Putting things in perspective

- Re-entry vehicle
- Ariane 5/Vulcain 2
- Power load \([\text{MW/m}^2]\)
- Rolls Royce Trent 900
- ITER steady-state
- ITER transients

Energy Days, Tu/E, 31 May 31
Plasma-wall coupling

- Any physical system is defined by its boundary conditions
  - True also for a fusion device: the wall strongly affect the plasma behaviour
  - Edge plasma and first wall = strongly coupled system [1]

\[
N_{\text{wall}} = \Phi A_{\text{wall}} = 5 \times 10^{21} m^{-2} \times 100 m^2 = 5 \times 10^{24} \text{part}
\]

Wall inventory much larger than plasma inventory

\[
N_{\text{plasma}} = n V_{\text{plasma}} = 10^{20} m^{-3} \times 10^3 m^3 = 10^{23} \text{part}
\]

Any physical system is defined by its boundary conditions

- True also for a fusion device: the wall strongly affect the plasma behaviour
- Edge plasma and first wall = strongly coupled system

Impurities control (conditioning)

- Physical/chemical sputtering
  - Effect on morphology
  - Effect on composition (mixed materials)

Effect of the plasma on the PFM

Effect of the PFM on the plasma

Plasma cooling/dilution

Release of impurities
Effect of plasma impurities

- Plasma must be kept as clean as possible
- Impurities not fully ionized
- Power loss by radiations

Plasma is quasi-neutral: each impurity of charge Z 'displaces' Z fuel-fuel ions

Losses through:
- Dilution (low-Z): $n_{DT} = n_e (1 - Z n_Z)$
- Radiation (high-Z): $P_{rad} / V = L_Z n_Z n_e$
Effect of plasma impurities

Conditions at which ignition can be reached depending on impurity fraction

Fatal fraction: fraction of impurities for which radiation losses = alpha heating power

Low-Z elements are very favourable in terms of plasma contamination

NB: 1mm$^3$ tungsten sphere (2x10$^{20}$m$^{-3}$)=1% plasma content
Properties of a plasma-facing material

- High heat conductivity and capacity
- High melting point
- Large thermal shock resistance
- Good machining properties
- Little degradation of thermophysical properties
- Low activation and transmutation due to neutrons
- Low tritium retention
- Low erosion due to plasma ions
- Low erosion due to ‘local’ effects (electric arcs, hot spots)
- Low energy loss by radiation if atom enters plasma

There’s just one more thing that bothers me…
Does this material exist??
Melting point of different metals
A brief travel in time (1/3)

👩‍💻 Earliest USSR tokamaks were built with glass wall
👩‍💻 Stainless steel vacuum vessels + conditioning techniques subsequently developed to reduce impurity content (T-3 produced relatively hot plasmas)
👩‍💻 Limiters (and divertors) used to protect vessel walls and concentrate PMIs on a ‘sacrificial structure’
👩‍💻 Refractory materials (W) were favoured (high melting point, low sputtering)

Performances were strongly limited by high levels of radiative power losses
Impurity accumulation in the core, hollow temperature profiles
Quite some materials have been tested as PFM over the years:

StSt (TEXT, PLT), Mo (Alcator-A, TFR), W (DOUBLET-II, ORMAK), Al (ST), \( \text{Al}_2\text{O}_3 \) (PETULA), \( \text{B}_4\text{C} \) (TFR), Be (ISX-B, JET), \( \text{Au} \) (DIVA), Ti (PDX, DITE), Li (CDX-U), TiC (W-AS), TiB\(_2\) (ISX-B), Cu (ASDEX), C (CFC, graphite)…

**Turning point: reactor grade fine grain graphite** (low atomic number, good thermal conductivity, isotropic material but: limited strength)

- PLT used a carbon limiter → 50% increase in \( T_e \) although C and O levels were similar for W and C limiters
- Following those results, C (graphite, CFC) became the standard PFM
  - Extensive conditioning techniques (GDC, boronization, etc…) necessary to counter-act the natural affinity of C with H and O
- High field tokamaks (FTU, C-mod) retained High-Z metals (Mo, W)
ITER materials

- Materials chosen to optimize plasma conditions and allow some margin wrt transient events
- **700m² beryllium**
  - First wall
  - Low Z, good oxygen getter, good thermal conductivity
- **100m² tungsten**
  - Baffle region, dome
  - Low sputtering yield, high melting point
- **50m² carbon fibre composite**
  - Divertor targets
  - Good power handling, no melting

→ No relevance to a future reactor, CFC to be replaced by tungsten
ITER divertor

Hugely complex and expensive structure (few 100 million €), water cooled → state of the art power handling technology
The interaction of a thermonuclear plasma with surrounding surfaces represents a daunting challenge because of the magnitude of the issues at stake.

Taming those issues is a must on the way to fusion energy.

Multi-scale problem requiring cross-discipline research.
ITER divertor

Hugely complex and expensive structure (few 100 million €), water cooled \( \rightarrow \) state of the art power handling technology

Energy Days, Tu/E, 31 May 31
ITER Divertor:

- 54 cassette assemblies
- ~4000 heat flux elements
- ~200,000 individual monoblocks

Must survive for more than a decade in the most hostile region of the tokamak

Energy Days, Tu/E, 31 May 31
Main PMI issues...

- Material lifetime
  - Physical/chemical sputtering
  - Transients
  - Transport
  - Re-deposition
  - Plasma contamination
  - Dust

- Tritium retention
  - Co-deposition
  - Implantation
  - Effect of neutron
  - Safety
  - Breeding ratio

- Material modification
  - Mixed materials
  - Morphology
  - Modified properties (melting point, thermal properties)
  - Structural integrity

NB: effects associated with neutron damage not considered here, synergistic effects might exist
Wall erosion: sputtering

- Kinetic ejection of surface atoms by incident energetic ions or atoms due to collision processes

- Plasma contact with the wall generates charge-exchange neutrals
- In turn generates strong erosion of the wall

\[ \text{D}^+ + \text{D}^0 \rightarrow \text{D}^0 + \text{D}^+ \]

S. Lüke, POP/DPIW
### Wall erosion: sputtering


<table>
<thead>
<tr>
<th>Device</th>
<th>$P_{\text{HEAT}}$ (MW)</th>
<th>$\tau_{\text{annual}}$ (s/yr)</th>
<th>$E_{\text{load/yr}}$ (P_{\text{HEAT}} \times \tau_{\text{annual}}$) (TJ/yr)</th>
<th>Net wall erosion (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beryllium</td>
</tr>
<tr>
<td>DIII-D</td>
<td>20</td>
<td>$10^4$</td>
<td>0.2</td>
<td>0.11</td>
</tr>
<tr>
<td>JT-60 SA</td>
<td>34</td>
<td>$10^4$</td>
<td>0.34</td>
<td>0.19</td>
</tr>
<tr>
<td>EAST</td>
<td>24</td>
<td>$10^5$</td>
<td>2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>ITER</td>
<td>100</td>
<td>$10^6$</td>
<td>100</td>
<td>64</td>
</tr>
<tr>
<td>Reactor</td>
<td>400</td>
<td>2.5x$10^7$</td>
<td>10,000</td>
<td>5300</td>
</tr>
</tbody>
</table>

- Wall lifetime is obviously an issue
- Large uncertainties make it difficult to predict: between 1000 and 50000 discharges for ITER

**BUT: where does all this material go?**