Overview of available *post mortem* data: JET's main chamber

Presenter: *I. Jepu*
Material: *JET Contributors*

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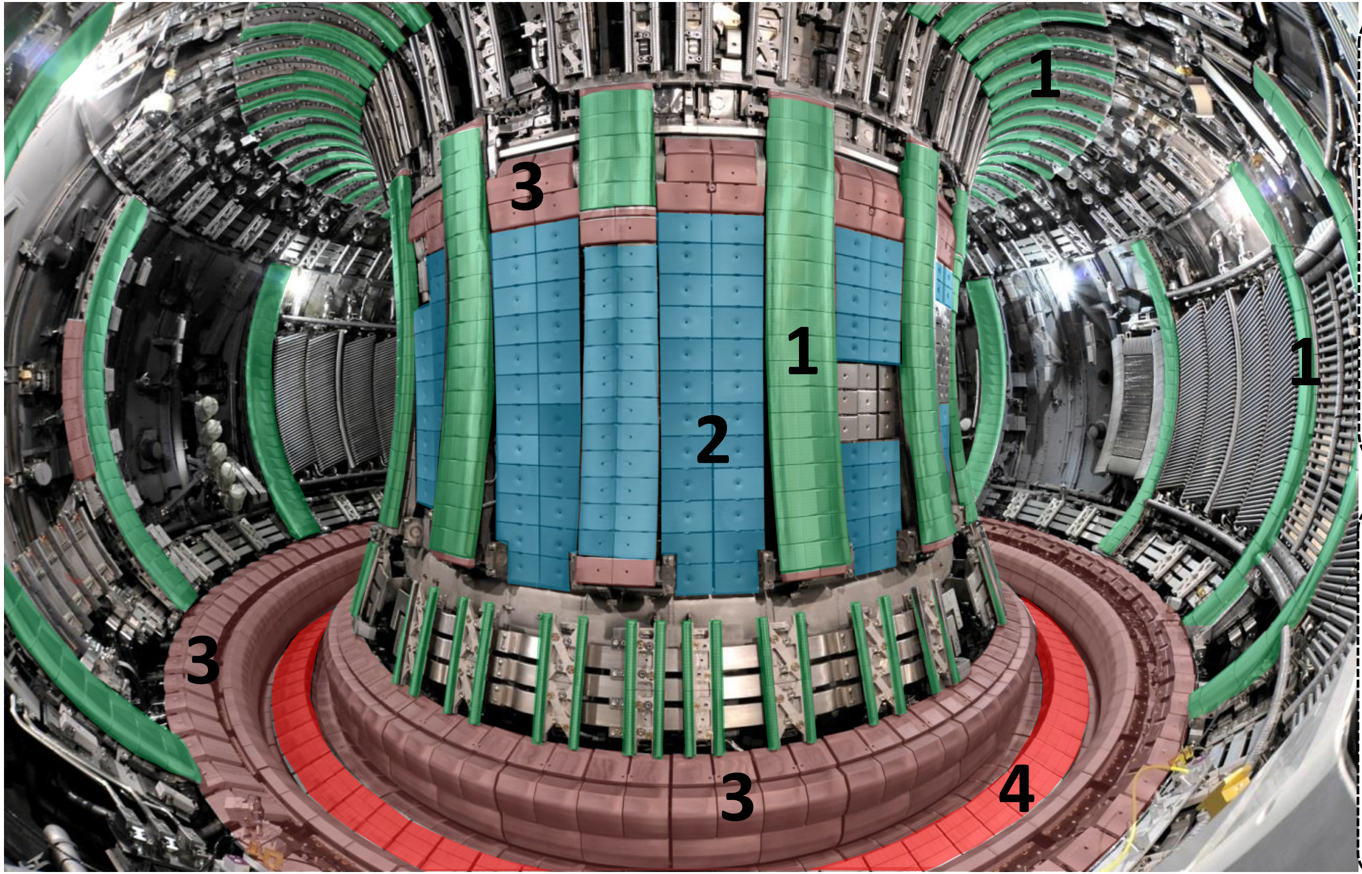
Overview – JET's PFCs



