Overview of Fuel Inventory in JET with the ITER-Like Wall

Anna Widdowson
• JET ITER-like wall (JET-ILW) operates with ITER relevant plasma facing components (PFCs)
  • Beryllium (Be) in the main chamber
  • Tungsten (W) in the divertor
• ITER relevant samples for post mortem analysis
  • Long term fuel retention assessment
  • Material migration studies
  • Detritiation studies
• No active cooling and use of W coatings on some PFCs
## JET-ILW campaign parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Limiter phase</td>
<td>6 hours</td>
<td>6 hours</td>
</tr>
<tr>
<td>Divertor phase</td>
<td>13 hours</td>
<td>14 hours</td>
</tr>
<tr>
<td>Hydrogen (H) campaign</td>
<td>None</td>
<td>0.6 hours</td>
</tr>
<tr>
<td>Inner strike point</td>
<td>Predominantly Tile 3</td>
<td>Predominantly Tile 4</td>
</tr>
<tr>
<td>Outer strike point</td>
<td>Predominantly Tile 5</td>
<td>Predominantly Tile 6</td>
</tr>
</tbody>
</table>

### Strike point distribution

#### ILW-1 Tiles 3 & 5

![ILW-1 Tiles 3 & 5](image)

#### ILW-2 Tiles 4 & 6

![ILW-2 Tiles 4 & 6](image)
Post mortem analysis

Post mortem analysis of samples removed from JET-ILW enable the study of long-term fuel/deuterium (D) retention and material migration

- Poloidal set of main chamber tiles (    )
- Poloidal set of divertor tiles (    )
- Analysis of individual tiles show local fuel retention of material migration
- Extrapolation from individual tile analysis is used to assess global long term fuel retention in JET
Bulk Be PFCs
Bulk W
Be-coated inconel PFCs
W-coated CFC PFCs

25 µm tungsten (W) coating on carbon-fibre composite (CFC) tile

Bulk beryllium (Be)
Castellated structure

Bulk tungsten (W)
Lamellae structure
### Analysis methods

<table>
<thead>
<tr>
<th>Fuel retention study</th>
<th>Erosion deposition study</th>
<th>Analysis depth (µm)</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Be, C</td>
<td>10</td>
<td>Nuclear Reaction Analysis (NRA)</td>
</tr>
<tr>
<td>D</td>
<td>Be, W, Mo….</td>
<td>50</td>
<td>Secondary ion mass spectrometry (SIMS)</td>
</tr>
<tr>
<td>HD, D₂, DT, T₂</td>
<td>Be…</td>
<td>bulk</td>
<td>Thermal desorption spectroscopy (TDS)</td>
</tr>
<tr>
<td>D</td>
<td>Be and heavier</td>
<td>10</td>
<td>Rutherford/Elastic backscattering spectroscopy (RBS/EBS)</td>
</tr>
<tr>
<td>D</td>
<td>O, C, N</td>
<td>10</td>
<td>Elastic recoil detection analysis (ERDA)</td>
</tr>
</tbody>
</table>

- Large international effort - EUROfusion Work Programme & EU-Japan Broader Approach
- Thousands of measured and analysed points, covering a fraction of 100 m² JET chamber area.
- Results provide direct measurement of material erosion, deposition and fuel retention.
- Examples illustrate key fuel retention and material migration results for JET-ILW.
JET-ILW: terminology

S-coordinate:
Distance along divertor surface in millimeters

Divertor tile numbering HFGC(0), 1, 3, 4, 5, 6, 7, 8, B, C

ILW-1: Tiles exposed during the first ITER-Like Wall Campaign 2011-12

ILW-2: Tiles exposed during the second ILW campaign 2013-14

ILW-1&2: Tiles exposed during both ILW campaigns
Mechanisms of long-term fuel retention

Long-term fuel retention by:
Implantation in Be (or W) and Co-deposition with Be (or W)

1. D-Implantation, Diffusion, Trapping
2. Be, D
3. Codeposition

Co-deposition dominates fuel retention

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Deposition at upper inner divertor

- Deposition after ILW-1 & 2 2011-2014 (2 campaigns)
- Plasma shadowed regions & deposition regions clearly visible
Deposition at upper inner divertor

- Rough surface
- Deposition layer well adhered
- No flaking deposits or mobile dust
- Reduced dust/flake production

- After ILW-1&2 approx. 40 µm Be-rich deposit formed at upper inner divertor.

