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

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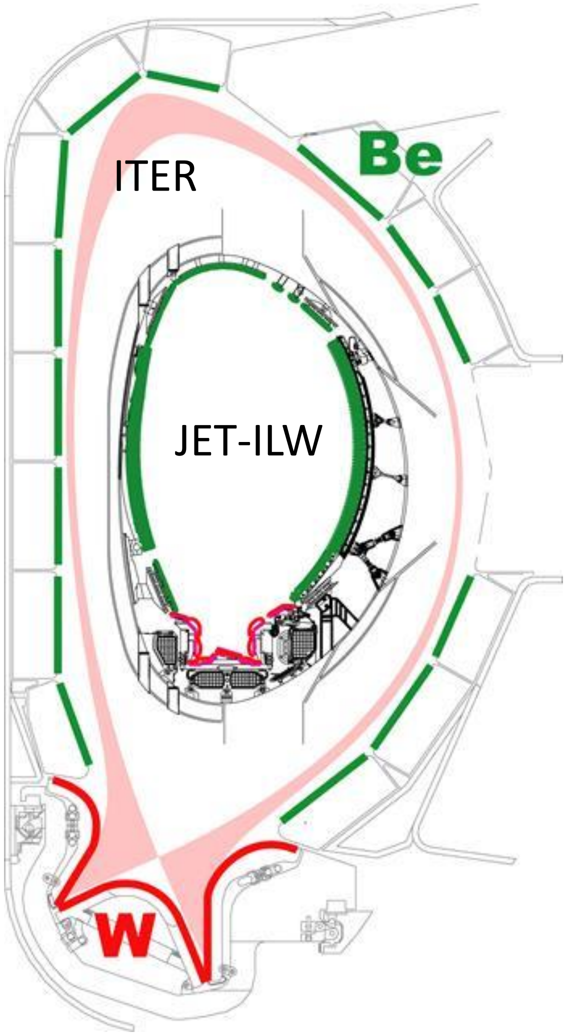
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

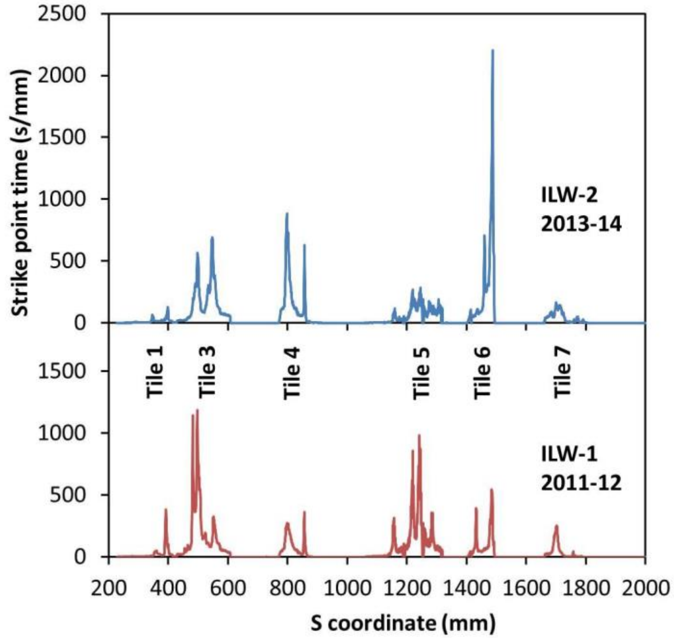


- JET ITER-like wall (JET-ILW) operates with ITER relevant plasma facing components (PFCs)
  - Beryllium (Be) in the main chamber
  - Tungsten (W) in the divertor
- ITER relevant samples for *post mortem* analysis
  - Long term fuel retention assessment
  - Material migration studies
  - Detritiation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

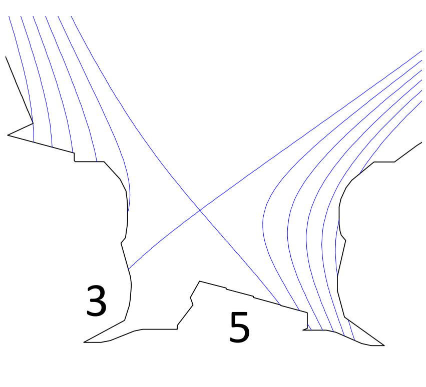
JET-ILW campaign parameters

	ILW-1: 2011-2012	ILW-2: 2013-2014
Limiter phase	6 hours	6 hours
Divertor phase	13 hours	14 hours
Hydrogen (H) campaign	None	0.6 hours
Inner strike point	Predominantly Tile 3	Predominantly Tile 4
Outer strike point	Predominantly Tile 5	Predominantly Tile 6

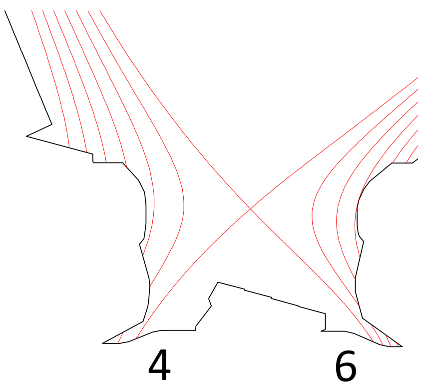
Strike point distribution



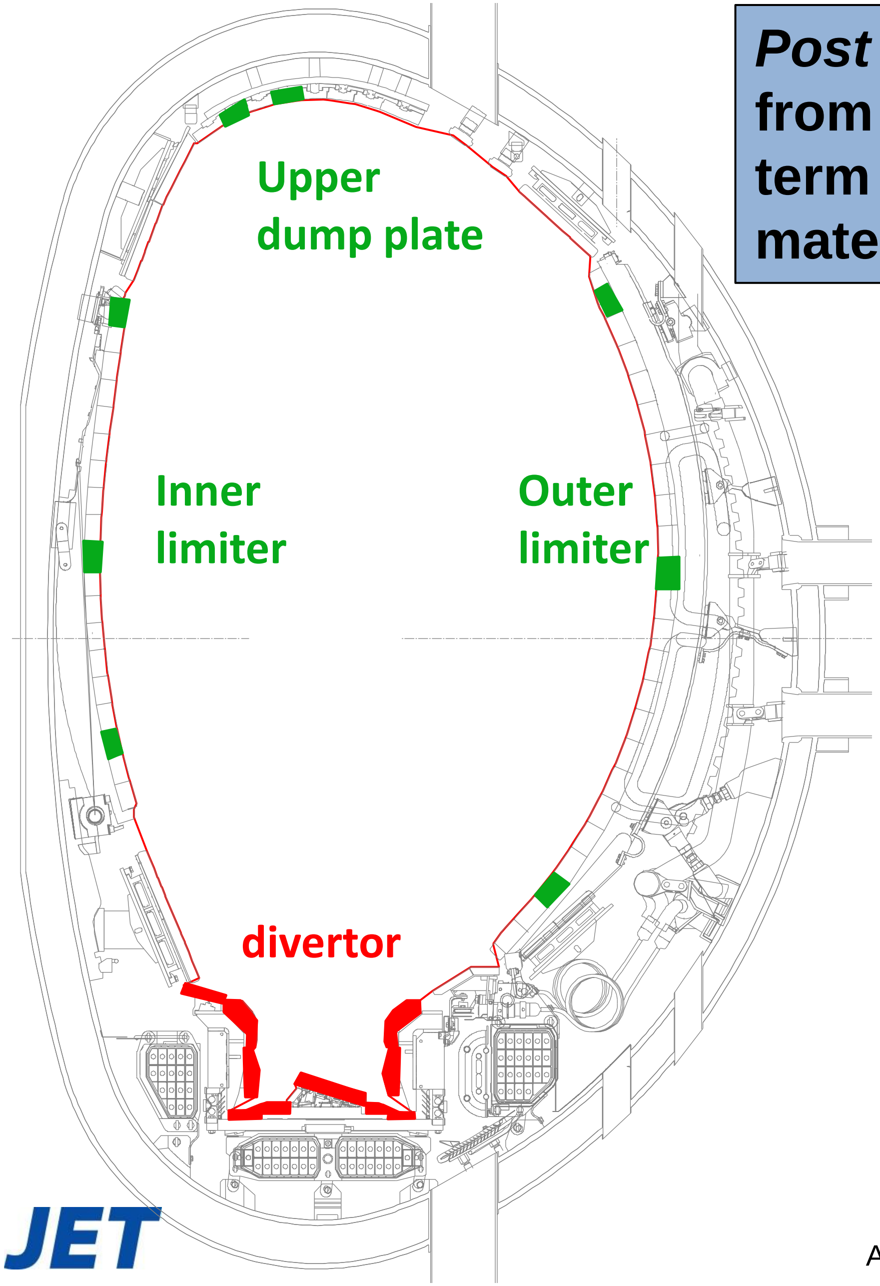
ILW-1 Tiles 3 & 5



ILW-2 Tiles 4 & 6



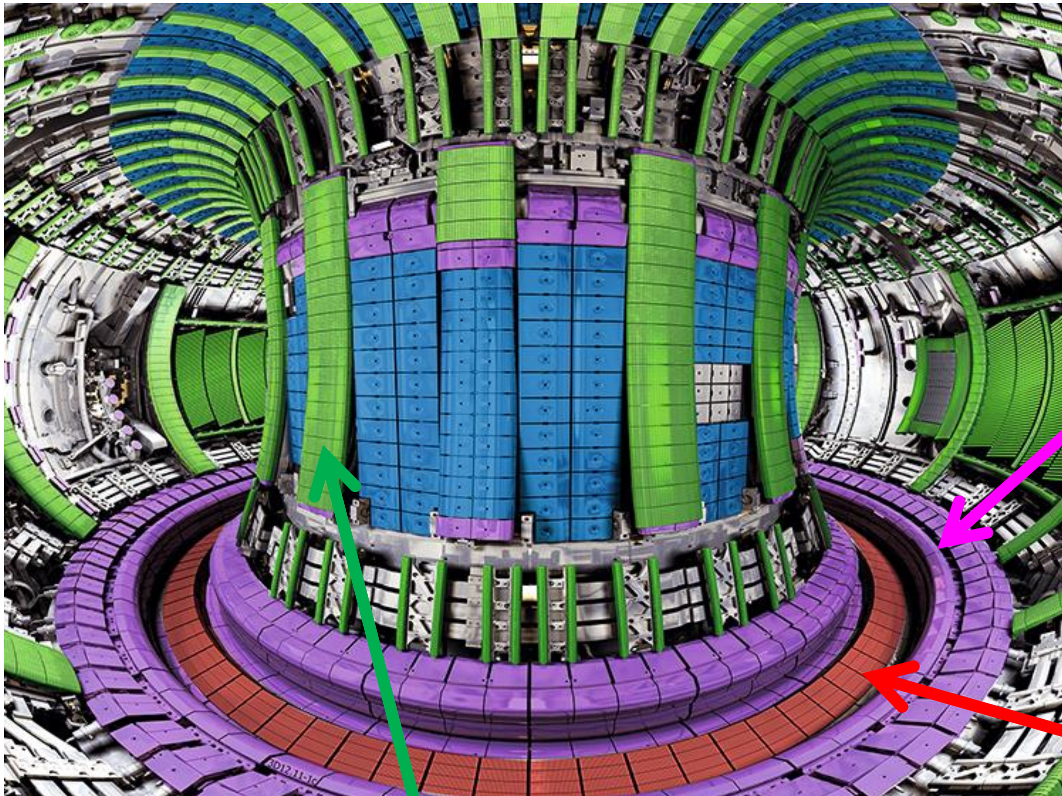
Post mortem analysis



***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 (green)
- Poloidal set of divertor tiles (red)
- 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

JET-ILW Plasma Facing Components (PFCs)

