$^{13}$C transport studies in the ASDEX Upgrade tokamak

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Transport of elements is a key research issue...

... because when hot plasma interacts with the walls of a fusion reactor the result is:

- **erosion** of the wall materials ⇒ **lifetime** of plasma-facing components (PFC)?
- **transport** of the eroded material and impurities ⇒ **where do they end up**?
- **deposition** of material + plasma fuel on new locations ⇒ large **tritium inventories** on PFCs?

Erosion and deposition patterns typically asymmetric and different for different materials!

**Carbon**
- good mechanical and thermal properties
  ⇒ **one of the first-wall materials in ITER**
- suffers from erosion and co-deposition with tritium
  ⇒ **transport mechanisms need to be identified**
How to study erosion, deposition, and transport?

- **spectroscopic** techniques
  - "real-time" information on erosion (and deposition)
- **post mortem** surface analysis techniques
  - analysis of wall tiles ⇒ campaign-integrated data on erosion and deposition
  - analysis of probes exposed to a few plasma discharges ⇒ discharge-resolved data

Campaign-integrated data hard to interpret and probes provide data only from single locations

⇒ tracer injection experiments immediately before opening the vessel + post mortem analysis

⇒ data for modeling purposes, particularly of carbon

Spectroscopic approach (LIBS)

Post-mortem approach (SIMS)
**13C injection experiments in ASDEX Upgrade**

ASDEX Upgrade
- located in Garching, Germany
- **full-W first wall since 2007**
  ⇒ carbon present only as a trace impurity

In ASDEX Upgrade, carbon transport has been studied with the help of **13C experiments**
- isotopically labelled methane (\(^{13}\text{CH}_4\)) injected into the torus
- poloidal deposition profile of \(^{13}\text{C}\) on wall tiles determined

**Global** and **local** injection experiments since 2003, latest in 2009
  ⇒ **different plasmas, configurations and wall materials covered**
Overview of global $^{13}$C injection experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Plasma confinement</th>
<th>Location of the X point</th>
<th>Wall material</th>
<th>Plasma gas</th>
<th>Plasma density</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>low</td>
<td>bottom</td>
<td>W</td>
<td>D</td>
<td>low</td>
</tr>
<tr>
<td>2005</td>
<td>low</td>
<td>bottom</td>
<td>W + C</td>
<td>H</td>
<td>high</td>
</tr>
<tr>
<td>2004</td>
<td>high</td>
<td>top</td>
<td>W + C</td>
<td>H</td>
<td>high</td>
</tr>
<tr>
<td>2003</td>
<td>high</td>
<td>bottom</td>
<td>W + C</td>
<td>H</td>
<td>high</td>
</tr>
</tbody>
</table>

See:
Analysis of $^{13}$C on wall tiles: case 2007 experiment

- In 2007, two sets of tiles removed for analyses from neighboring poloidal cross sections
  - lower-divertor marker tiles $\Rightarrow$ $^{13}$C on C
  - W-coated tiles from the lower divertor and the main chamber $\Rightarrow$ $^{13}$C on W
- Also Si samples $\Rightarrow$ deposition in remote areas
- Cylindrical samples (diam. 17 mm, height $\approx$ 10 mm) drilled from each tile at VTT
- Analyses made using secondary ion mass spectrometry (SIMS)
SIMS analysis & data evaluation

- 5-keV $O_2^+$ primary ion beam, current $\approx 500$ nA
- beam rastered across a 300×430-μm$^2$ area
- high mass resolution used to distinguish $^{13}C$ from closely-lying isobars ($^{12}CH^+$)
- typical sputtering rates: 0.37 nm/s for tungsten coating, 1.5 nm/s for graphite
- $^{13}C$ deposited on a 10-50 nm thick surface layer
- results converted to quantitative ones with the help of calibration samples ($^{13}C$ on W or on C)

**SIMS produces depth profiles!**

Different slits are used to:
(i) image the secondary-ion beam to the detector
(ii) select ions with the desired energy and the correct m/z fraction (using B)
(iii) determine the mass resolution $\Delta m/m$


- **lower divertor**: deposition largest in the inner divertor
- **main chamber**: deposition largest at the upper divertor and close to the injection valve
- **silicon samples**: large deposition below the high-field side roof baffle; barely nothing next to the injection valve