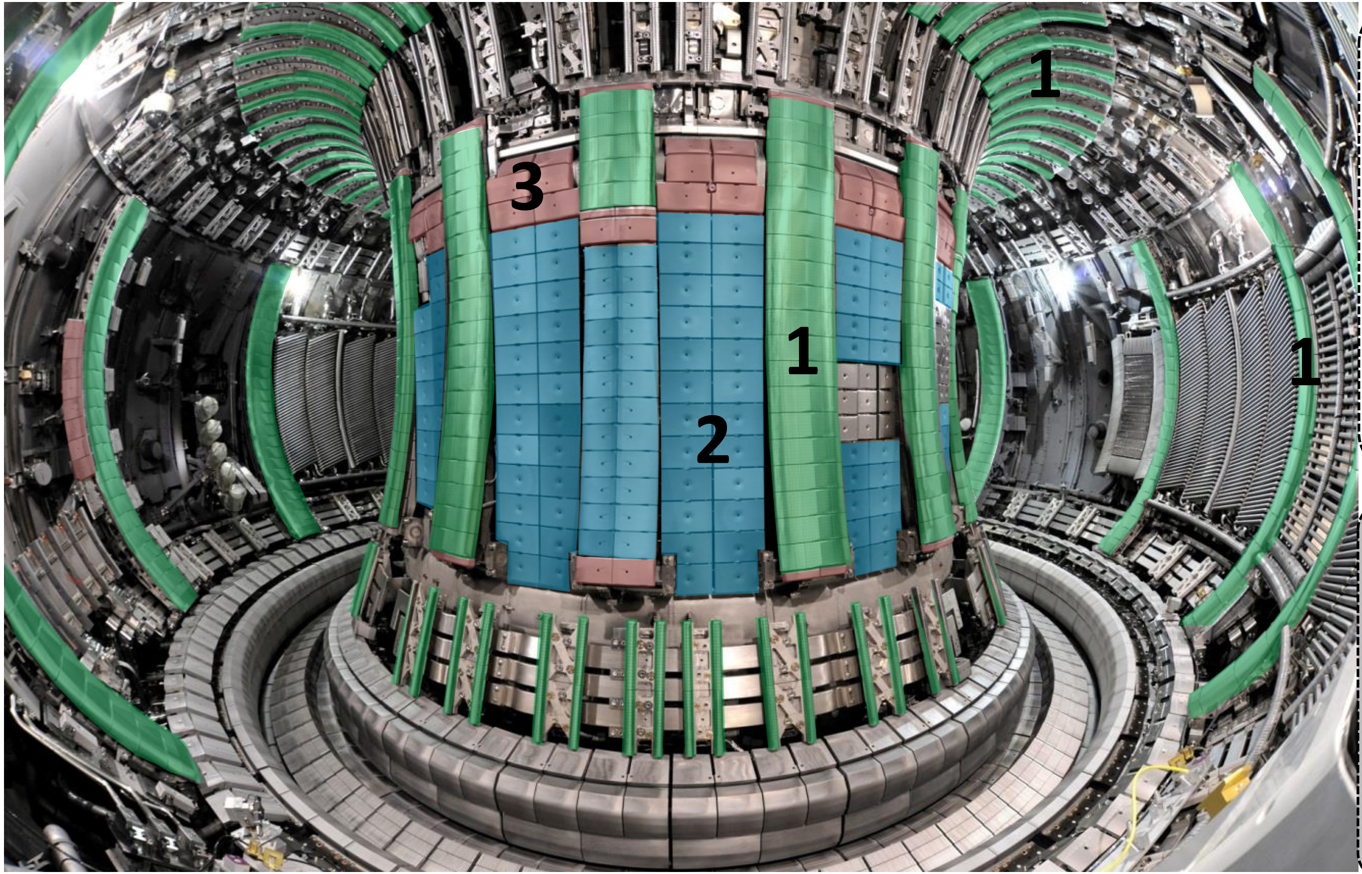
Main chamber

1	Bulk Be
2	Be coated inconel
3	W – coated CFC

DIVERTOR

3	W – coated CFC
4	Bulk W

Overview – JET’s main chamber PFCs



Main chamber

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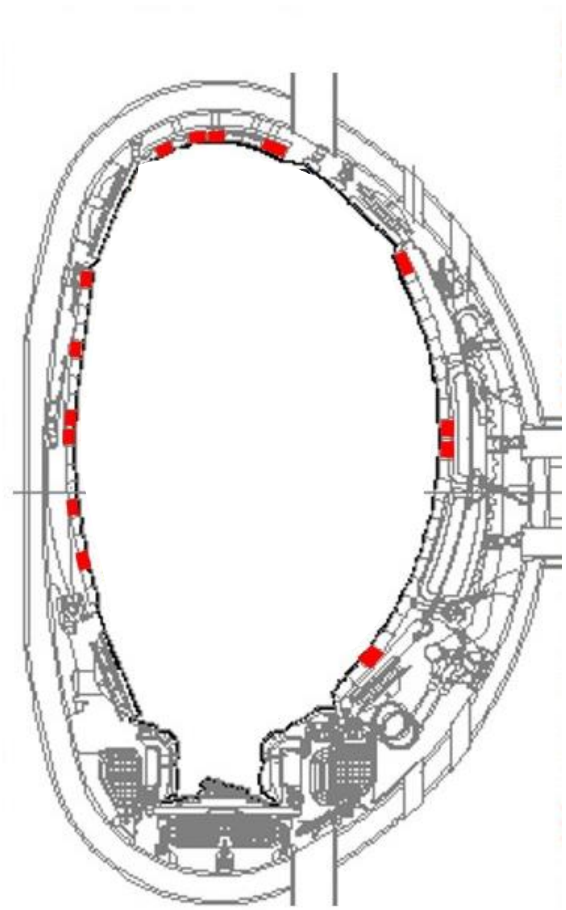
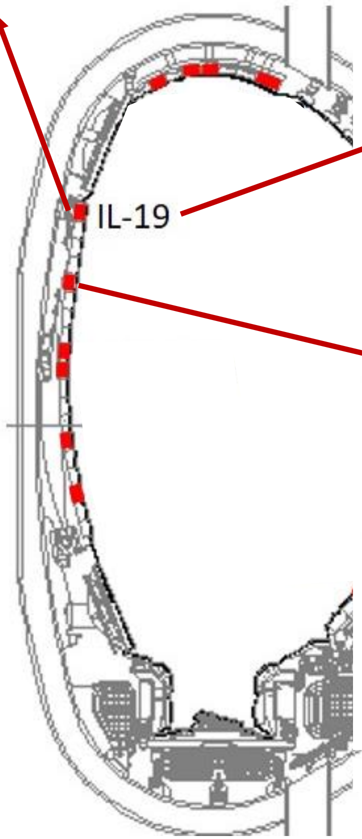
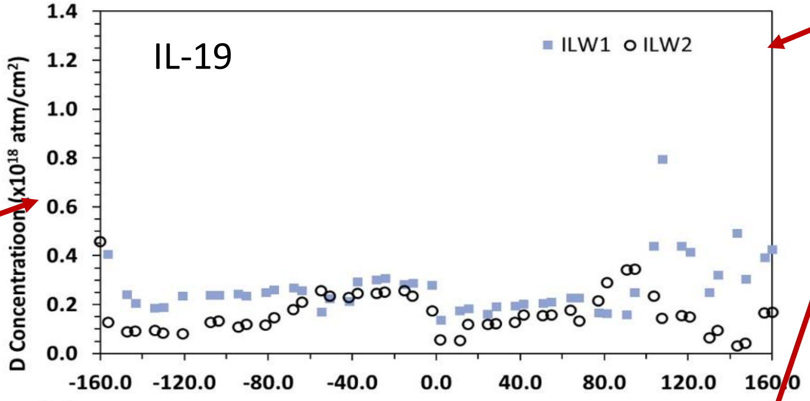
Overview – JET's main chamber PFCs: <u>Beryllium limiters</u>

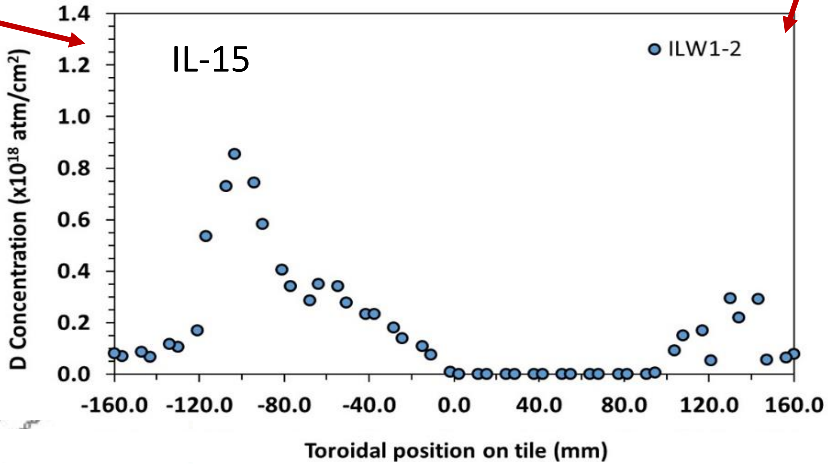


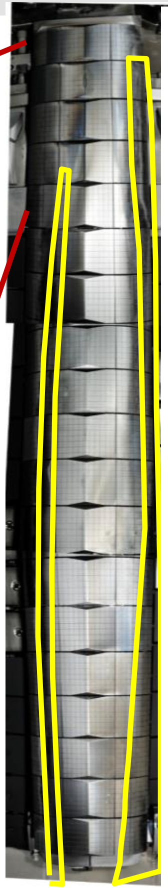
Overview – JET’s main chamber PFCs: Beryllium limiters – Fuel retention (IBA data)