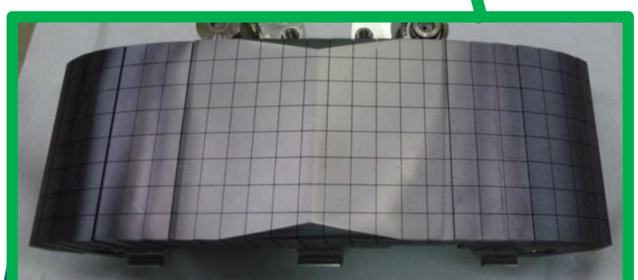


Bulk Be PFCs | Be- coated inconel PFCs
Bulk W | W- coated CFC PFCs

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

Bulk tungsten (W)
Lamellae structure

Bulk beryllium (Be)
Castellated structure



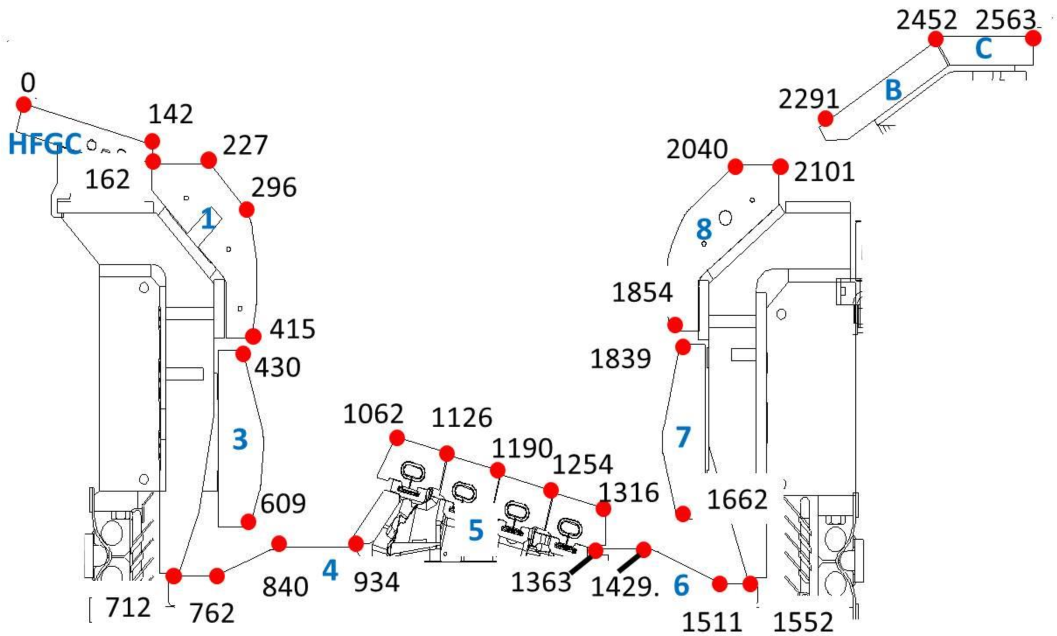
Analysis methods

Fuel retention study	Erosion deposition study	Analysis depth (μm)	Technique
D	Be, C	10	Nuclear Reaction Analysis (NRA)
D	Be, W, Mo….	50	Secondary ion mass spectrometry (SIMS)
HD, D_2, DT, T_2,	Be…	bulk	Thermal desorption spectroscopy (TDS)
D	Be and heavier	10	Rutherford/Elastic backscattering spectroscopy (RBS/EBS)
D	O,C,N	10	Elastic recoil detection analysis (ERDA)

- Large international effort - EUROfusion Work Programme & EU-Japan Broader Approach
- Thousands of measured and analysed points, covering a fraction of 100 m^2 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

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

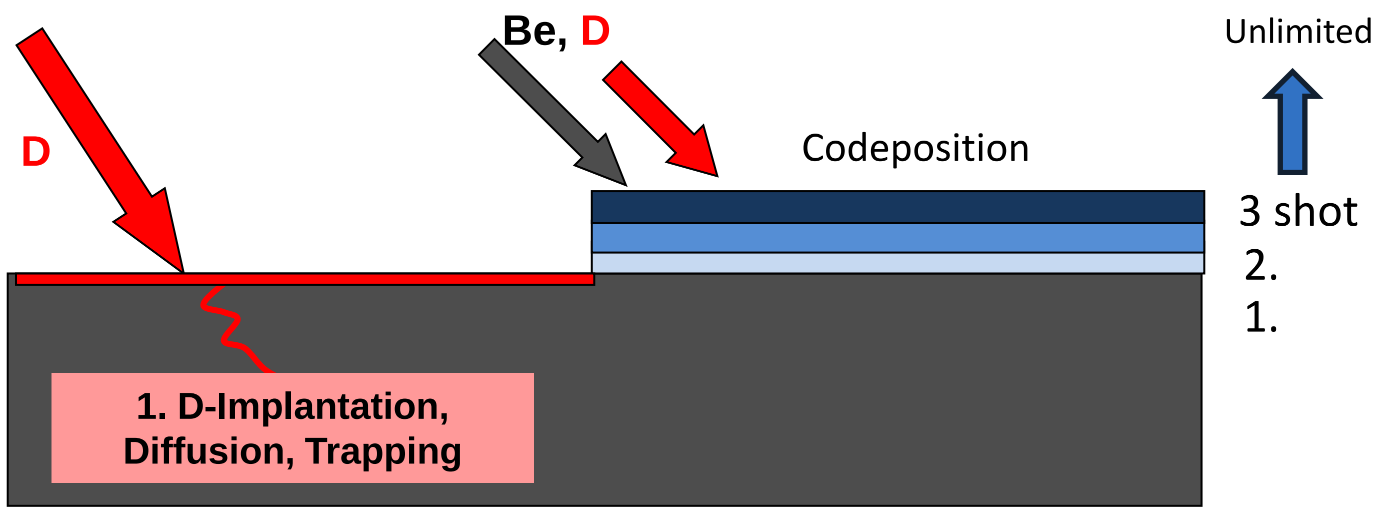
ILW-2: Tiles exposed during the second ILW campaign 2013-14

ILW-1&2: Tiles exposed during both ILW campaigns

Mechanisms of long-term fuel retention

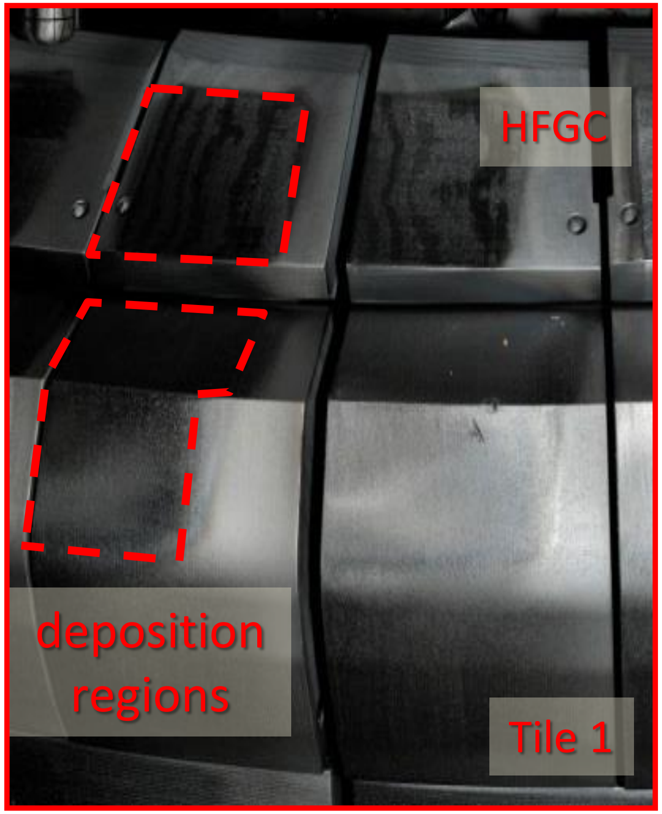
Long-term fuel retention by:

Implantation in Be (or W) and **Co-deposition** with Be (or W)

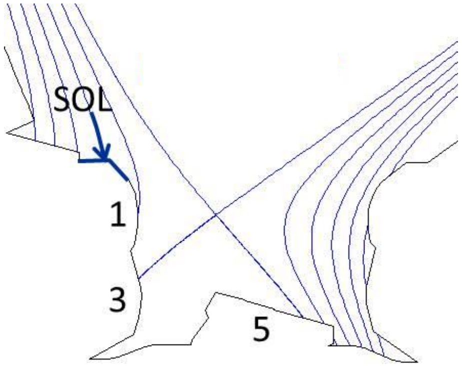


Co-deposition dominates fuel retention

Deposition at upper inner divertor

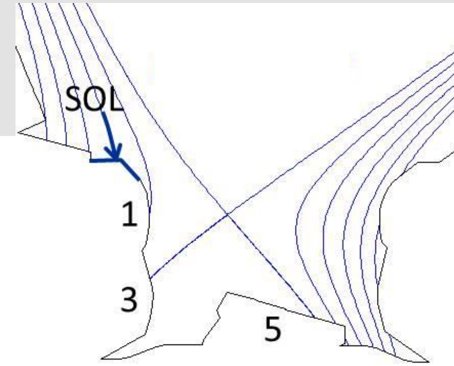


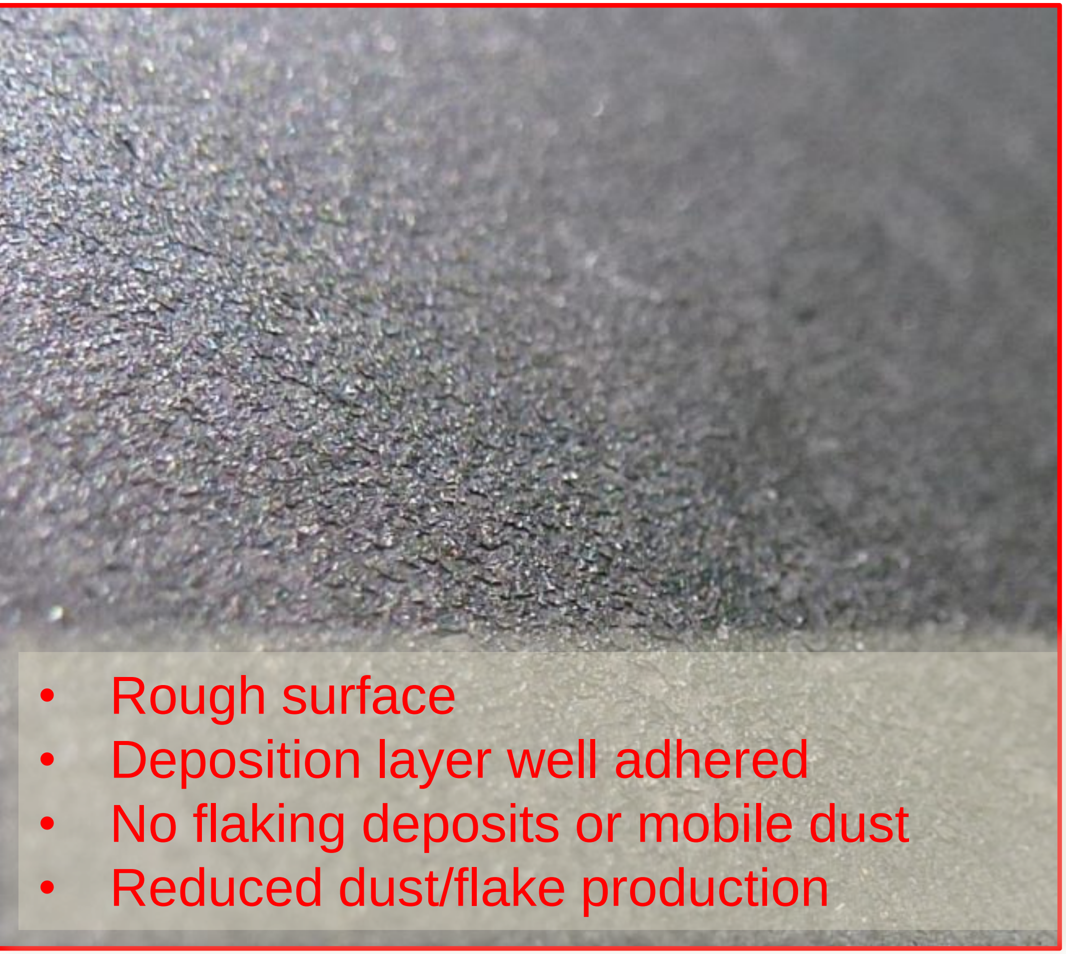
Magnetic field



- 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

Ashikawa Ex/P6-19, Grzonka/Fortuna-Zalesna Ex/P6-20

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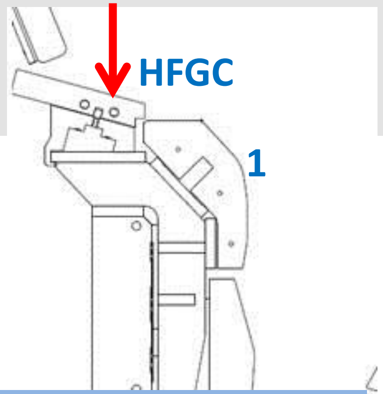
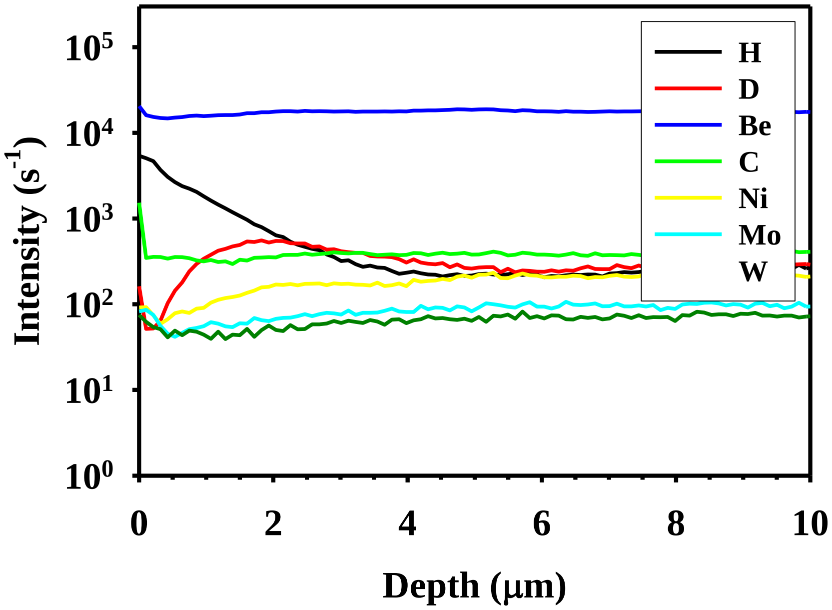
Effect of H campaign on D retention



