest tokamak
Before 2010: carbon wall and divertor
Since 2010: JET-ILW with Be main wall and W divertor

For ITER scaling:
As possible close to ITER parameter (particles fluxes, energy)
Example: JET-C MkII SRP

**Outer divertor:**
- erosion on vertical targets
- deposition on horizontal targets

**Inner divertor:**
- everywhere deposition-dominated
- largest carbon deposition on plasma-shadowed areas

P. Coad, J. Likonen, M. Rubel et al.
Main wall: main source for carbon net erosion

(chemical erosion & physical sputtering)

↓

asymmetric flows in SOL

↓

transport to inner divertor

↓

local transport to divertor
Laser Ablation Based Methods:

LIBS: Laser Induced Breakdown Spectroscopy

- **Particle source & excitation**
- Independent of plasma operation.
- Very complex non-equilibrium process
- $10^4$-$10^5$ atoms/photon

LIAS: Laser Induced Ablation Spectroscopy

- **Particle source** only
- Excitation and ionization by fusion plasma
- Application of impurity models
- ~100 atoms/photon

![Diagram of LIBS and LIAS processes](image)
Experimental setup

Proposed ITER-setup

Setup at EAST


Suited for wall conditioning and implantation studies of H, D
Simple LIAS: Inverse photon efficiency

Competing processes for neutral atom:

**Excitation:** $A_0 + e^- \rightarrow A_0^* + e^- \rightarrow A_0 + hv + e^-$ observed

Description:
- Excitation rate coefficient $<\sigma v>_{exc}(T_e)$,
- Collisional radiative model $\rightarrow$ **Photon emission coefficient** $PEC(n_e, T_e)$

**Ionisation:** $A^0 + e^- \rightarrow A^+ + 2e^-$ no observation

Description: **Ionization rate coefficient** $<\sigma v>_{ion}(T_e)$

Evaluation of rate coefficients for radiative collisional model for fixed $n_e, T_e$:

**Inverse Photon efficiency:**

$$\eta(T_e, n_e) = \frac{\text{Ionizations}}{\text{Photon}}$$
Inverse photon efficiency for atomic hydrogen

Collisional-radiative model in steady-state situation in homogeneous plasma:

Data: ADAS database

Tokamak: Inhomogenous plasma

Balmer-\(\alpha\) inverse photon efficiency

\[
 n_e (r') = n_{e,LCFS} \cdot \exp \left( -\frac{r'}{\lambda_{n_e}} \right)
\]

\[
 T_e (r') = T_{e,LCFS} \exp \left( -\frac{r'}{\lambda_{T_e}} \right)
\]

Numerical values are quite robust for tokamak SOL gradients.
First experimental results

\( \text{H}_\alpha \) emission on C sample in EAST

\#63703 LIAS signal, background subtracted intensity

190 \( \mu \text{s} \)

200 ms 200 ms \( t_{\text{wait}} \) 200 ms 200 ms

EAST discharge time
First piggy back experiments (2016)

Variation of $t_{\text{wait}}$ in different EAST discharges. black: $0.95 < R_{bg} < 1.05$, brown: otherwise

- Early data indicates LIAS could be suited for in situ dynamic retention studies in nuclear fusion environments.
- Dedicated experiments required (later this year)
Summary

The wall of a magnetic fusion device is essential to its operation
- Maintain clean vacuum
- Provide 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
- Mixed material formation
- Hydrogen isotope retention and release

ITER will be first machine with extended D-T burning plasma
- Neutrons will lead to additional (deep) traps and transmutations

Plasma-wall interaction processes are a key challenge on the way to a fusion power plant.

In situ diagnostic and theoretical understanding urgently required.