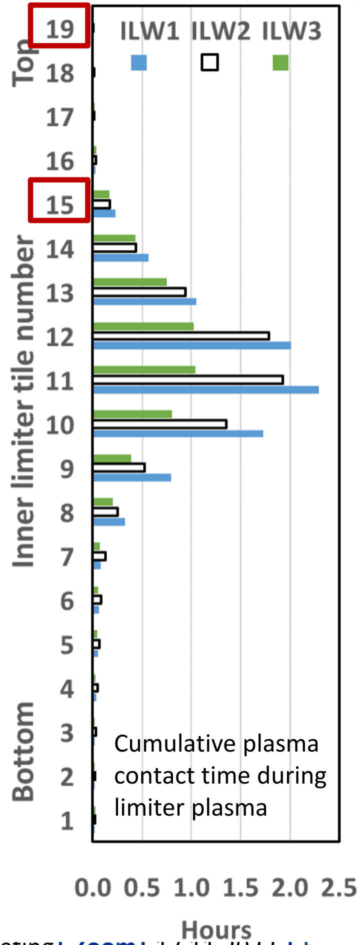
IWGL





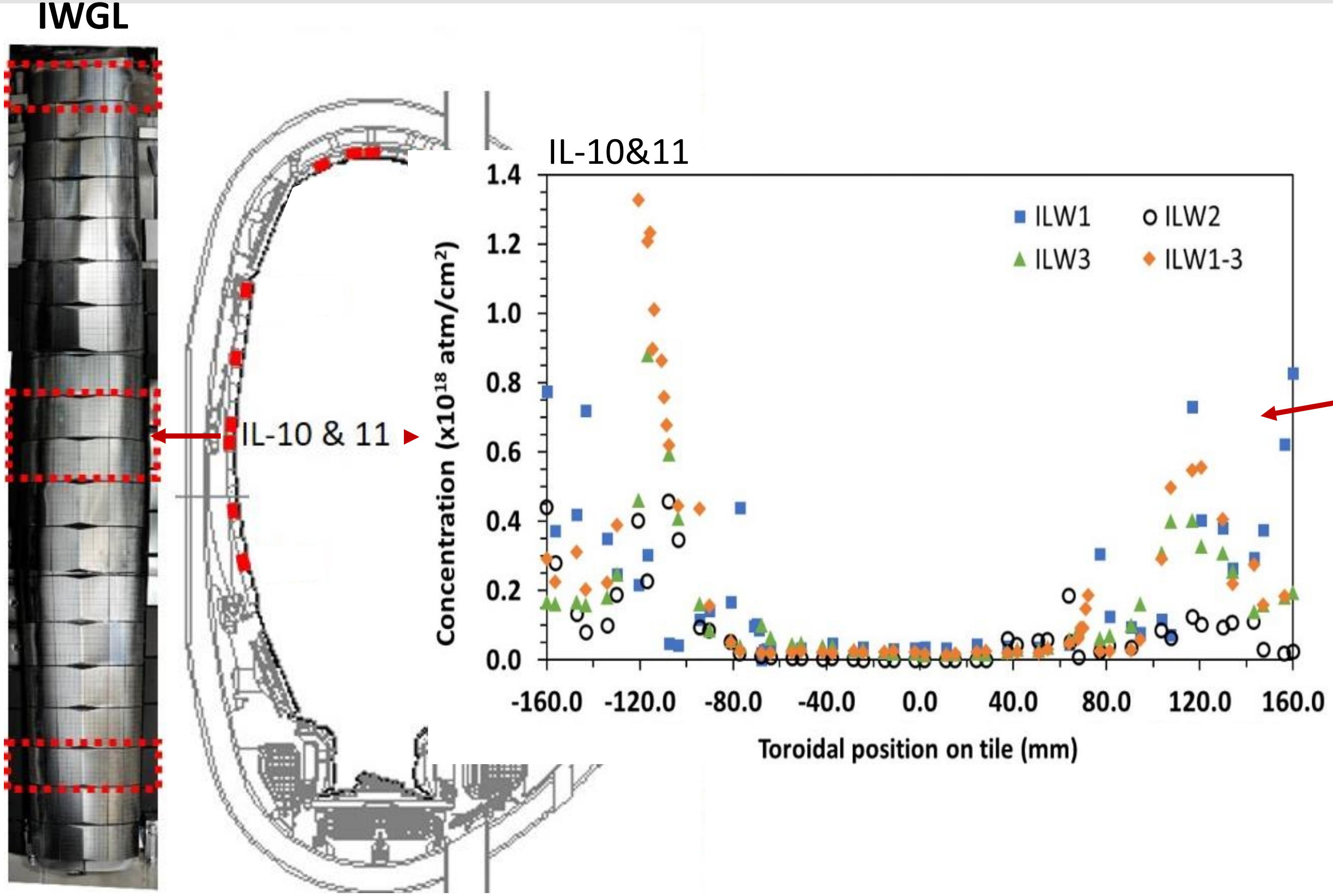


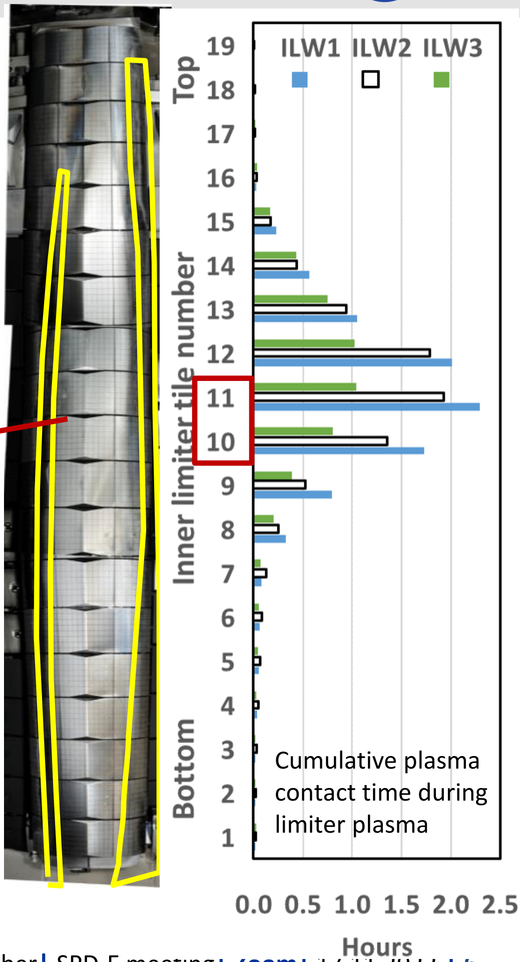




[1] A Widdowson et al 2020 Phys. Scr. 2020 014051

Overview – JET's main chamber PFCs: Beryllium limiters – Fuel retention (IBA data)





[1] A Widdowson et al 2020 Phys. Scr. 2020 014051

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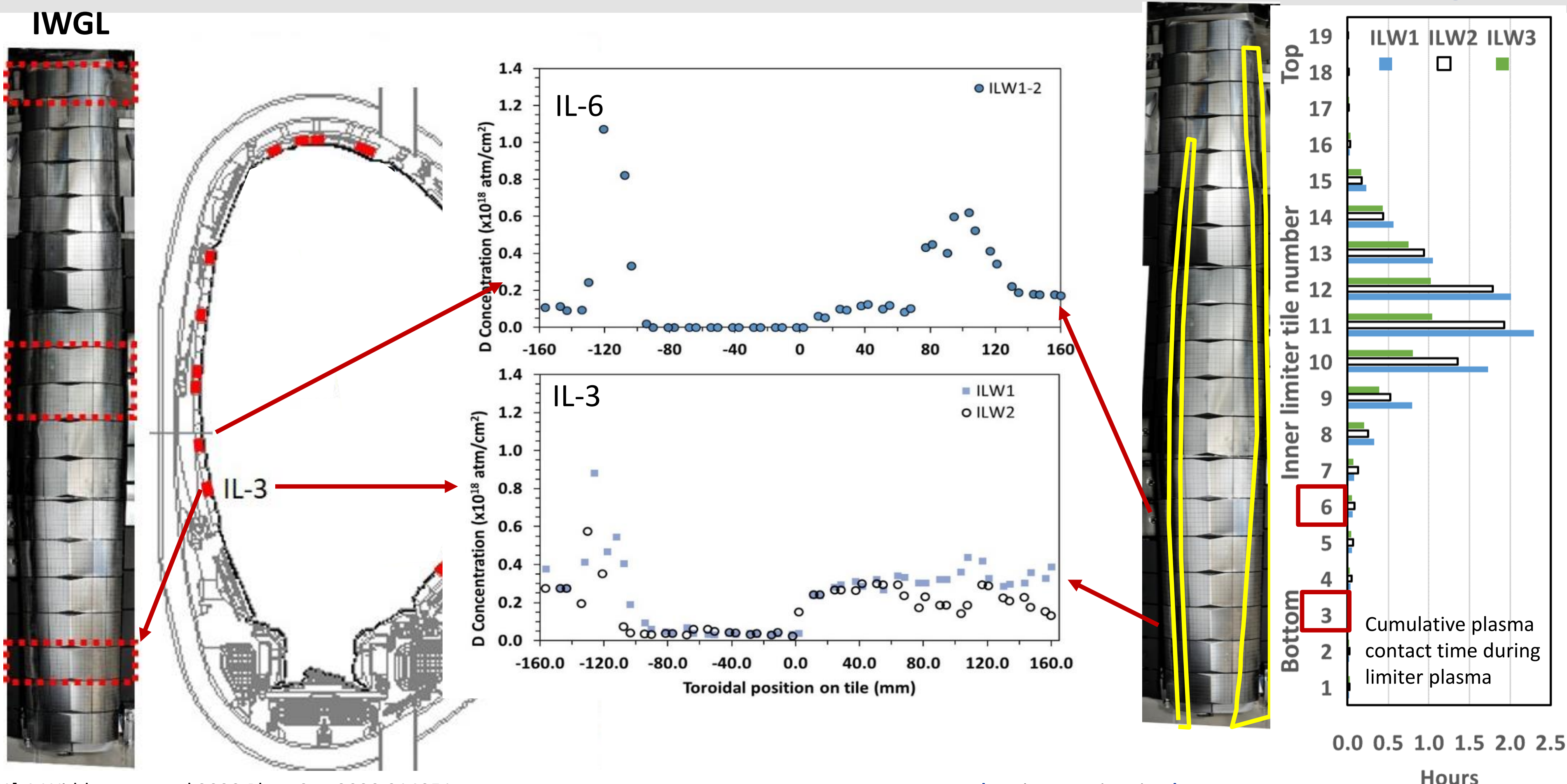