SIMS depth profile of deposit exposed To H (Tile 0 HFGC ILW-1&2)



- *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.***

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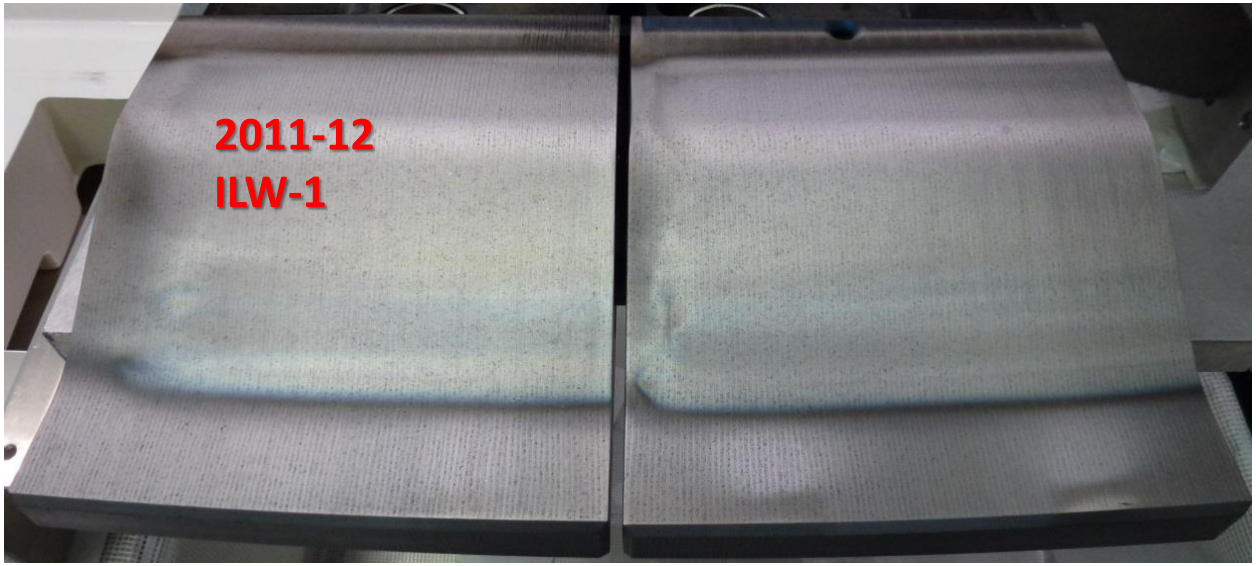
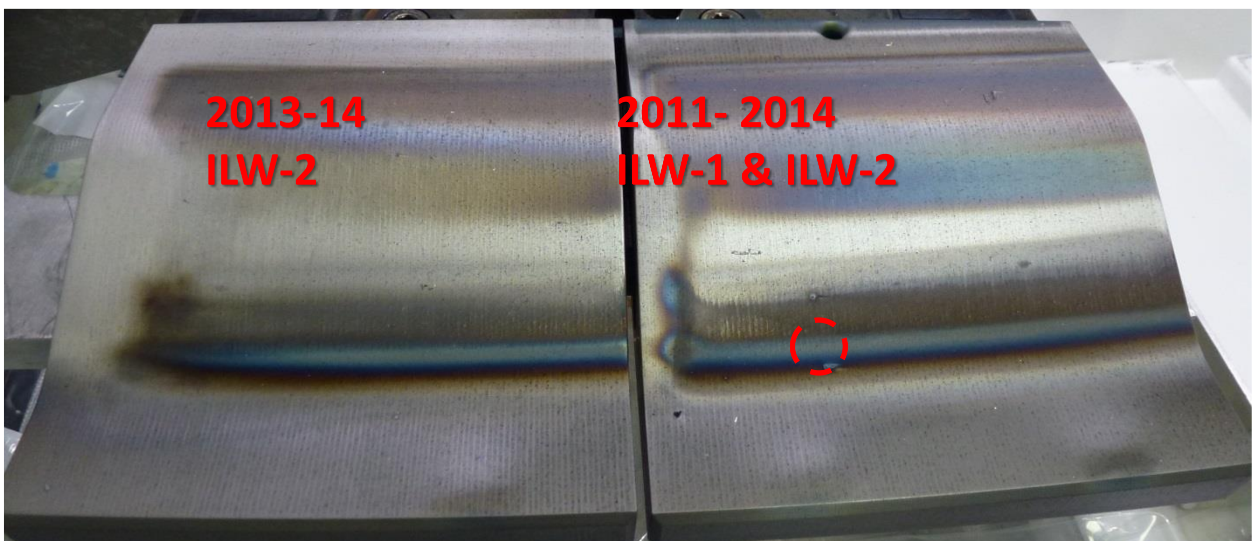
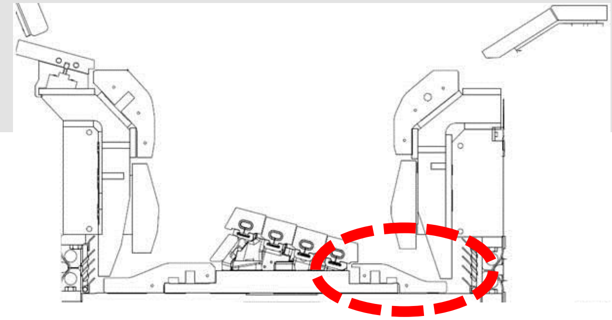
Outer divertor corner

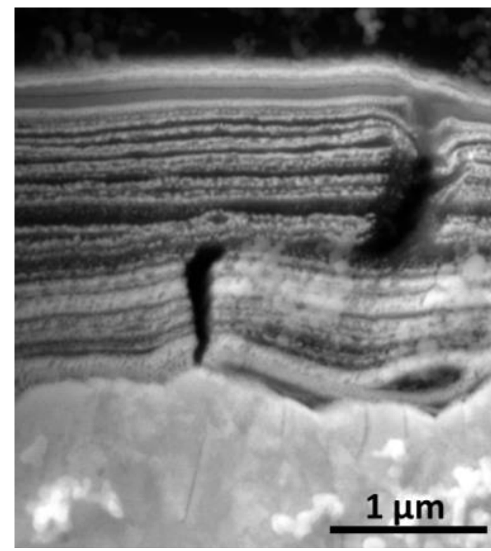
Comparison of tiles from ILW-1 and ILW-2







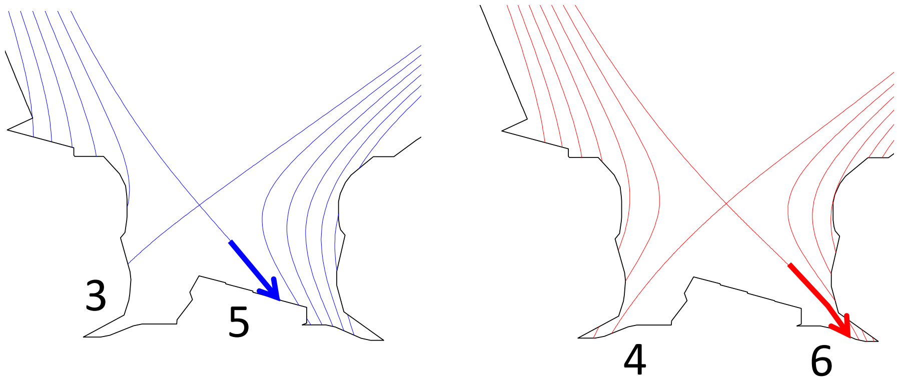
- 2-3 µm layered deposit after two campaigns
- Layers probably related to varying campaign parameters

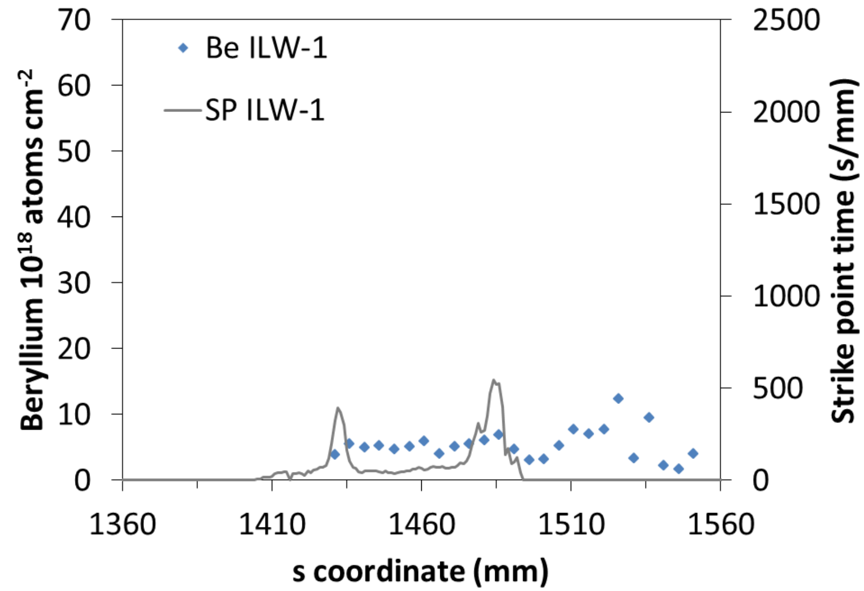


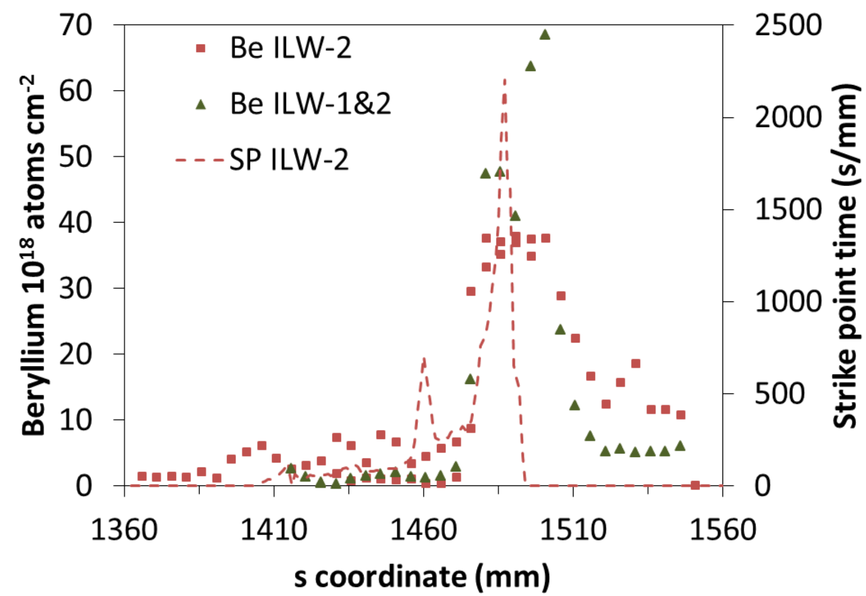
Cross sections from tile exposed ILW-1 & 2