⇒ These are the only thick deposits found in JET-ILW.
- Be remains where it is first deposited.

⇒ No multistep erosion-redeposition material migration for Be
Effect of H campaign on D retention

- **ILW-2 ended with hydrogen (H) pulses.**
- **Surface effect (~2 µm):** Increased H and depletion of D from surface of deposits due to *isotopic exchange in H campaign.*
  - Fuel concentration in thick deposits is similar for ILW-1 and ILW-2.
  - Fuel retention from surfaces with thin or no deposits is reduced.
  - Global fuel retention reduced by ending in H.

**SIMS depth profile of deposit exposed to H (Tile 0 HFGC ILW-1&2)**
Outer divertor corner

Comparison of tiles from ILW-1 and ILW-2

- 2-3 µm layered deposit after two campaigns
- Layers probably related to varying campaign parameters

Cross sections from tile exposed ILW-1 & 2
• Material transport to outer divertor influenced by Outer Strike Point (OSP) location
• Localised band of Be deposition just beyond OSP for ILW-2
• Long range material migration to outer corner is low
D distribution on divertor surfaces


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D distribution on divertor surfaces

Highest D concentration at the upper inner divertor

D & Be distribution on divertor surfaces


ILW-1 2011-12

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Thickest deposits are at the upper inner divertor.
Fuel retention in the divertor is dominated by co-deposition.
D & Be distribution on divertor surfaces

- Impurities influence fuel retention
- Lowest relative impurity concentration at upper inner divertor
- Provides most ITER relevant deposit (<15% C) for fuel release studies


Heinola Ex/P6-2

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JET-ILW: Bulk Tungsten Tile

Diagram with labeled components and numerical values.
• Deuterium concentration decreases from stack A to C
  - Inversely proportion to temperature
• Fuel retention in bulk tungsten surface is factor 100 lower than in co-deposits
  - <1% of global fuel retention
• Be locally deposited on stack D associated with outer strike point location
Fuel retention in Be castellation gaps

- Gap width 0.4 mm
- Deposition and fuel retention in within first 1 mm of tile surface
- 7 km of castellations in JET Be tiles
  - 3% of global fuel retention
- Fuel inventory increases with gap width
  \[ \Rightarrow \text{KEEP GAPS NARROW TO REDUCE INVENTORY} \]

Rubel Ex/P6-1

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Total fuel inventory $38.8 \times 10^{22}$ D atoms

- Fuel retention in JET-ILW is 0.3% of injected D
- Fuel retention rate reduced by factor $>18$ compared with carbon wall
- 65% of global deuterium retention in divertor region
- ILW-2 (2013-14) assessment ongoing

Heinola et al., Phys. Scr. 2016 T167 014075, Rubel Ex/P6-1
Material migration and fuel retention

- Sputtering of Be from recessed wall by low energy ions and charge exchange neutrals
- Transport of eroded Be in scrape off layer mainly to inner divertor

**JET-ILW vs JET CARBON WALL**

- Lower erosion in main chamber resulting in lower migration of material to the divertor
- Reduced chemical erosion of Be by D fuel
  - Reduced long range material migration to surfaces remote from the plasma
Deposition on Plasma Facing Materials

- WallDYN code is used to predict material migration and deposition in ITER.
- WallDyn reproduces deposition pattern at upper inner divertor.