[1] A Widdowson et al 2020 Phys. Scr. 2020 014051

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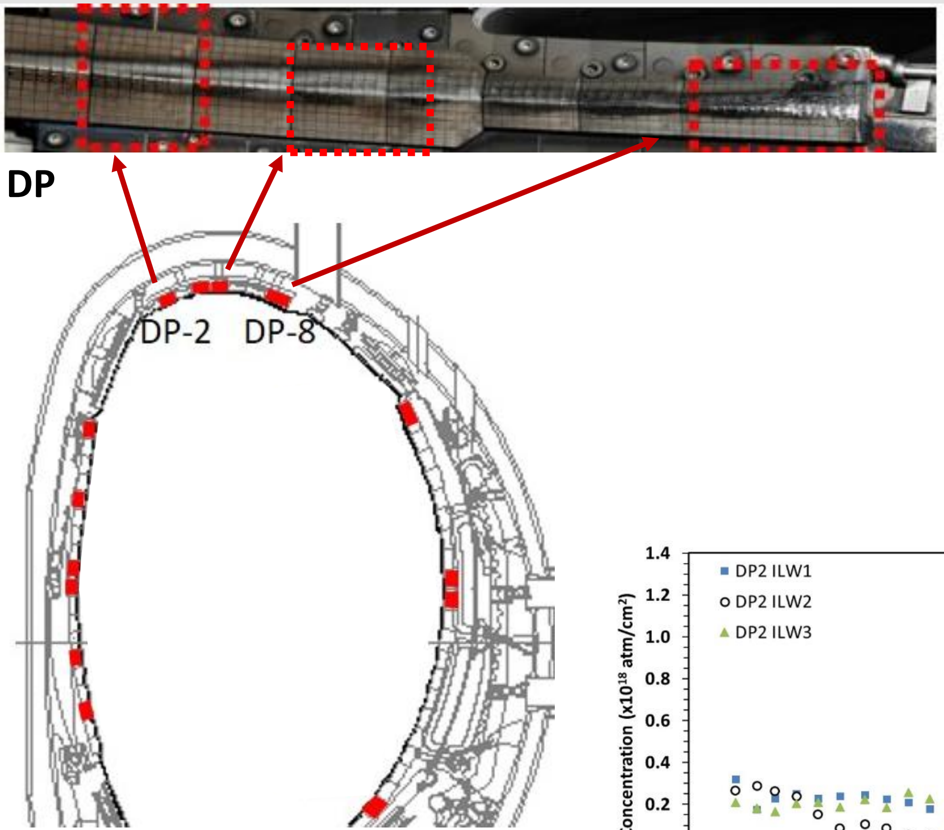
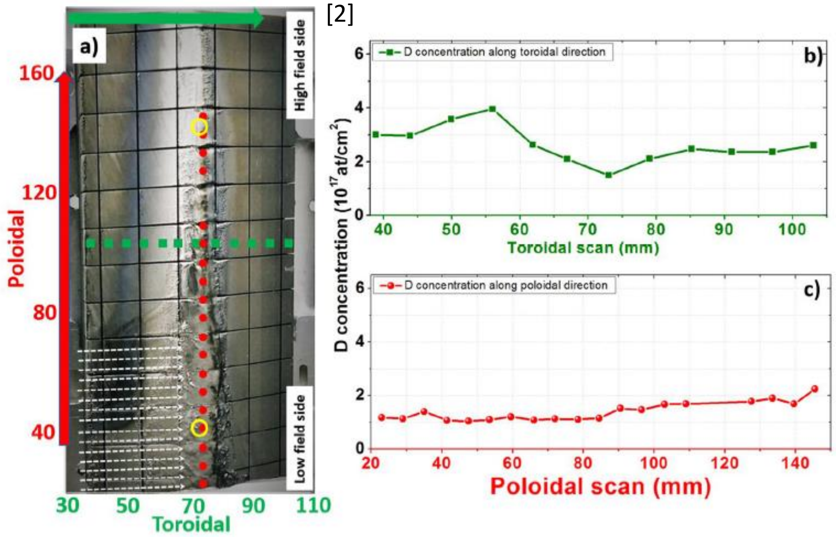
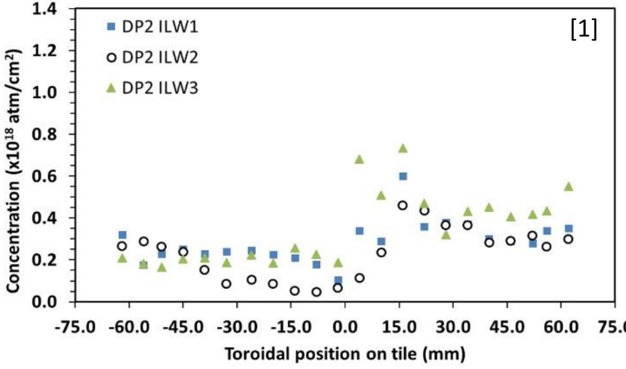
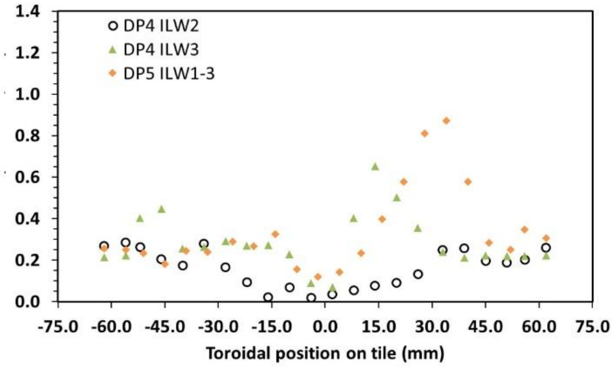