Outer divertor corner

ILW-1 Tiles 3 & 5 *ILW-2 Tiles 4 & 6*





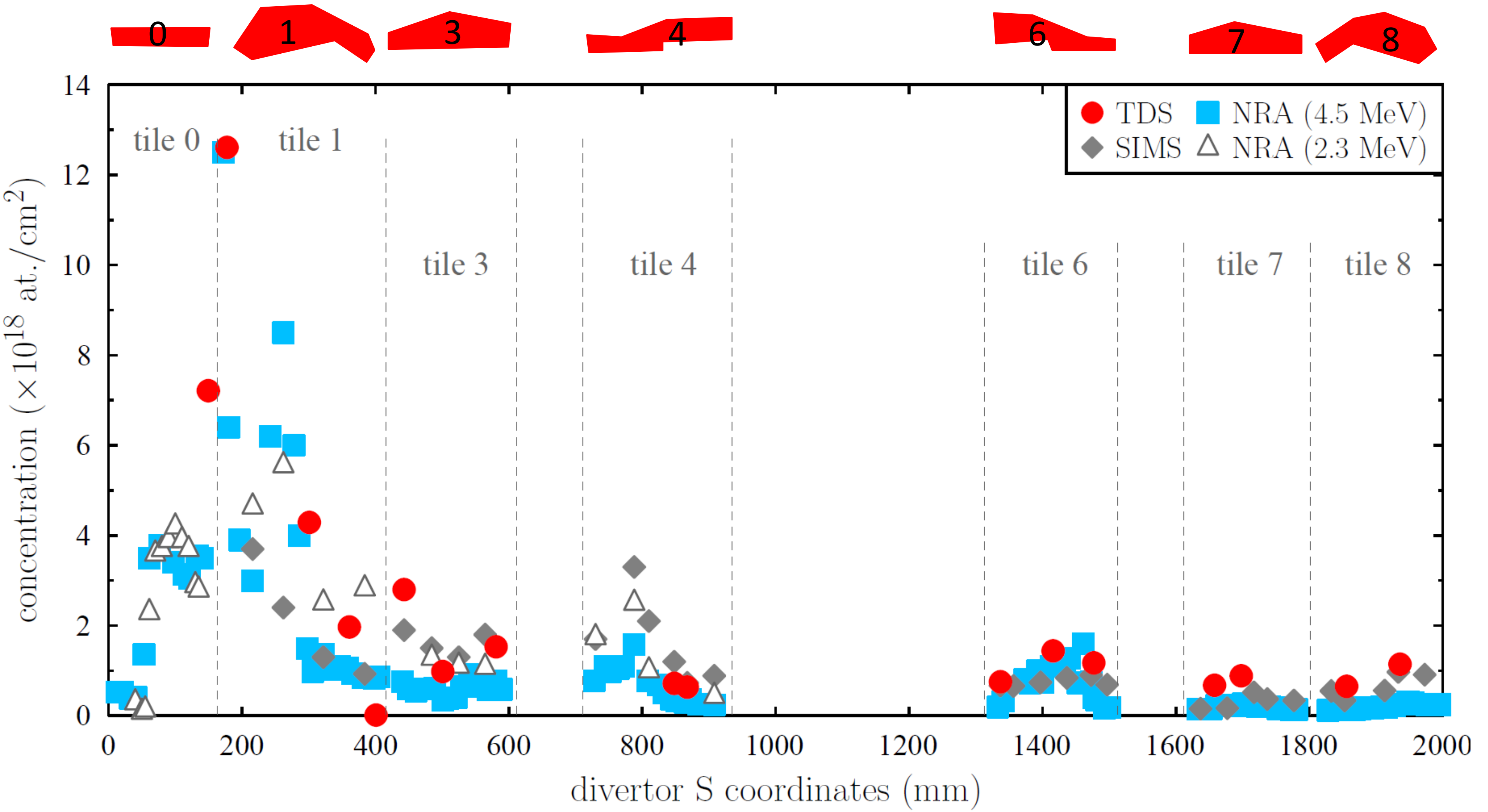


- Material transport to outer divertor influenced by Outer Strike Point (OSP) location
- Localised band of Be deposition just beyond OSP for ILW-2
- Long range material migration to outer corner is low

