Global migration of impurities in tokamaks: what have we learnt?

Euratom-Tekes Annual Seminar

Silja Serenade, 28 May, 2013

Antti Hakola, Markus Airila and many others

VTT Technical Research Centre of Finland
Naturally, our advances are thanks to the efforts of numerous collaborators from all around Europe

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<th>VTT, Finland</th>
<th>Aalto University, Finland</th>
<th>IPP, Germany</th>
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<td>Leena Aho-Mantila</td>
<td>Mathias Groth</td>
<td>Albrecht Herrmann</td>
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<td>Markus Airila</td>
<td>Aaro Järvinen</td>
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<td>Seppo Koivuranta</td>
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<td>Toni Makkonen</td>
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<td>Juho Miettunen</td>
<td>Volker Rohde</td>
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<td>Anna Widdowson</td>
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Here we will focus on data gathered from JET and ASDEX Upgrade (AUG)
This presentation deals with migration of materials in tokamaks...

...so we need to keep in mind some key terms and definitions.

Photograph of the tokamak torus (ASDEX Upgrade)

Poloidal cross section

- Edge plasma
- Core plasma
- Scrape-off layer (SOL)
- X-point
- Separatrix
- Strike points
- MAIN CHAMBER
- DIVERTOR

LSN = LOWER SINGLE NULL
X-point at the bottom

USN = UPPER SINGLE NULL
X-point at the top

DN = DOUBLE NULL
Two X-points at the bottom and at the top

HIGH-FIELD (INNER) SIDE

LOW-FIELD (OUTER) SIDE
Material migration: why is it important?

"Material migration is important because it is net, rather than gross, erosion which is of practical consequence" (P. C. Stangeby)

In other words, necessary step between

- erosion of the plasma-facing components (PFCs) and
- deposition of the eroded material and impurities together with plasma fuel on new locations

Thick co-deposited layers may contain unacceptably high amounts of tritium (> 700 g in ITER) and flaking of the layers can increase the dust inventory of the vessel

⇒ Serious problems!!!
⇒ Better to know beforehand where material is likely to end up...

Example:
What happens to W PFCs in AUG?
It does matter with the material

ITER will use **tungsten, beryllium, and possibly carbon** in the form of carbon fibre composite (CFC) on its first wall

The whole soup is **flavoured by H, D, T, He, N, O, Ne, Ar,…**

⇒ **we should understand the physics behind migration of all these elements**

**Carbon (CFC)**
- possibly the strike-point areas at the divertor
  ⇒ tolerates the highest power and particle loads

**Tungsten (W)**
- the rest of the divertor
  ⇒ small erosion and retention of T

**Beryllium (Be)**
- main chamber
  ⇒ radiation losses in the plasma small
Material migration is a multiparameter problem

Migration and the resulting deposition profiles are affected (at least) by:

- **background plasma** (density, type of species, power levels)
- **operational conditions** (L- vs. H-mode, magnetic configuration)
- **source** of the impurities (location, geometry, energy)
- **wall material** (beryllium vs. carbon vs. tungsten, dirty vs. clean surface, roughness)
- **impurity element** (beryllium vs. carbon vs. nitrogen)

In the modelling, we also have to take into account:
- **flows** in the SOL
- various drifts
- multiple re-erosion/re-deposition chains
- surface chemistry…

In the end, we want to understand – and predict – the outcomes of future experiments in tokamaks
How can the migration mechanisms in tokamaks be elucidated?

Elementary, dear Watson! We can

1. Use special PFCs and determine the deposition profiles of certain marker elements; e.g., W on Cr (steel) or $^{10}$Be on $^9$Be – BUT results integrated over all kinds of plasmas

2. Use marker probes and expose them to well-known discharges – BUT this way only local information obtained

3. Carry out tracer-injection experiments during plasma discharges
   - tracer element should be non-existent in the tokamak or its natural abundance should be low (< 1-2 at.%)
   - deposition should be easy to determine using standard surface analysis techniques

Example:
Re-deposition of W on Mo and Cr, AUG in 2010-2011

$^{13}$C (natural 1.1%) in the form of $^{13}$CH$_4$ or $^{13}$C$_2$H$_4$

$^{15}$N (natural 0.37%) in the form of $^{15}$N$_2$

Si in the form of SiD$_4$

W in the form of WF$_6$
Tracer-injection experiments have been carried out in different tokamaks since 1990’s