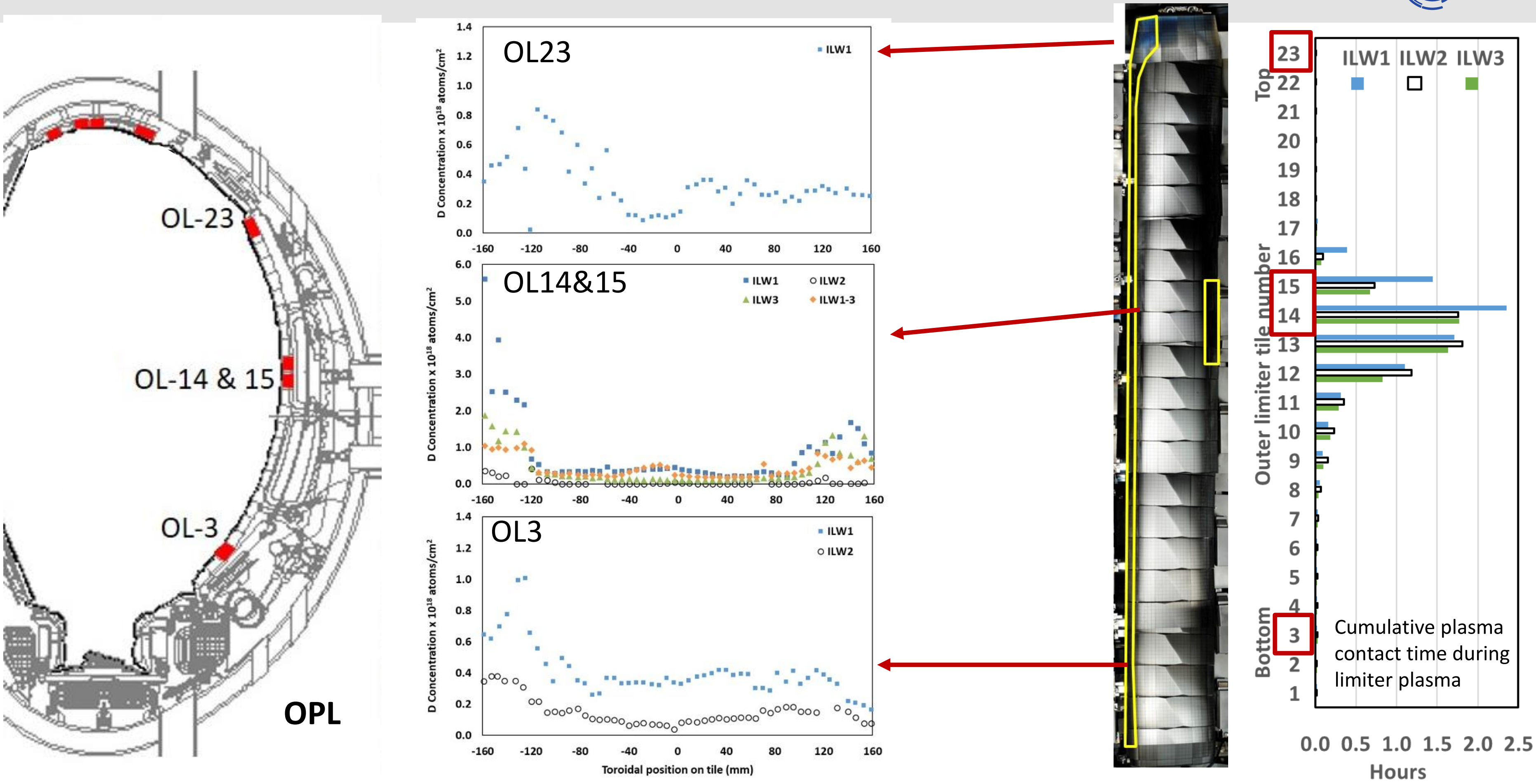






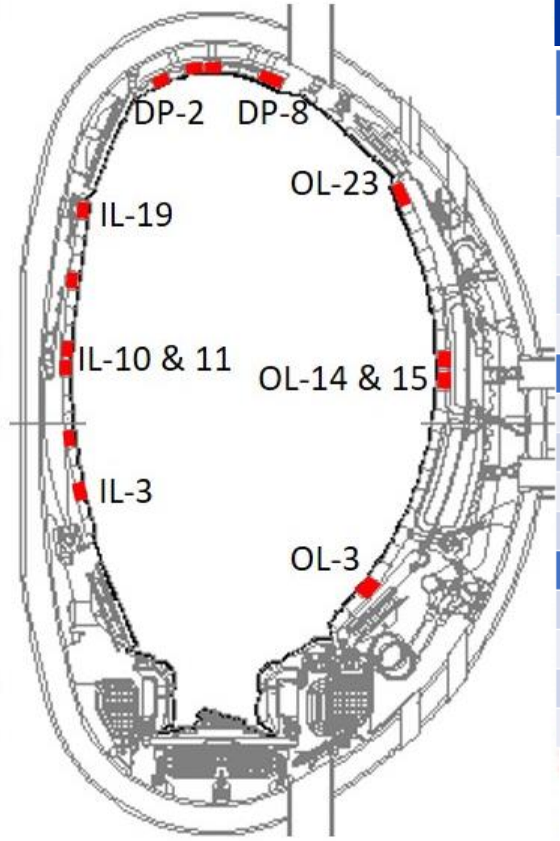
[1] A Widdowson et al 2020 Phys. Scr. 2020 014051
[2] I. Jepu et al 2019 Nucl. Fusion 59 086009

Overview – JET's main chamber PFCs: Beryllium limiters – Fuel retention (IBA data)



A Widdowson et al 2020 Phys. Scr. 2020 014051

Overview – JET's main chamber PFCs: <u>Beryllium limiters</u> – Fuel retention summary(IBA data)



Exposure period in JET of analysed tiles

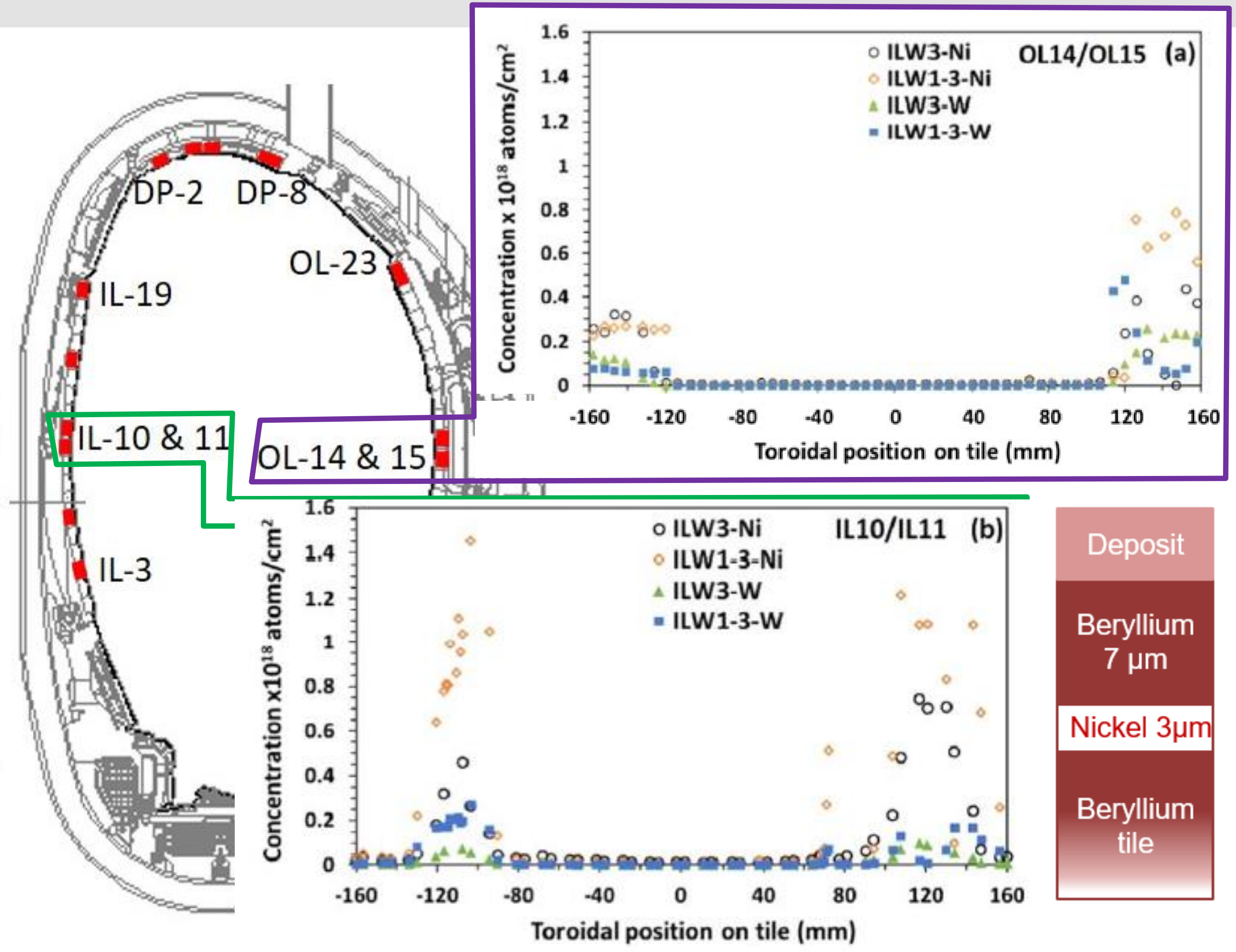
Inner limiter tiles	ILW1 (2011-12)	ILW2 (2013-14)	ILW3 (2015-16)
IL-3	↔	↔	↔
IL-6	No IBA data	No IBA data	↔
IL-10	↔	↔	↔
IL-11	↔	↔	↔
IL-15	No IBA data	No IBA data	↔
IL-19	↔	↔	↔
Outer limiter tiles			
OL-3	↔	↔	↔
OL-14	↔	↔	↔
OL-15	↔	↔	↔
OL-23	↔	No IBA data	No IBA data
Dump plate tiles			
DP-2	↔	↔	↔
DP-4	↔	↔	↔
DP-5	↔	↔	↔
DP-8	↔	↔	↔

<u>Fuel retention summary</u>

- Fuel retention on limiter tiles concentrated in deposits
- Contribution to total fuel retention in surface of beryllium limiter tiles <0.03%
- Retention lowest in high heat load/erosion areas at midplane inner/outer limiters & dump plate ridge
- Deposits for ILW1-3 tiles thicker than analysis depth therefore total deuterium underestimated

A Widdowson et al 2020 Phys. Scr. 2020 014051

Overview – JET's main chamber PFCs: Beryllium limiters – Material migration (Mid&high-Z)



A Widdowson et al 2020 Phys. Scr. 2020 014051

Material Migration

- Erosion of inner and outer beryllium limiters occurs mainly during limiter phase;
- For all three ILW operating periods erosion/deposition pattern shows similar distribution
- Tungsten, nickel, iron, chromium found in deposits for all ILW operating periods