JET

D distribution on divertor surfaces

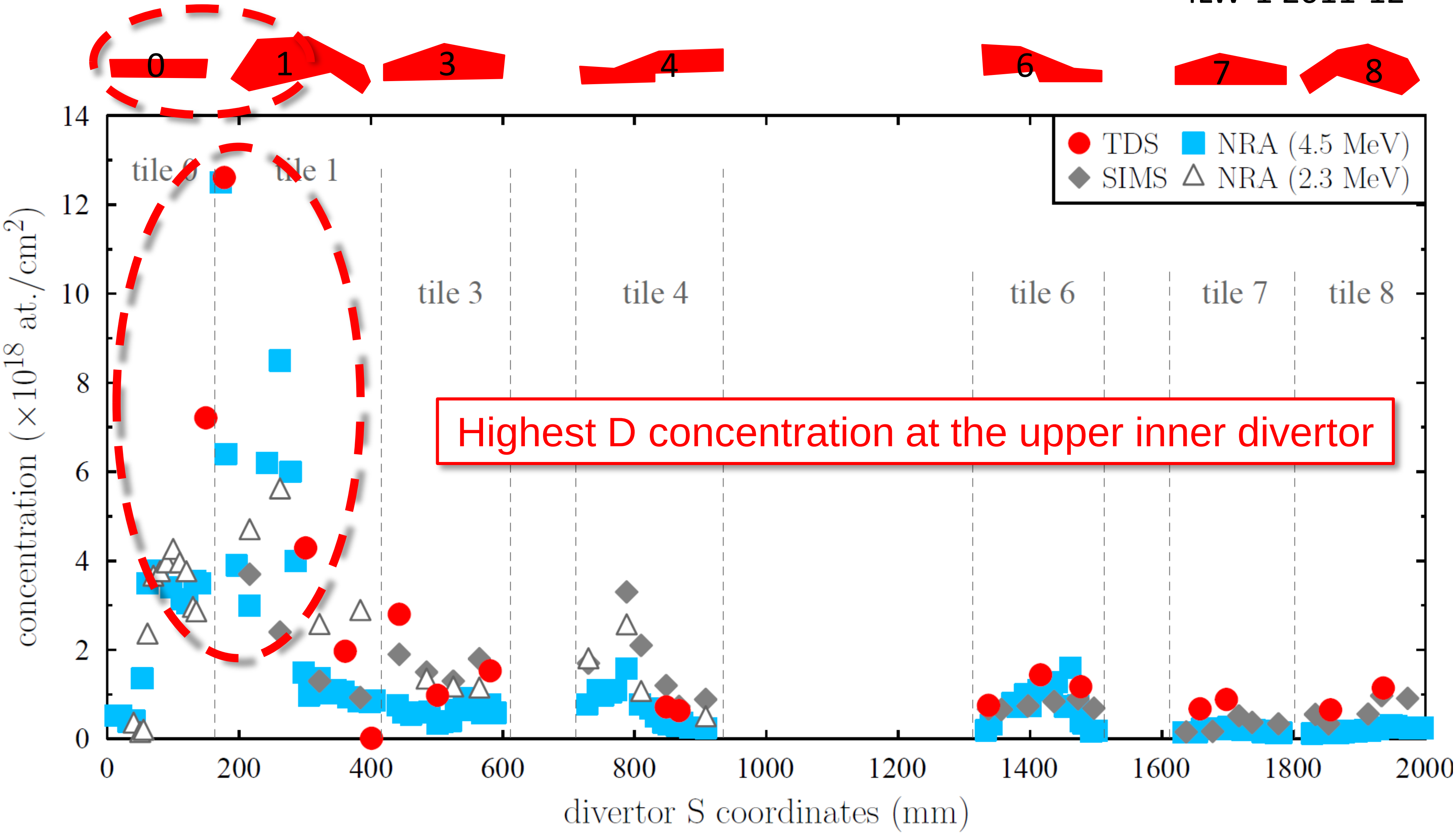
ILW-1 2011-12



Heinola, et al., Phys. Scr. T167 (2016) 014075

D distribution on divertor surfaces

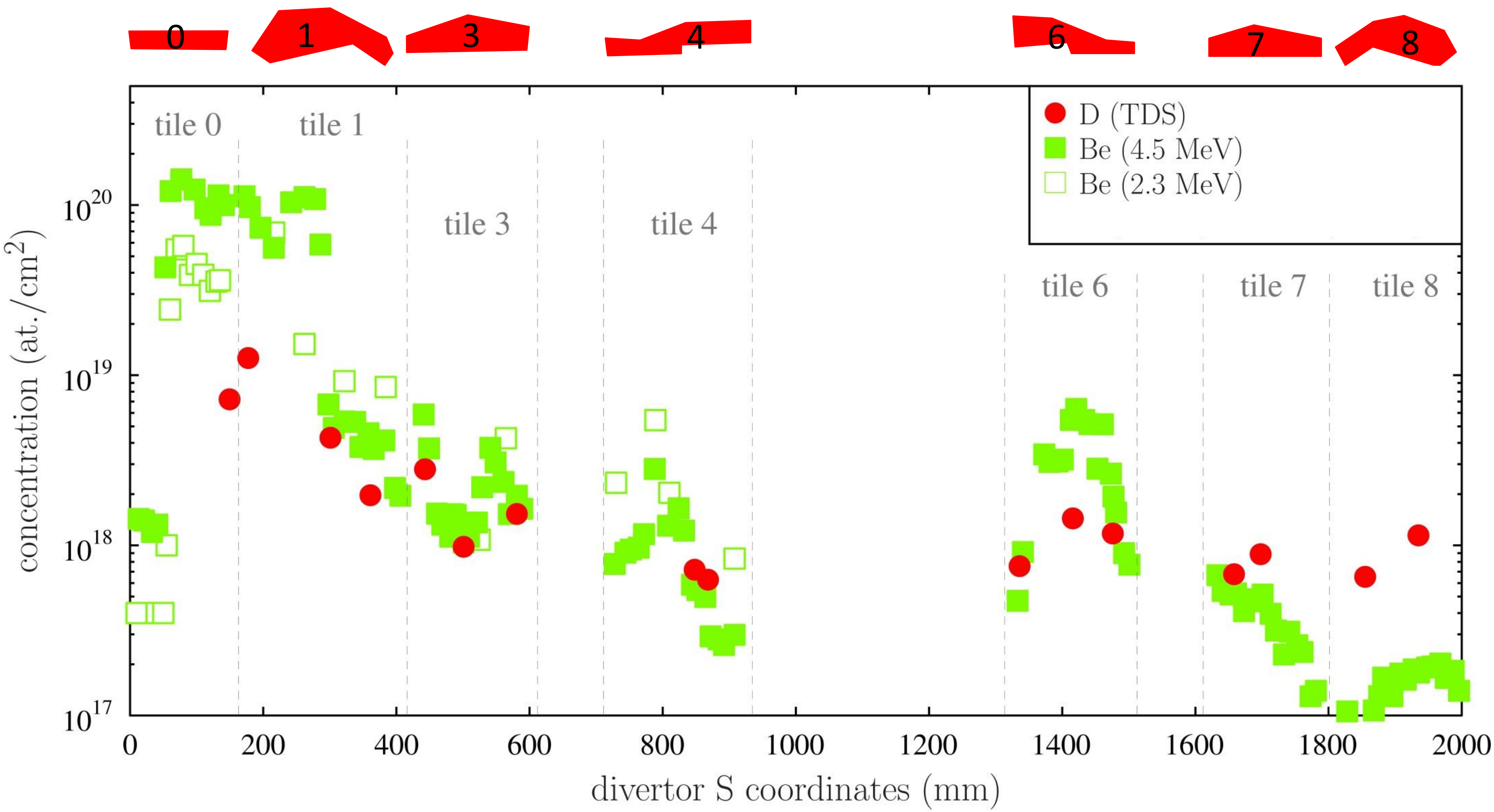
ILW-1 2011-12



Heinola, et al., Phys. Scr. T167 (2016) 014075

D & Be distribution on divertor surfaces

ILW-1 2011-12

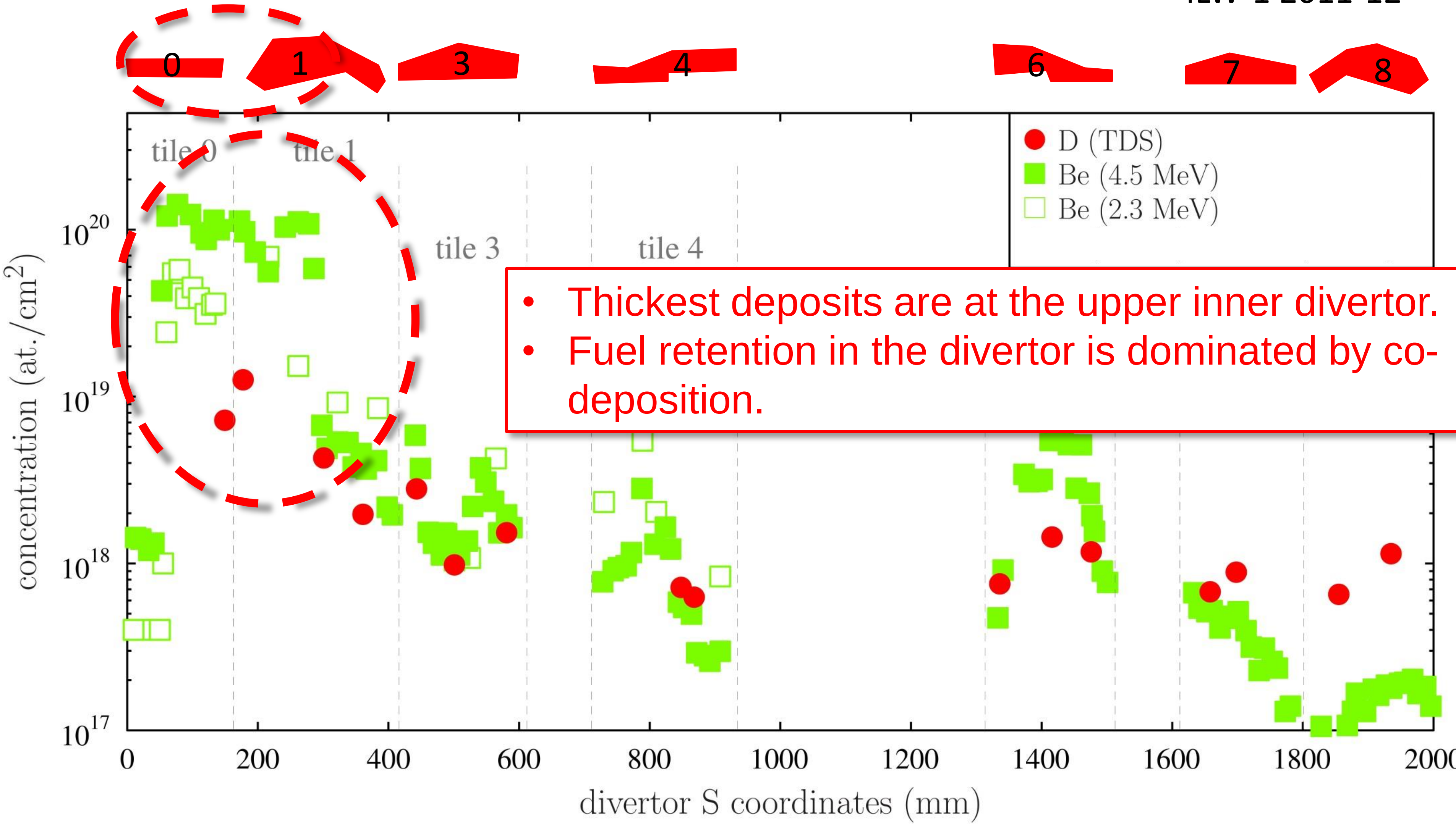


Heinola, et al., Phys. Scr. T167 (2016) 014075

JET

D & Be distribution on divertor surfaces

ILW-1 2011-12



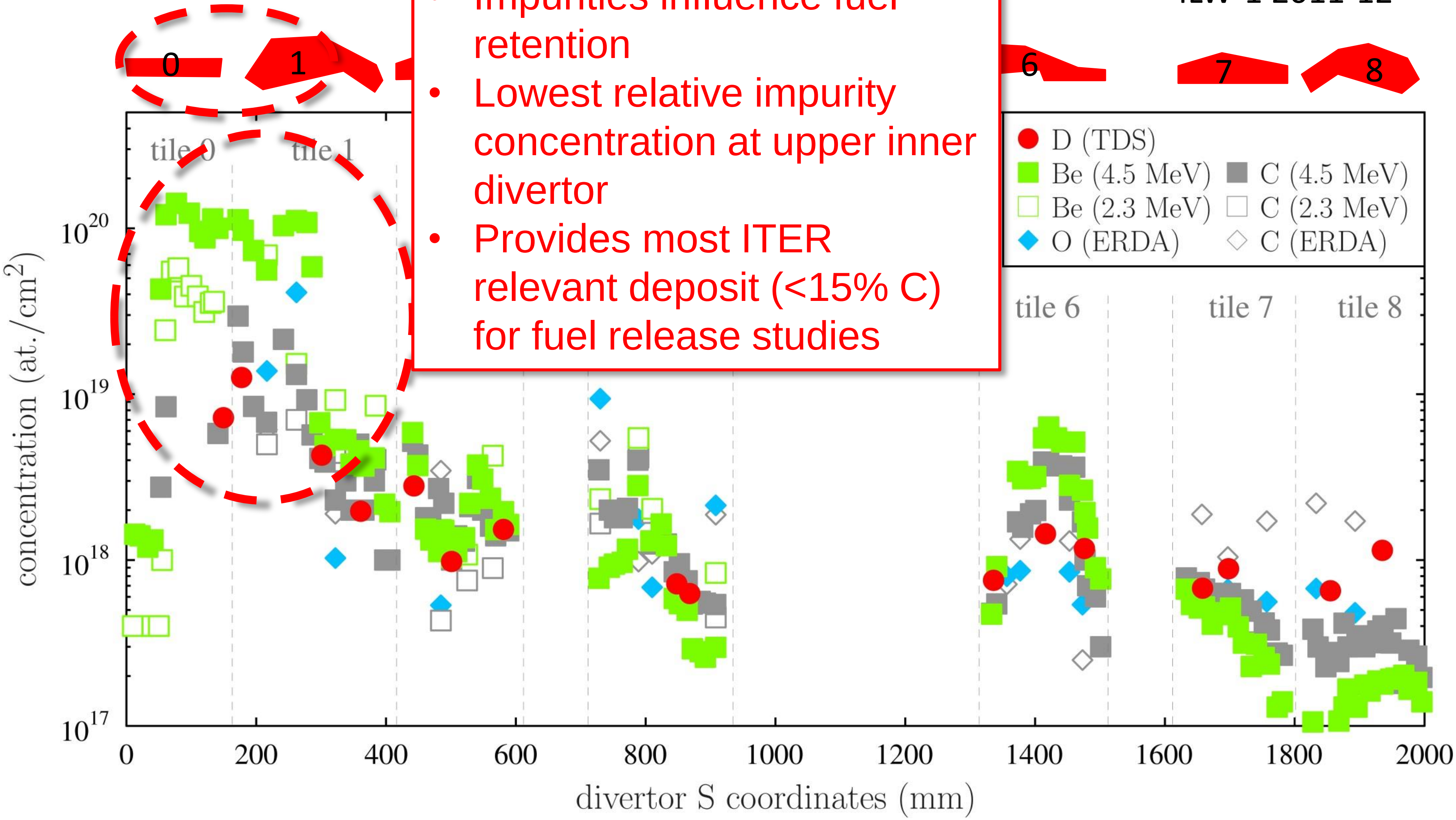
- Thickest deposits are at the upper inner divertor.
- Fuel retention in the divertor is dominated by co-deposition.

Heinola, et al., Phys. Scr. T167 (2016) 014075

D & Be distribution on divertor surfaces

ILW-1 2011-12

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



Heinola, et al., Phys. Scr. T167 (2016) 014075

Heinola Ex/P6-2

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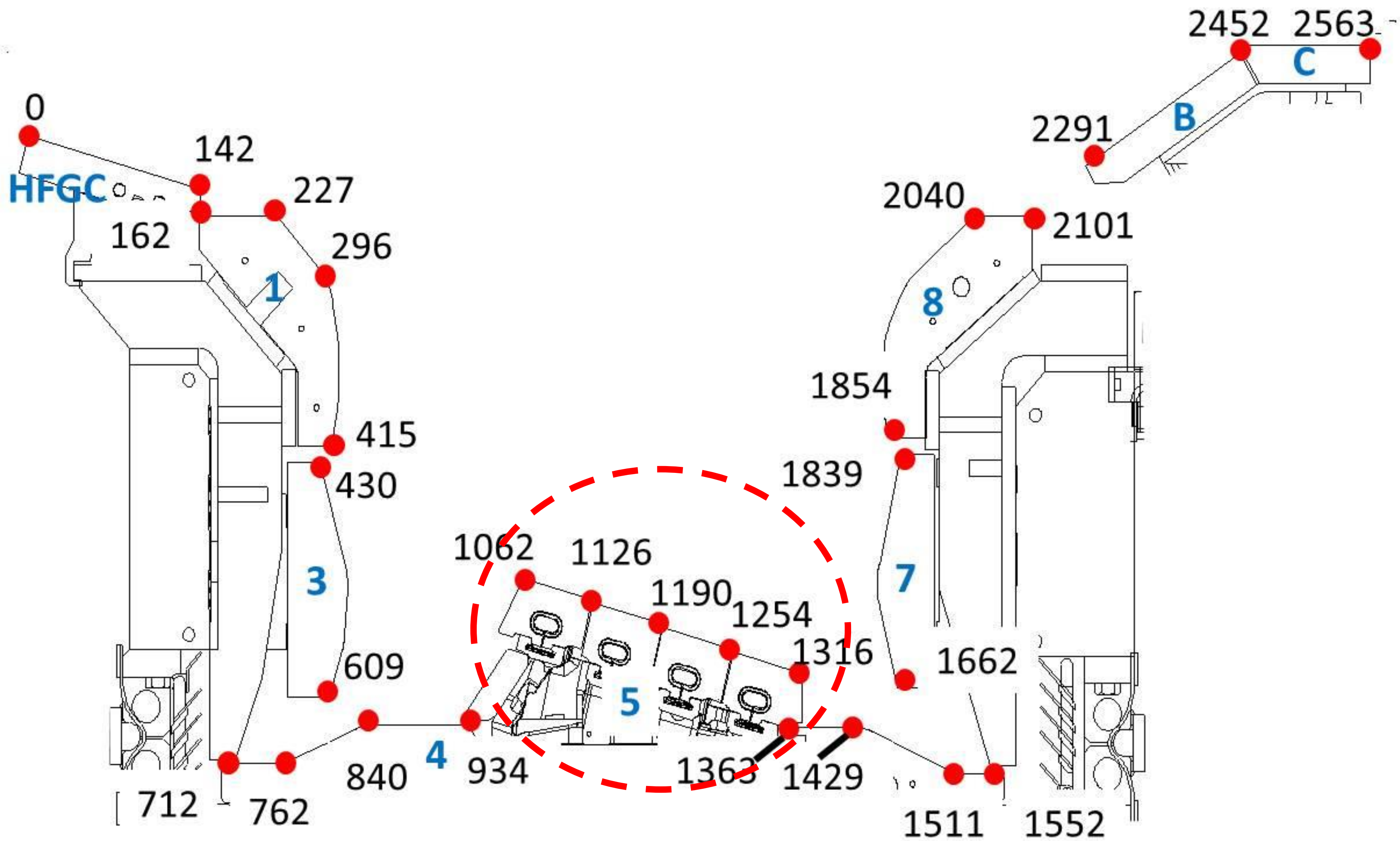
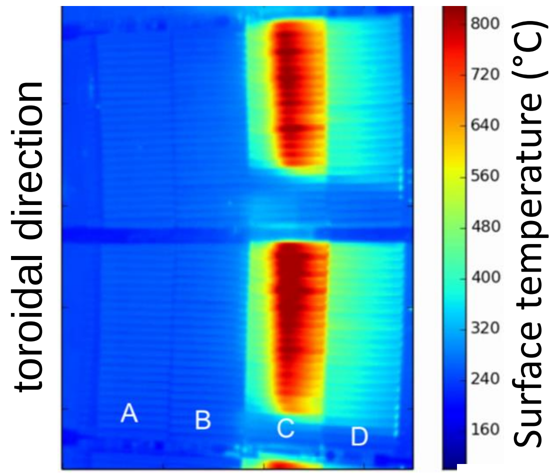
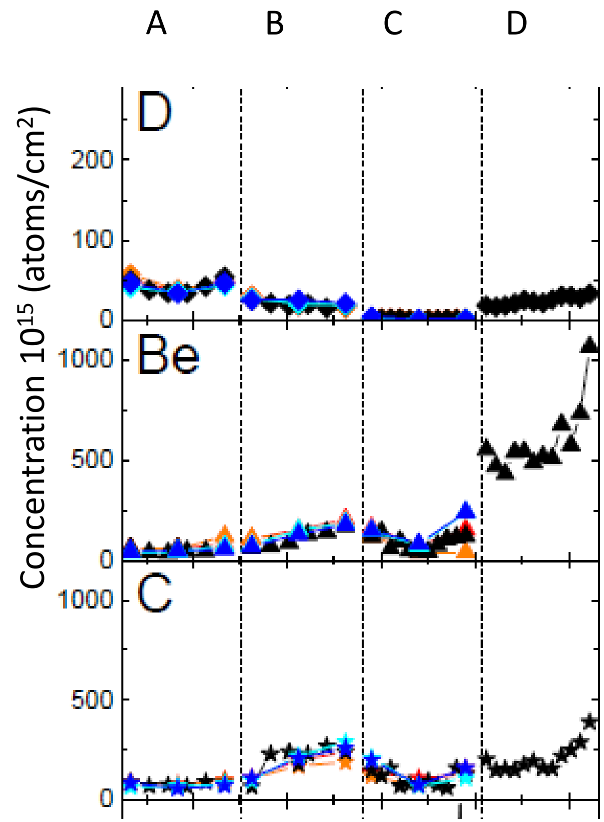
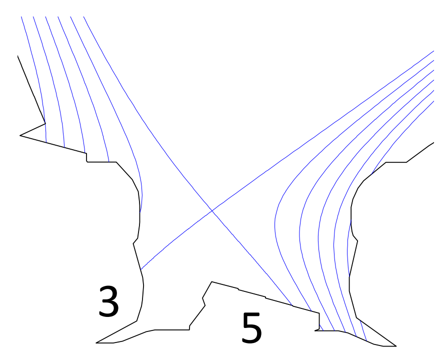
JET-ILW: Bulk Tungsten Tile