*Schmid Nucl. Fusion 55 2015*

Retention is gaps potentially low

- Keep gaps narrow

*Rubel Ex/P6-1*

Retention in bulk tungsten is low compared with co-deposits
Summary

- *Post mortem* analysis programme of JET-ILW plasma facing components continues to provide an insight into the long term fuel retention and material migration patterns.
- JET-ITER like wall demonstrates reduced fuel retention due to reduced overall deposition compared with an all carbon wall.
  - Optimistic results for ITER on retention in bulk tungsten surfaces and narrow gaps.
- Future analysis programme:
  - Deposition build up, fuel retention and fuel release in key areas for JET operations up to 2016.
Thank you

Related IAEA FEC contributions
• Ashikawa, P6-19
• Grzonka/Fortuna-Zalesna, P6-20
• Heinola, P6-2
• Rubel, P6-1

Other references
• Arnoux, Phys. Scripta T159 014009 (2014)
• Heinola, Phys. Scr. T167 (2016) 014075
• Heinola, Phys. Scr. T159 (2014) 014013
Dust collection by vacuuming from JET tile surfaces

• <2g dust collected after ILW-1 and ILW-2
  • Significantly less than collected from the JET carbon wall (~200 g)
  • Fuel inventory in dust insignificant

Ashikawa P6-19, Grzonka/Fortuna-Zalesna P6-20
Be deposition at upper inner divertor

**NRA/EBS analysis**

- Distribution of deposit at inner divertor influenced by inner strike point location.
- Scrape off layer (SOL) extends further down Tile 1 in ILW-2.
- Deposition extends further down Tile 1 surface after ILW-2 compared with ILW-1.
Fuel inventory on limiter tiles associated with limiter plasma operations

- Fuel retention is mainly by co-deposition at ends of tiles
- Very low D content in areas of high thermal loads
- ITER limiter plasma time will be short compared with divertor plasma time, therefore main chamber co-deposition and fuel retention reduced
• Erosion at inner limiter during limiter phase
• Fuel retention dominated by local co-deposition of eroded material at ends of limiter tiles
Effect of impurities and temperature on fuel retention

PISCES

JET-ILW

S. Brezinsek NF2013

BeC

BeO+C

WC

[\( T/X \)]

PISCES

JET

FW

t

tile 0/1 tile 6

Be

W

tile 0

tile 1

tile 3

tile 4

tile 6

tile 7

tile 8

JET

T \(_{FW} \) JET

D (TDS) T (TDS) \( \times 10^3 \)

Be (4.5 MeV) C (4.5 MeV)

Be (2.3 MeV) C (2.3 MeV)

O (ERDA) C (ERDA)

concentration (at./cm\(^2\))

divertor S coordinates (mm)

concentration (at./cm\(^2\))

concentration (at./cm\(^2\))

concentration (at./cm\(^2\))

concentration (at./cm\(^2\))

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concentration (at./cm\(^2\))
Deposition at upper inner divertor

SIMS depth profile in deposit on HFGC ILW-1&2 2011-14

• SIMS data provides thickness data
• Deuterium (D) penetrates to porous tungsten coating
• Quantification of D in coating ongoing
⇒ Specific to JET-ILW tungsten coated CFC tiles
Global retention summary

<table>
<thead>
<tr>
<th>Divertor Tungsten</th>
<th>Inventory (10^{22} D atoms)</th>
<th>Main chamber Beryllium</th>
<th>Inventory (10^{22} D atoms)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Plasma facing surfaces</td>
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<td></td>
</tr>
<tr>
<td>Inner divertor*</td>
<td>17</td>
<td>Inner limiters*</td>
<td>1.4</td>
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<tr>
<td>Outer divertor*</td>
<td>3.9</td>
<td>Outer limiters*</td>
<td>5.2</td>
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<td>Bulk tungsten†</td>
<td>0.3</td>
<td>Dump plate*</td>
<td>2.1</td>
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<td></td>
<td>Recessed/remote surfaces and gaps</td>
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<tr>
<td>Inner corner*</td>
<td>2.0</td>
<td>Inner wall*</td>
<td>2.8</td>
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<tr>
<td>Outer corner*</td>
<td>2.2</td>
<td>Outer wall*</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Castellation gaps‡</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Heinola et al., Phys. Scr. 2016 T167 014075, ‡ Rubel, P6-1, † this presentation