Mid-Z and high-Z impurities migrate throughout vessel

- Roughly follow global deposition patterns for beryllium

Impurities migrate until they reach a remote region not accessible to plasma

- Upper inner divertor, divertor corners and ends of main chamber limiter tiles

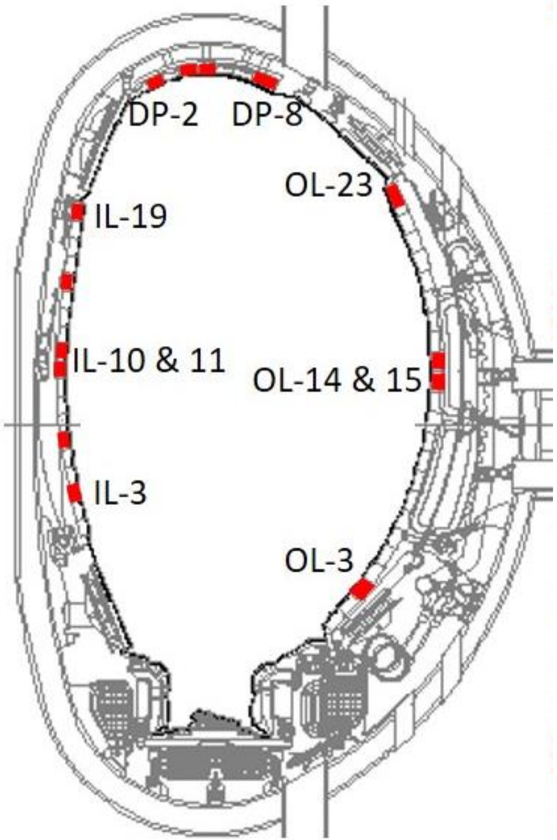
Campaign to campaign variations in concentration are modest

- Deposition patterns influenced by plasma configurations and operating conditions

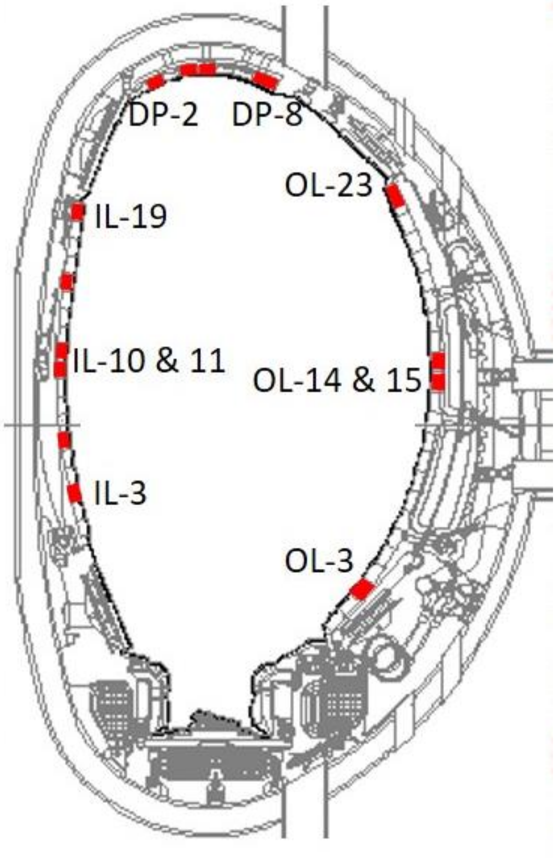
Continuing sources of W, Ni, Cr, Fe throughout all operating periods

Ratios of Ni, Cr, Fe impurities show that Inconel is the source

Overview – JET’s main chamber PFCs: Beryllium limiters – Material migration (Low-Z)



Overview – JET's main chamber PFCs: Beryllium limiters – Material migration (Low-Z)



Nuclear Materials and Energy 18 (2019) 331–338

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Beryllium global erosion and deposition at JET-ILW simulated with ERO2.0

J. Romazanov[*,a], S. Brezinsek[a], D. Borodin[1,a], M. Groth[b], S. Wiesen[a], A. Kirschner[a], A. Huber[a], A. Widdowson[c], M. Airila[d], A. Eksaeva[a,e], I. Borodkina[a,e], Ch. Linsmeier[a], JET Contributors[2]

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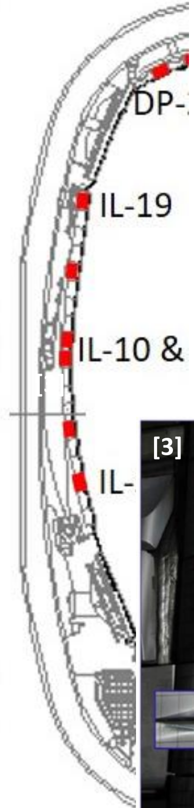
J. Romazanov et al 2019 Nuclear Mat and Eng. 18 331-338

Overview – JET's main chamber PFCs: <u>Beryllium limiters</u> – VDEs damage



Plasma disruption

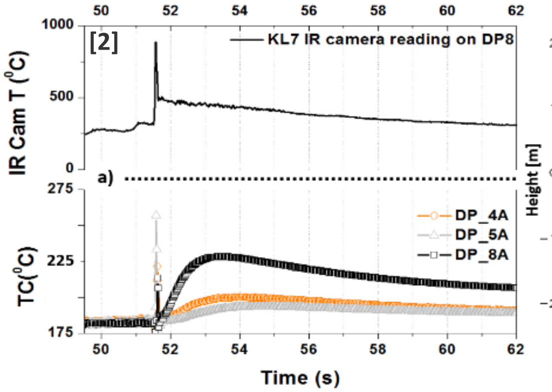
Termination of plasma with rapid loss of thermal and magnetic energy

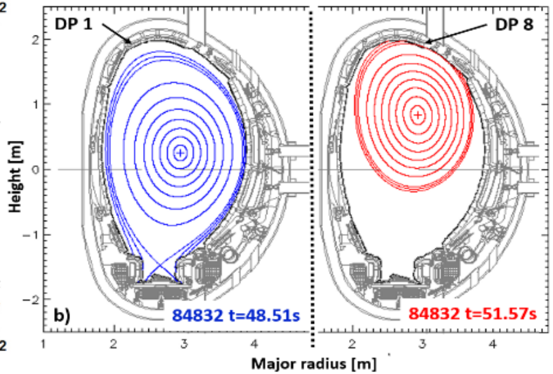
↓

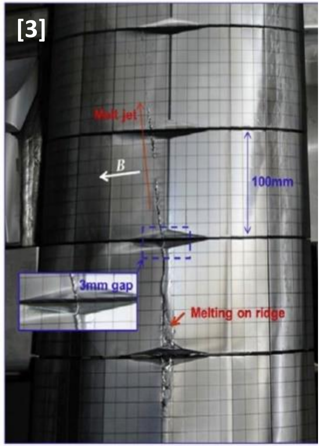
HUGE thermal and mechanical loads on the structure

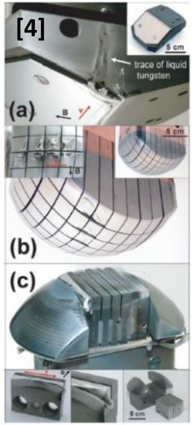
<u>Consequences of the disruptions</u>

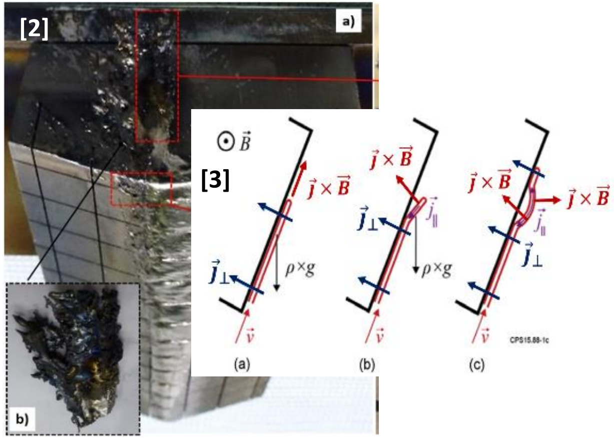
- Thermal loads/Fast melting and electromagnetic forces