Bulk tungsten tile: ILW-1 2011-2012

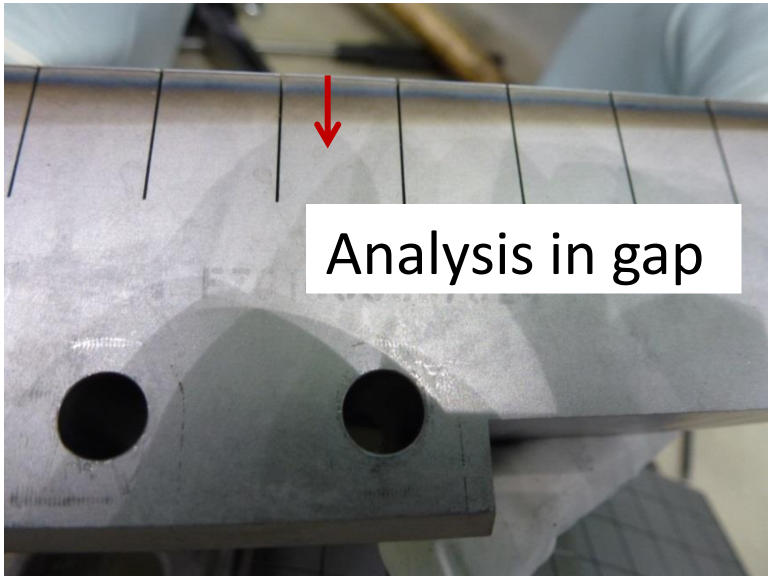


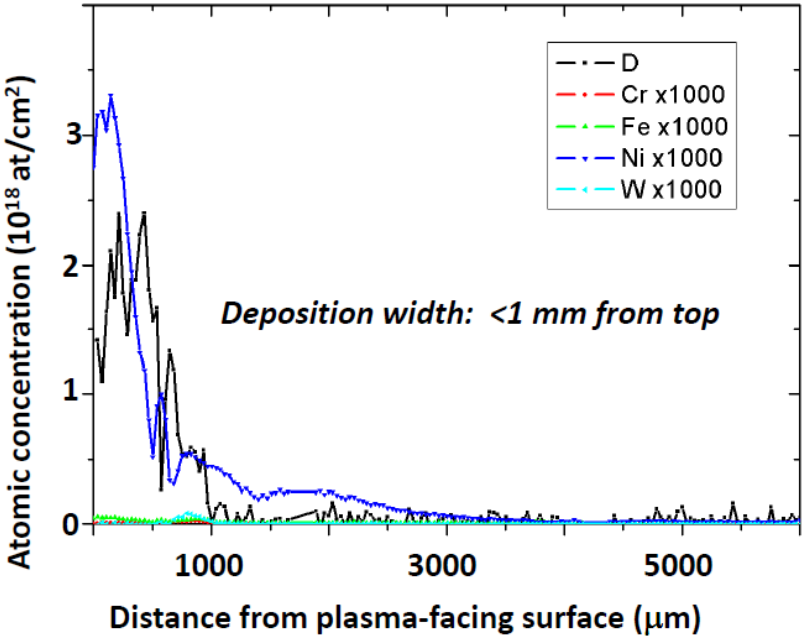




- Deuterium concentration decreases from stack A to C
  - *Inversely proportion to temperature*
- Fuel retention in bulk tungsten surface is factor 100 lower than in co-deposits
  - *<1% of global fuel retention*
- Be locally deposited on stack D associated with outer strike point location