JET
- Several options for tracer injection experiments
- In the divertor region, injection can be toroidally periodic

NB! All the experiments done with CFC walls (before 2010)

ASDEX Upgrade
- **full-metal (tungsten)** first wall since 2007
- Injections only from single valves at the outer midplane or at the outer divertor
- But interesting physics questions have still been solved…
Tracer-injection experiments have been carried out in different tokamaks since 1990’s

Example:
Local experiments in AUG: field reversal changes the deposition patterns because of the $\mathbf{E} \times \mathbf{B}$ drift (adapted from L. Aho-Mantila et al., NF 52 (2012) 103007).
We focus on the global scale – and want to obtain a concise picture on the related physics

Master table of experiments carried out at JET…

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Injection source</th>
<th>Type of discharges</th>
<th>Plasma gas</th>
<th>Density ($\times 10^{19}$ cm$^{-3}$)</th>
<th>Wall material</th>
<th>Injected gas (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET 2001</td>
<td>Top</td>
<td>Ohmic LSN</td>
<td>D</td>
<td>7.5</td>
<td>CFC</td>
<td>2.8</td>
</tr>
<tr>
<td>JET 2004</td>
<td>Outer divertor</td>
<td>H-mode LSN</td>
<td>D</td>
<td>7.8</td>
<td>CFC</td>
<td>9.3</td>
</tr>
<tr>
<td>JET 2007</td>
<td>Outer midplane</td>
<td>H-mode LSN</td>
<td>D</td>
<td>10.8</td>
<td>CFC</td>
<td>2.0</td>
</tr>
<tr>
<td>JET 2009</td>
<td>Outer divertor</td>
<td>H-mode LSN</td>
<td>D</td>
<td>14.8</td>
<td>CFC</td>
<td>7.1</td>
</tr>
</tbody>
</table>

See
- J. D. Strachan et al., Nucl. Fusion **48** (2008) 105002

In all the experiments, $^{13}$CH$_4$ injected before opening the vessel
We focus on the global scale – and want to obtain a concise picture on the related physics

... and at AUG

<table>
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<tr>
<th>Experiment</th>
<th>Injection source</th>
<th>Type of discharges</th>
<th>Plasma gas</th>
<th>Density ($\times10^{19}$ cm$^{-3}$)</th>
<th>Wall material</th>
<th>Injected gas (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG 2003</td>
<td>Outer midplane</td>
<td>H-mode LSN</td>
<td>H</td>
<td>8.5</td>
<td>C/W</td>
<td>0.69</td>
</tr>
<tr>
<td>AUG 2004</td>
<td>Outer midplane</td>
<td>H-mode USN</td>
<td>H</td>
<td>9.0</td>
<td>C/W</td>
<td>0.045</td>
</tr>
<tr>
<td>AUG 2005</td>
<td>Outer midplane</td>
<td>L-mode LSN</td>
<td>H</td>
<td>6.0</td>
<td>C/W</td>
<td>1.1</td>
</tr>
<tr>
<td>AUG 2007</td>
<td>Outer midplane</td>
<td>L-mode LSN</td>
<td>D</td>
<td>3.3</td>
<td>W</td>
<td>0.58</td>
</tr>
<tr>
<td>AUG 2011</td>
<td>Outer midplane</td>
<td>L-mode DN</td>
<td>H</td>
<td>5.8</td>
<td>W</td>
<td>1.0 ($^{13}$C) + 1.1 ($^{15}$N)</td>
</tr>
</tbody>
</table>

See

$^{13}$CH$_4$ experiments except in 2011 when also $^{15}$N$_2$ was injected
Codes used in modelling the experiments

Step #1: produce the background plasma

**SOLPS or EDGE2D**
- 2D fluid codes
- iteratively coupled to the kinetic Monte Carlo code Eirene
t   ⇒ motion of neutral particles
+ produce 2D maps for $n_e$, $T_e$, $T_i$, flow velocity, electric potential,…
+ can be run with cross-field drifts ($E \times B$, $\nabla B$,…) (SOLPS)
+ feedback of impurity radiation can be taken into account
+ self-consistent solutions
+ migration of impurities can be treated as a separate fluid (EDGE2D)
- 2D instead of 3D
- ad-hoc radial transport model and simplified interaction model with the wall
- computational grid does not extend all the way to the wall
- difficulties to reproduce observations with divertor detachment as well as the measured poloidal flows
- obtaining a self-consistent solution very time consuming...