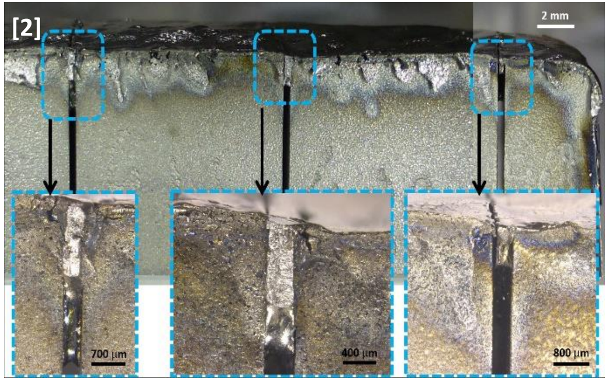






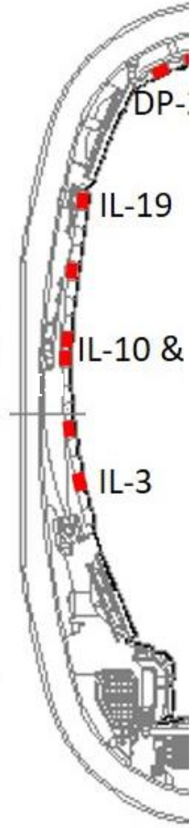






[2] I. Jepu et al, Nucl. Fusion 59 (2019) 086009
[3] G.F. Matthews, et al., Phys. Scr. T167 (2016) 014070 (7pp)
[4] G. Sergienko et al., Phys. Scr. T128 (2007) 81–86

Overview – JET's main chamber PFCs: <u>Beryllium limiters</u> – VDEs damage - modelling

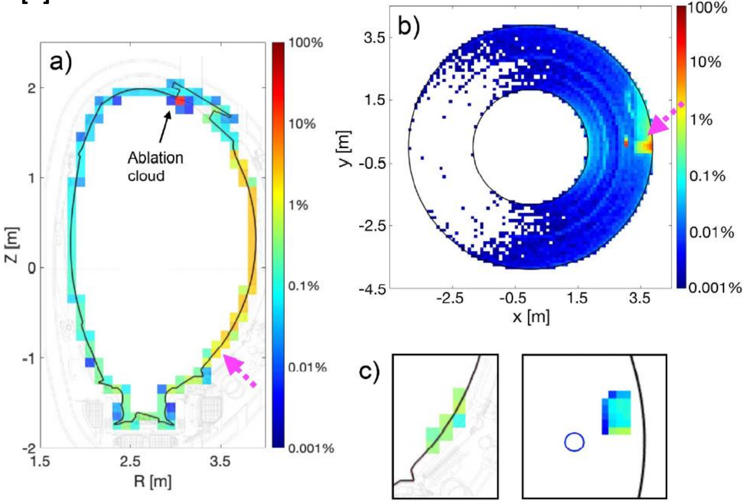


IOP Publishing Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion 62 (2020) 064001 (11pp) https://doi.org/10.1088/1361-6587/ab8610

An insight on beryllium dust sources in the JET ITER-like wall based on numerical simulations

Plasma Phys. Control. Fusion 62 (2020) 064001 A Uccello et al

[5]



A. Uccello et al, Plasma Phys. Control. Fusion 62 (2020) 064001 (11pp)

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Nucl. Fusion 62 (2022) 036016 (10pp) https://doi.org/10.1088/1741-4326/ac47b7

Simulations of liquid metal flows over plasma-facing component edges and application to beryllium melt events in JET [6]

L. Vignitchouk et al. Nucl. Fusion 62 (2022) 036016 (10pp)

Nucl. Fusion 62 (2022) 036016 L. Vignitchouk et al

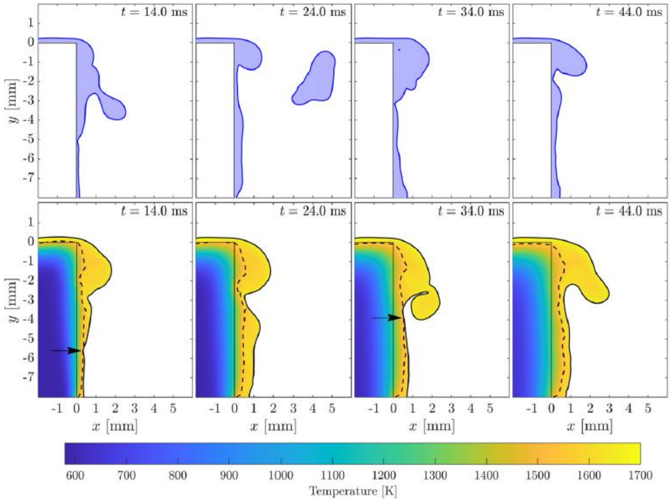


Figure 7. Comparison of simulation results with (lower row) and without (upper row) heat transfer for $h = 200\ \mu m$ and $v = 3\ m\ s^{-1}$. Dashed black curves in the lower row highlight the position of the re-solidification front. Arrows indicate locations where the free surface and the re-solidification front are found to meet tangentially, meaning that the liquid domain is split in two nearly independent layers. The older layer is almost fully solidified and behaves effectively as a substrate on which the newer layer propagates. Video clips are provided as supplementary material.

[5] A. Uccello et al, Plasma Phys. Control. Fusion 62 (2020) 064001 (11pp)
[6] L. Vignitchouk et al. Nucl. Fusion 62 (2022) 036016 (10pp)

[5] A. Uccello et al, Plasma Phys. Control. Fusion 62 (2020) 064001 (11pp)

Overview – JET's main chamber PFCs: Beryllium limiters – VDEs damage - modelling

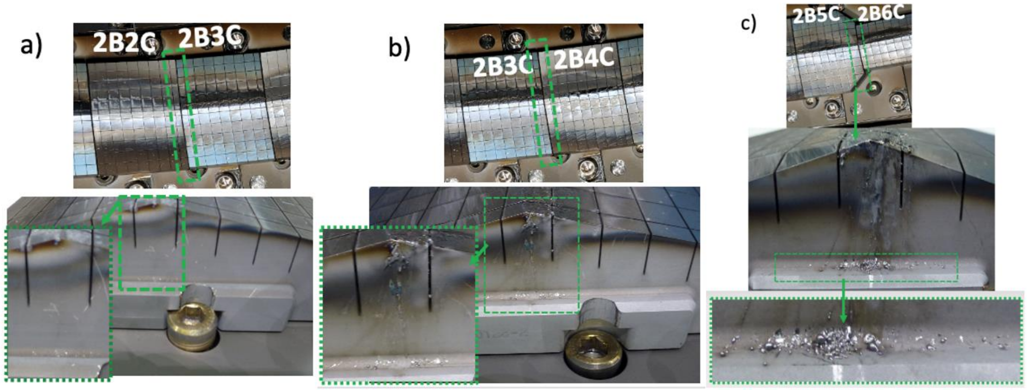


Figure S5 a) Close-up of Be droplets found between DP-2 and DP-3; b) close-up of Be droplets between DP-3 and DP-4 and c) close-up of Be droplets found in gaps between tiles DP-5 and DP-6.