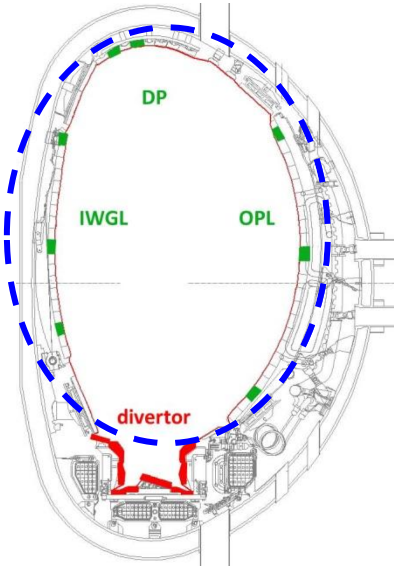
Fuel retention in Be castellation gaps





- 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

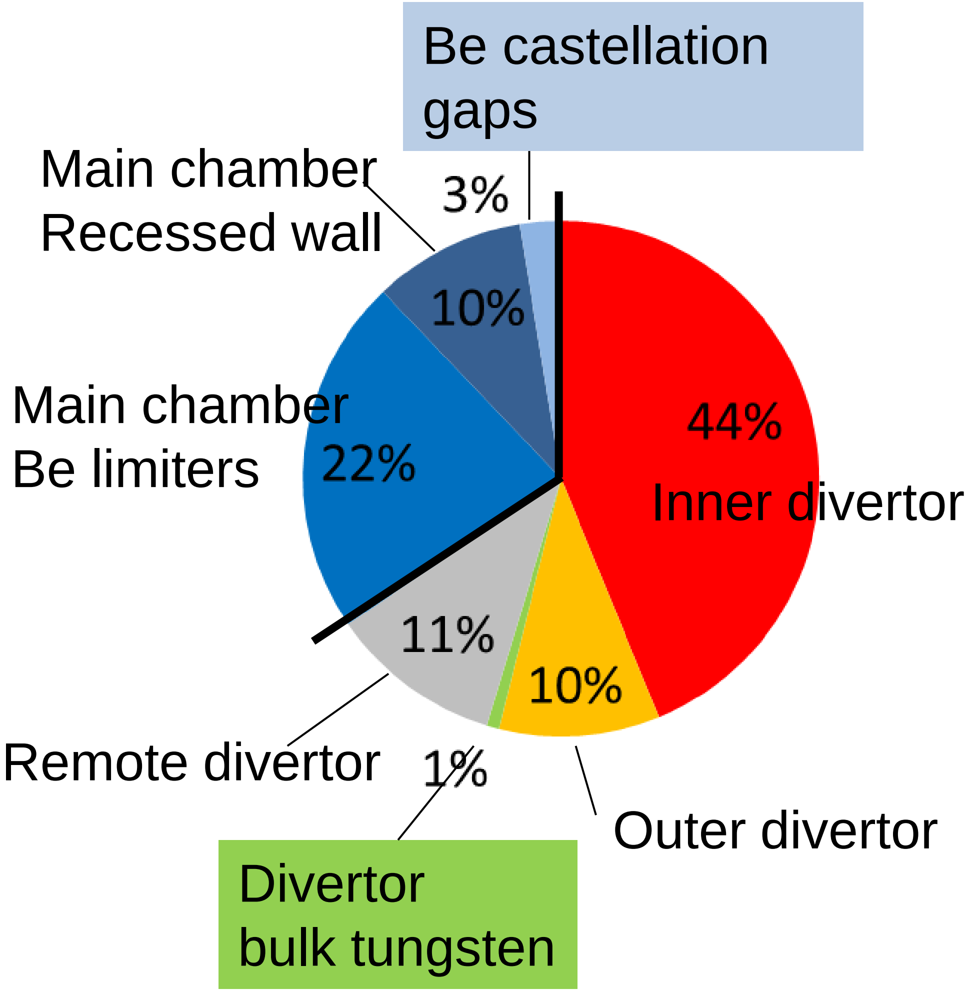
⇒ KEEP GAPS NARROW TO REDUCE INVENTORY



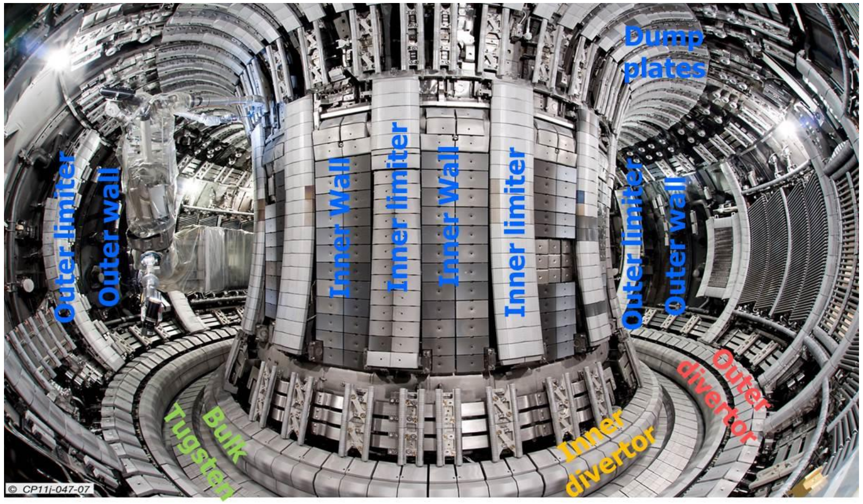
Rubel Ex/P6-1

Global fuel inventory ILW-1 2011-12

Total fuel inventory 38.8 x 10^{22} D atoms

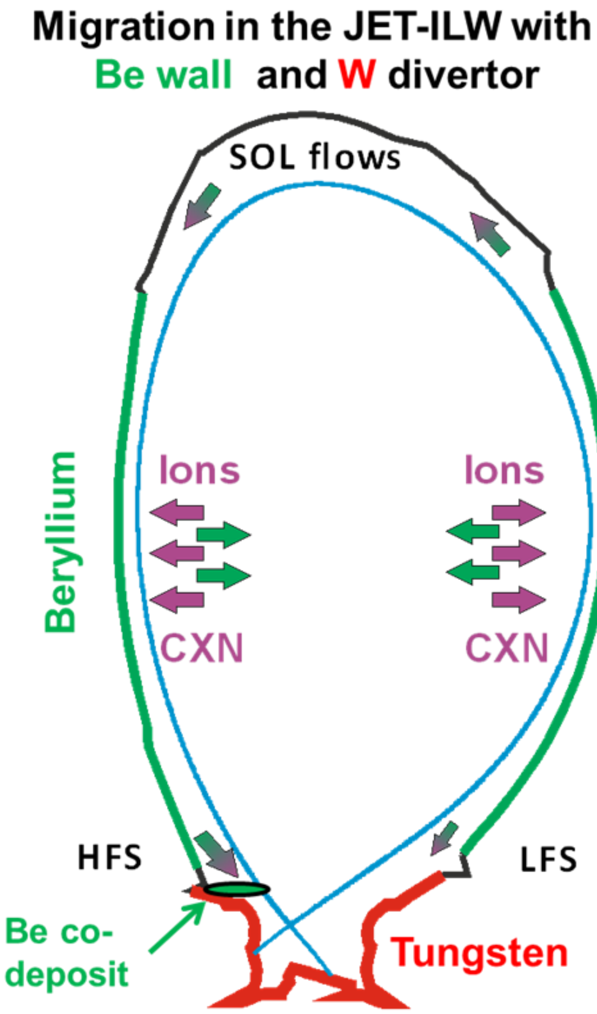


Heinola et al., *Phys. Scr.* 2016 T167 014075, Rubel Ex/P6-1



- 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

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

ITER Outlook

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

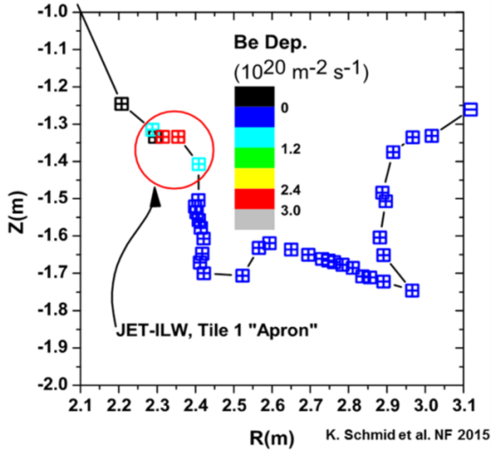
Retention is gaps potentially low

- Keep gaps narrow

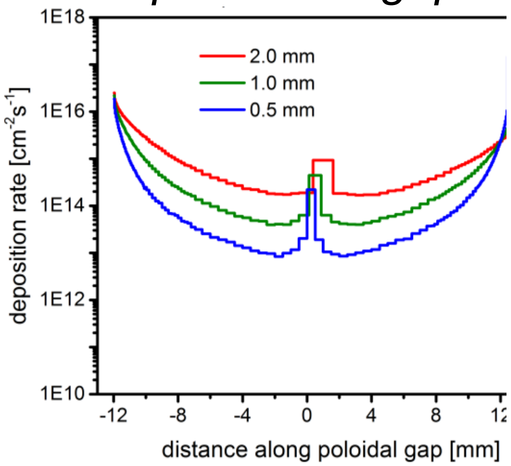
Rubel Ex/P6-1

Retention in bulk tungsten is low compared with co-deposits

WallDYN deposition pattern for JET-ILW



Deposition in gaps



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

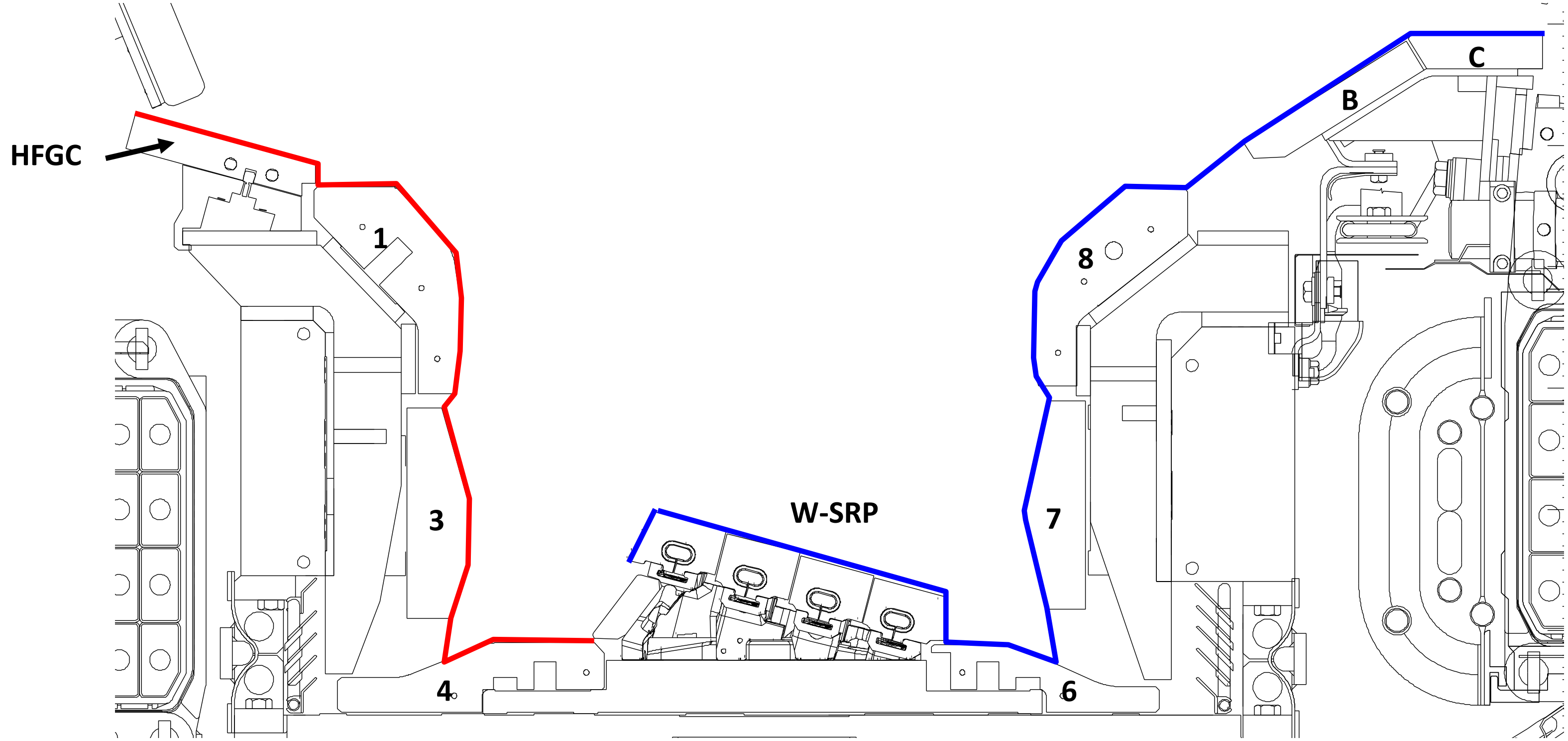
Related IAEA FEC contributions

- Ashikawa, P6-19
- Grzonka/Fortuna-Zalesna, P6-20
- Heinola, P6-2
- Rubel, P6-1

Other references

- Arnoux, Phys. Scripta T159 014009 (2014)
- Baron-Wiechec, J. Nucl. Mat.*463 (2015) 157*
- Heinola, Phys. Scr. T167 (2016) 014075
- Heinola, Phys. Scr. T159 (2014) 014013

JET *Dust* collection: vacuuming

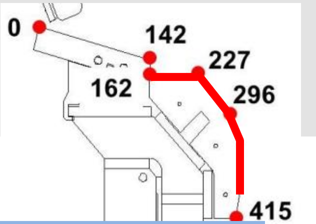


- Dust collection by vacuuming from JET tile surfaces
- <2g dust collected after ILW-1 and ILW-2
  - Significantly less that collected from the JET carbon wall (~200 g)
- Fuel inventory in dust insignificant

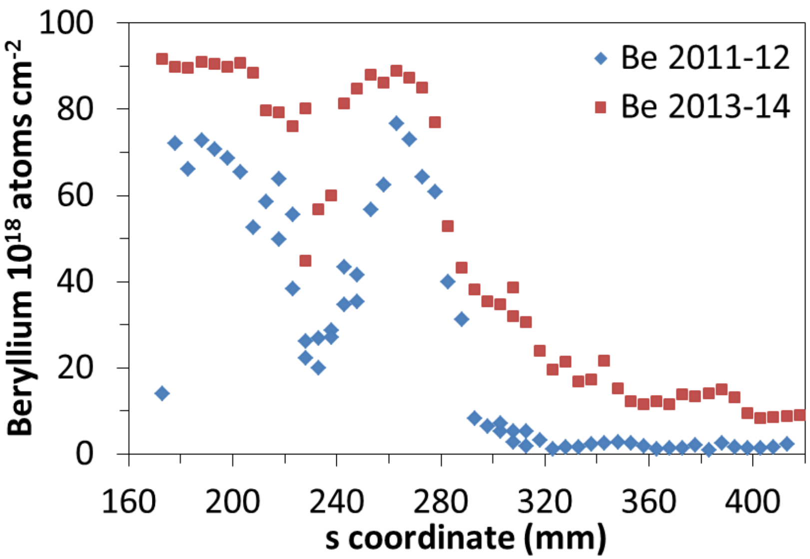
Ashikawa P6-19, Grzonka/Fortuna-Zalesna P6-20

JET

Be deposition at upper inner divertor



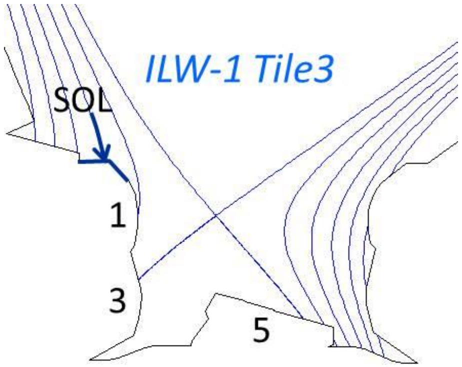
NRA/EBS analysis

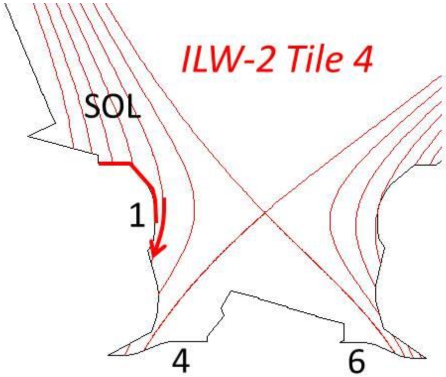


- Distribution of deposit at inner divertor influenced by inner strike point location.
- Scrape off layer (SOL) extends further down Tile 1 in ILW-2.

⇒ Deposition extends further down Tile 1 surface after ILW-2 compared with ILW-1.

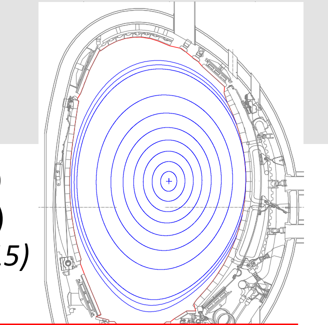
Predominant inner strike point location



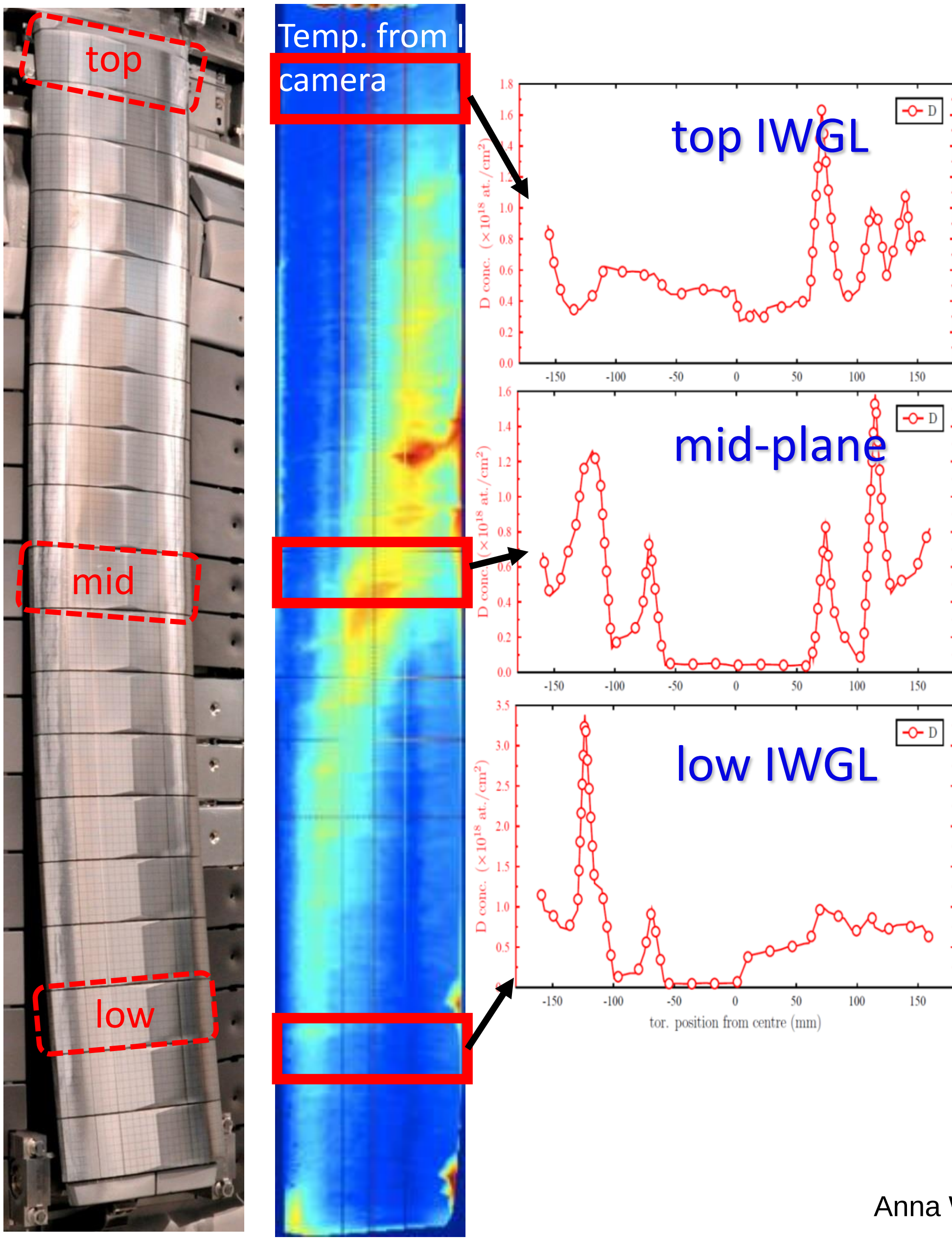


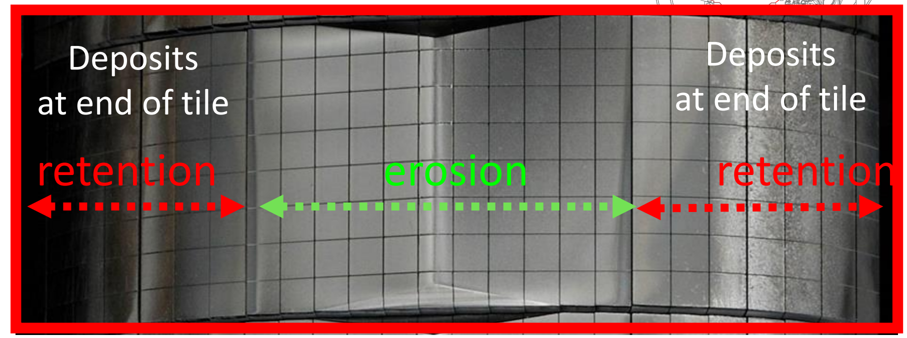
JET

D distribution on inner wall limiter



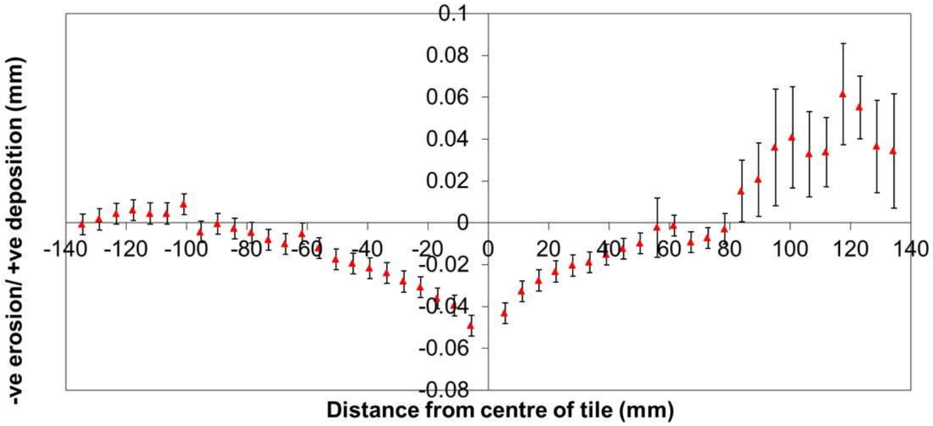
G. Arnoux, Phys. Scripta T159, 014009 (2014)
K. Heinola, Phys. Scripta T159, 014013 (2014)
A. Baron-Wiechec, J. Nucl. Mat. *463, 157 (2015)*