Example:
Simulating the AUG 2011 experiment using SOLPS

![Graph](image)
Codes used in modelling the experiments

Step #2: follow the migration of impurities

ERO
- 3D Monte Carlo impurity transport code
- Uses test particle approach, static plasma background from SOLPS, EDGE2D, 1D Onion Skin Model (OSM), …

- very extensive physics models implemented (transport, plasma-wall interaction)
- wide developer community (FZJ, Aalto/VTT, DIFFER, SCK-CEN, CEA), coordinated by FZJ
- applicable to all kinds of devices

- validation of models difficult in complex tokamak environments
- spatially limited simulation volumes
- presently poor scalability for parallel computation

Example:
JET 2011 experiment: close to the injection source
Codes used in modelling the experiments

Step #2: follow the migration of impurities

ASCOT
- 3D Monte Carlo code
- Follows the orbits or guiding centres of test particles in a static plasma background
- Particle-background interactions calculated using collision operators
  + drifts and features of the magnetic field automatically included
  + no restrictions with the computational grid
  - no re-erosion or temperature gradient force implemented presently
  - can only follow ions: not molecules or neutrals

Example:
AUG 2011 experiment:
predictive modelling
Codes used in modelling the experiments

Step #2: follow the migration of impurities

DIVIMP
• Monte Carlo code, typically used in 2D
• Similarly to ASCOT, follows the trajectories of impurity particles in a static plasma background
• Combines classical physics in the parallel direction with anomalous cross-field transport
  + all the necessary forces implemented, including temperature-gradient force
  + re-erosion and re-deposition can be included in the calculations
  – usually toroidal symmetry is assumed
  – computational grid difficult to extend to the walls

Example:
AUG 2007 experiment: best match with experiments and DIVIMP simulations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Exp.</th>
<th>DIVIMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner divertor</td>
<td>28%</td>
<td>31%</td>
</tr>
<tr>
<td>Outer divertor</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Private plasma region</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>Limiters</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>Inner heat shield</td>
<td>21%</td>
<td>27%</td>
</tr>
<tr>
<td>Top of the vessel</td>
<td>34%</td>
<td>23%</td>
</tr>
</tbody>
</table>
What did we learn?

• The resulting deposition patterns are generally asymmetric ⇒ 3D treatment!

• Surface densities **100-1000 times higher next to the injection source** than further (> 10 cm) away, toroidally or poloidally

• Particles migrate **towards the inboard side** of the vessel ⇒ strong flows in the SOL!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>JET 2009</th>
<th>AUG 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner divertor</td>
<td>1.6</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Outer divertor</td>
<td>&gt;4</td>
<td>0.4</td>
</tr>
<tr>
<td>Top</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Inner wall</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Main chamber</td>
<td>0.4</td>
<td>15</td>
</tr>
<tr>
<td>Close to the source</td>
<td>&gt;9</td>
<td>&gt;15</td>
</tr>
</tbody>
</table>
What did we learn?

- Observed amounts of impurities:
  - plasma-facing surfaces (JET): 15-50%
  - plasma-facing surfaces (AUG): 5-30%
  - tile gaps and remote areas: <30%
  - cryopumps (JET): ~30%

NB! Toroidal symmetry assumed

- Deposition 10-100 weaker on W than on C – but thick co-deposited layers (>100 nm) make the profiles coincide ⇒ strong substrate effect!

- $^{15}$N and $^{13}$C show qualitatively and quantitatively different deposition profiles: $^{15}$N profile more uniform, surface densities smaller in the main chamber but larger at the divertor
Summary

We have collected a very comprehensive database on material migration in 2001–2011 using smart tiles, marker probes and tracer injection in JET and ASDEX Upgrade

• Experimental highlights:
  - A common pattern is identified across tokamaks: plasma flow drives impurities from the outer towards inner divertor
  - Migration is very sensitive to certain parameters (e.g. surface material C/W)
  - Strong local variations of the deposition underline the need for serious 3D modelling

• Extensive numerical modelling with several complementary simulation codes:
  - Successful validation of local migration models to experiments
  - Demonstrated multi-scale modelling of local details and global migration
  - Significantly broadened scope of in-house developed and imported codes

Next two presentations will bring you deeper into the world of this modelling