<table>
<thead>
<tr>
<th>Region</th>
<th>Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner divertor</td>
<td>0.8%</td>
</tr>
<tr>
<td>Roof baffle</td>
<td>0.1%</td>
</tr>
<tr>
<td>Outer divertor</td>
<td>0.1%</td>
</tr>
<tr>
<td>Limiter region</td>
<td>0.3%</td>
</tr>
<tr>
<td>Upper divertor</td>
<td>1 - 6%</td>
</tr>
<tr>
<td>Heat shield</td>
<td>0.6%</td>
</tr>
<tr>
<td>Remote areas</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

4 - 9% of injected $^{13}$C found
\(^{13}\text{C}\) on C: inner and outer divertor equally important

- deposition profiles for \(^{13}\text{C}\) on W and \(^{13}\text{C}\) on C **totally different**, largest deviations in the outer divertor
- if the lower divertor consisted of carbon tiles, then the deposition would be
  - inner divertor: 2.5%
  - roof baffle: 0.6%
  - outer divertor: 4%
Comparison of global experiments (2003, 2005, 2007)

- deposition of $^{13}$C on W radically different from all the other curves
  \[ \Rightarrow \text{wall material!?} \]
- surface roughness does not explain the differences: W-coated tiles are rougher than the carbon areas of the marker tiles
- both marker tiles and W-coated tiles taken from the same sector
  \[ \Rightarrow \text{difference not related to toroidal asymmetry!} \]

- re-erosion of $^{13}$C larger from W?
- enhanced erosion from W due to physical sputtering?
DIVIMP simulations of the 2007 experiment

- 2007 global experiment simulated with the DIVIMP code
- \(^{13}\text{C}^+\) ions launched at the outer midplane and followed until they exit the calculation grid
- **taken into account:** impact ionization with electrons, recombination
  - **NOT considered:** re-erosion or recycling of \(^{13}\text{C}\)
- generation of the plasma background thoroughly studied

<table>
<thead>
<tr>
<th></th>
<th>Experimental (normalized to (^{13}\text{C}) inj.)</th>
<th>Experimental (normalized to (^{13}\text{C}) found)</th>
<th>DIVIMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner divertor</td>
<td>0.8%</td>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td>Outer divertor</td>
<td>0.1%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Limiter region</td>
<td>0.3%</td>
<td>4%</td>
<td>30%</td>
</tr>
<tr>
<td>PSL</td>
<td>0.04%</td>
<td>0.5%</td>
<td>18%</td>
</tr>
<tr>
<td>Upper divertor</td>
<td>&lt;6%</td>
<td>&lt;75%</td>
<td>38%</td>
</tr>
<tr>
<td>Heat shield</td>
<td>0.6%</td>
<td>8%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Gradient force pushes \(^{13}\text{C}\) ions to the top of the vessel
⇒ **deposition onto the grid edge**
Flow most likely incorrect
⇒ **too less \(^{13}\text{C}\) at the inner divertor**

Case: injection point 5 mm, diffusion coefficient
0.5 m\(^2\)/s, grid extension 2 cm
Local $^{13}$C experiment in 2007: $E \times B$ effect

- Local experiment performed during the 2007 global experiment from 2 valves at the outer divertor ⇒ what happens in the vicinity of the puffing holes?
- Experimental profile determined with nuclear reaction analysis at IPP-Garching
- Simulations done with the SOLPS and ERO codes
  ⇒ rather nice match when $E \times B$ drift taken into account ⇔ something new
  ⇒ $E \times B$ effect important for the migration of carbon, at least in present-day machines
Conclusions

Global $^{13}$C experiments

- On tungsten, $^{13}$C surface densities **larger in the inner than outer divertor**
- On graphite, deposition **equally pronounced in the inner and outer divertor**; surface densities 10—100 times higher than on W at the outer divertor
- Only 1—1.5% of injected $^{13}$C estimated to have been deposited in the divertor region; 1—6% deposited in the upper divertor, and 1% below the roof baffle
  \( \Rightarrow \) **where is the remaining 90%? gaps, remote areas, pumped away, toroidal asymmetry?**
- DIVIMP simulations indicate strong sinks for $^{13}$C in the main chamber but the match between the experiments and the simulations will be improved

Local $^{13}$C experiments

- SOLPS and ERO simulations of the local $^{13}$C experiment have revealed important physical mechanisms; particularly the effect of drifts