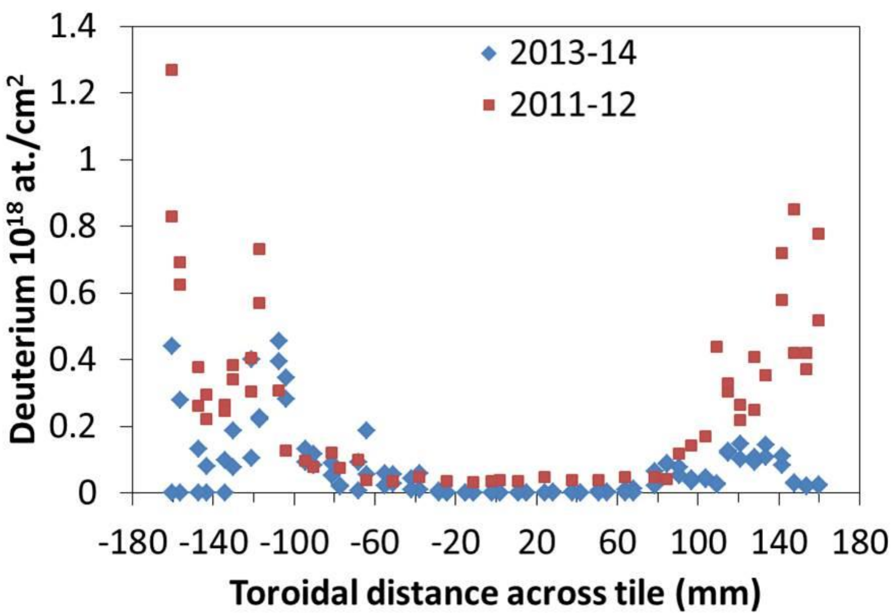


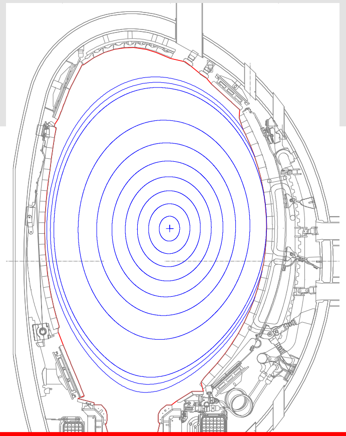


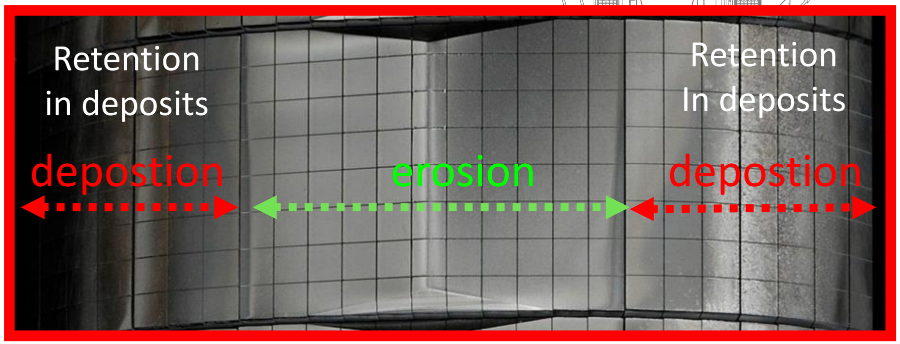
- Fuel inventory on limiter tiles associated with limiter plasma operations
- Fuel retention is mainly by co-deposition at ends of tiles
- Very low D content in areas of high thermal loads
- ITER limiter plasma time will be short compared with divertor plasma time, therefore main chamber co-deposition and fuel retention reduced

Be inner limiter tile







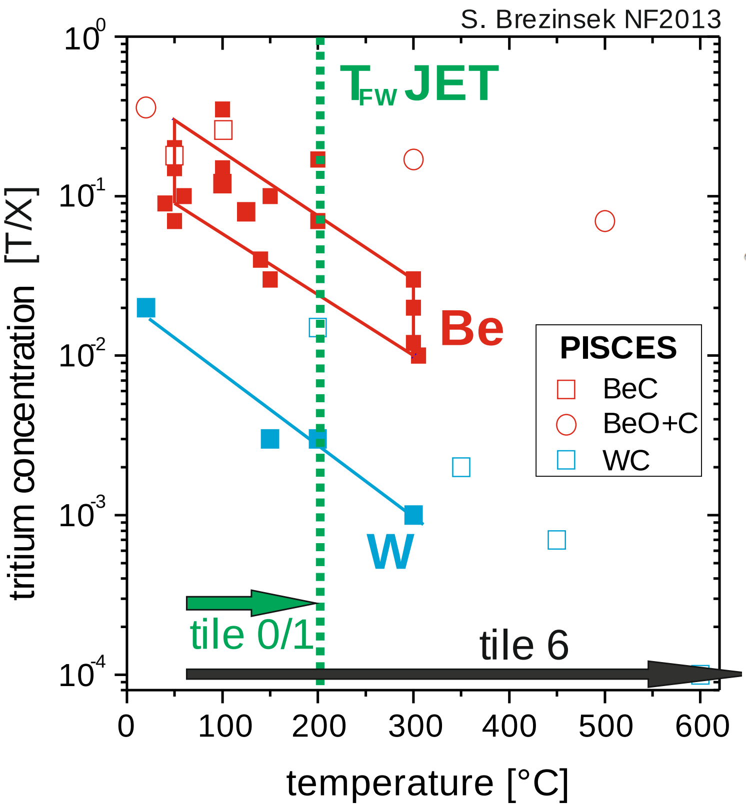


- Erosion at inner limiter during limiter phase
- Fuel retention dominated by local co-deposition of eroded material at ends of limiter tiles

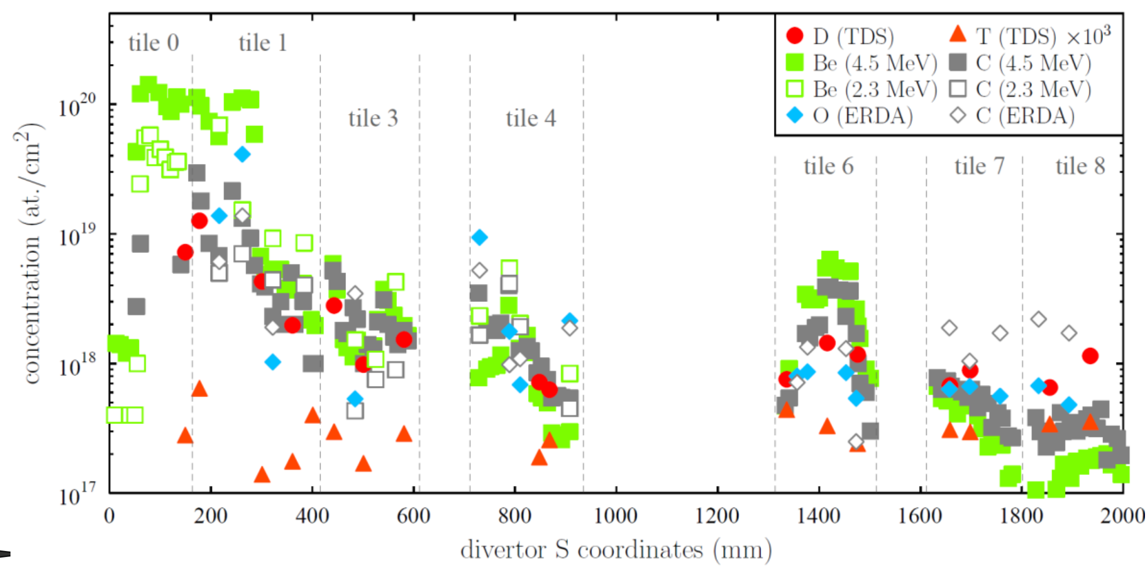
JET

Effect of impurities and temperature on fuel retention

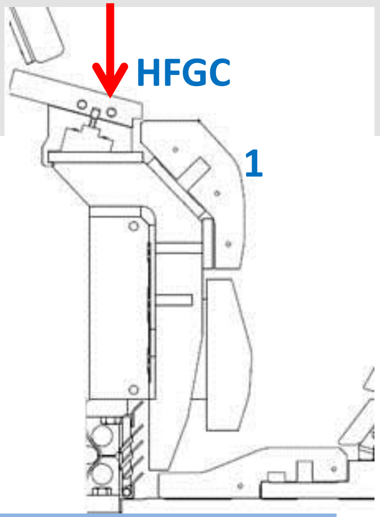
PISCES



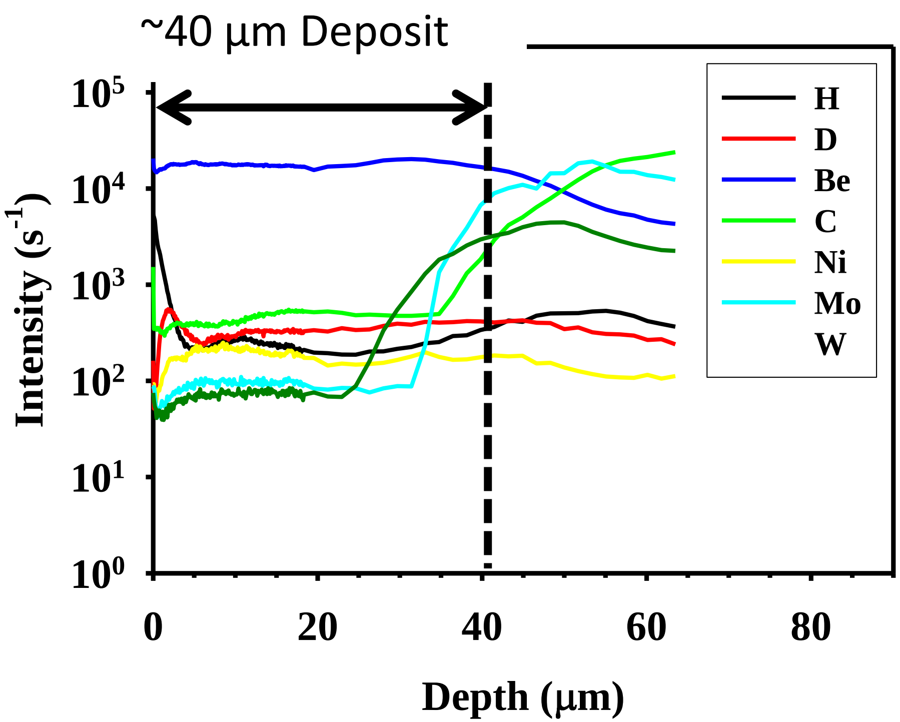
JET-ILW



Deposition at upper inner divertor



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



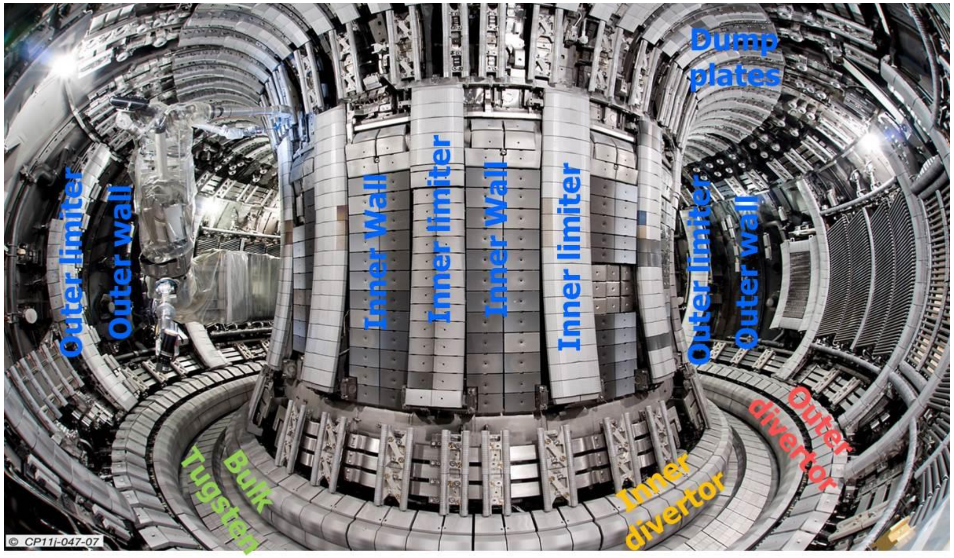
- SIMS data provides thickness data
- Deuterium (D) penetrates to porous tungsten coating
- Quantification of D in coating ongoing

⇒ Specific to JET-ILW tungsten coated CFC tiles

JET

Global retention summary

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



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