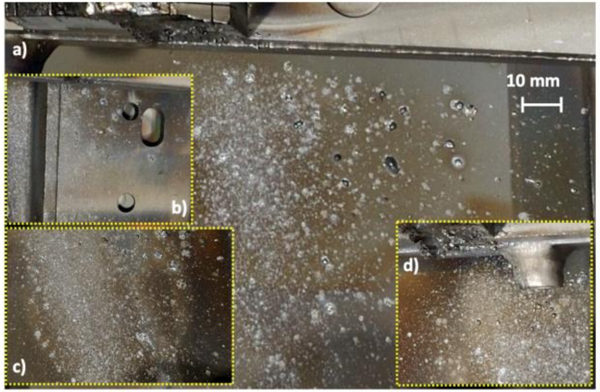
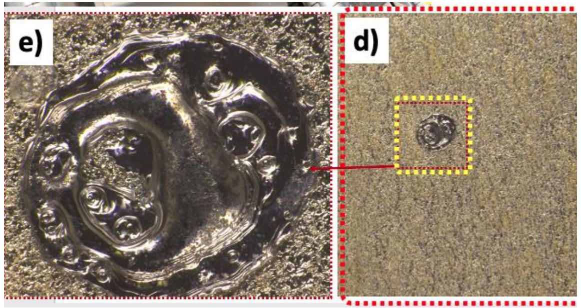
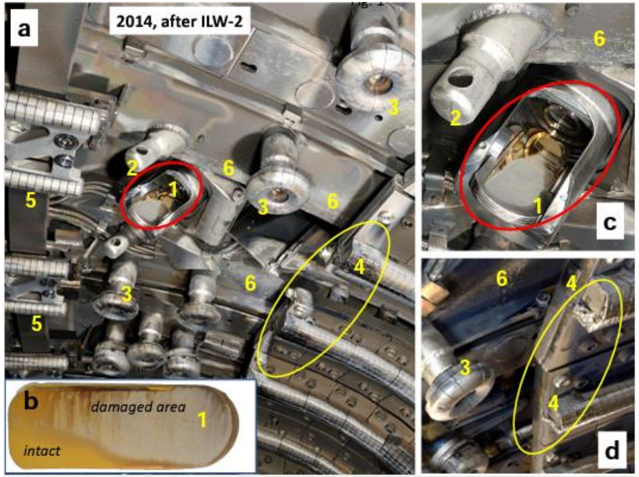
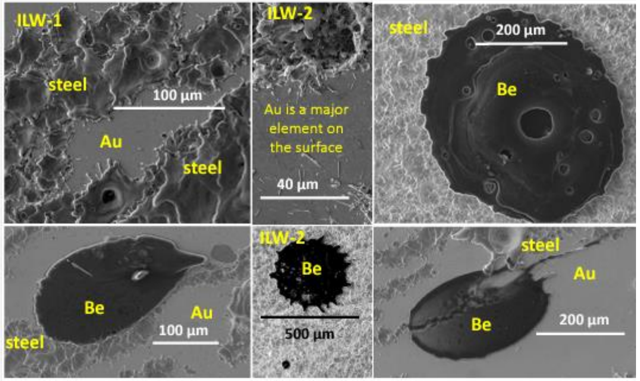


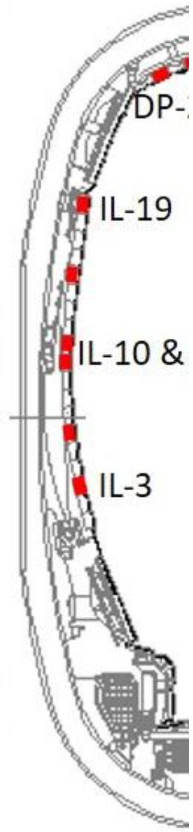
Figure S7 Close-up of Be droplets found on the outer wall in the vicinity of DP-8 with a) a scale dimension for a better understanding of the size of droplets found on the walls, while b), c) and d) are examples of droplets in different regions of the upper vessel. Scale in a) does not apply in b), c) and d).







Overview – JET's main chamber PFCs: <u>Beryllium limiters</u> – REs damage



Plasma disruption

Termination of plasma with rapid loss of thermal and magnetic energy

↓

HUGE thermal and mechanical loads on the structure

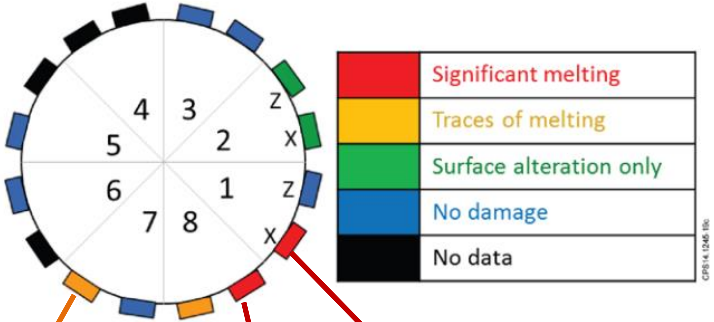
<u>Consequences of the disruptions</u>

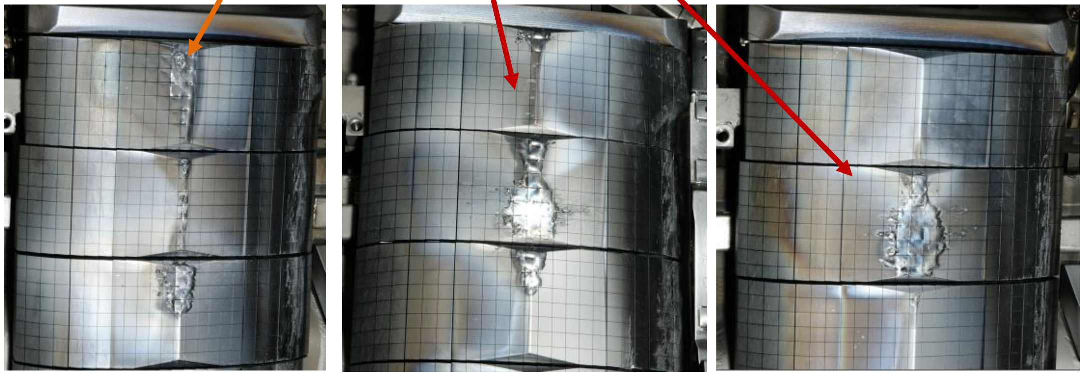
- Thermal loads/Fast melting and electromagnetic forces
- **High energy Runaway Electrons (RE)**

↓

Serious threats to future tokamaks

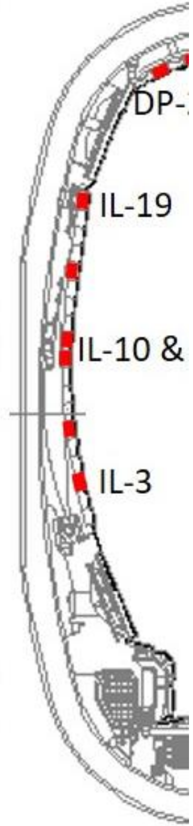
[7]



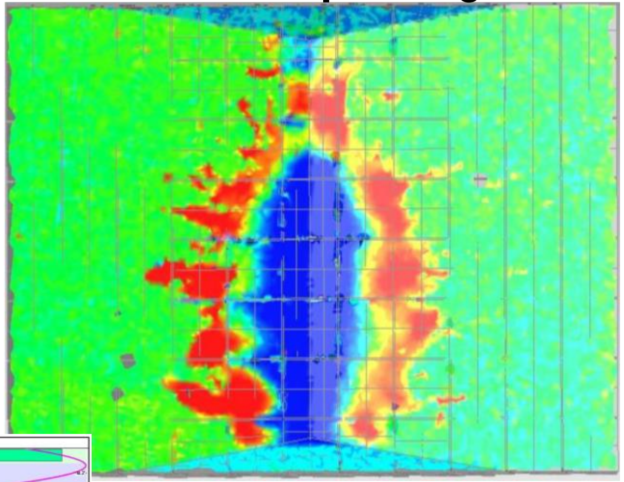


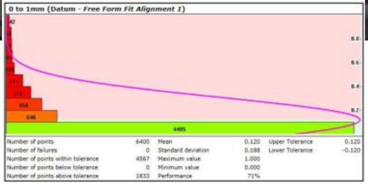
[7] C. Reux et al Nucl. Fusion 55 (2015) 093013

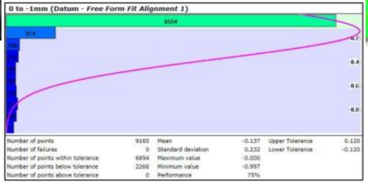
Overview – JET's main chamber PFCs: Beryllium limiters – REs damage

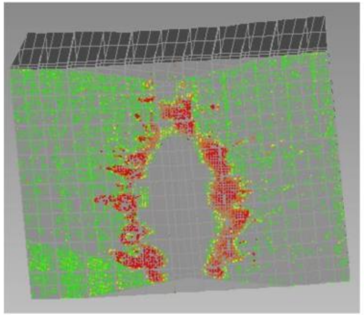


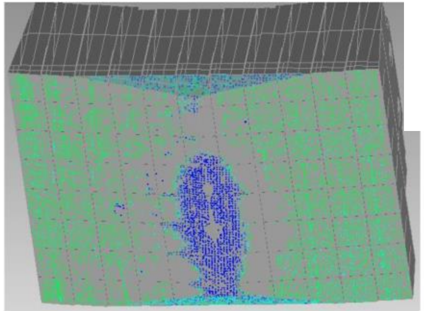
Laser 3D profiling





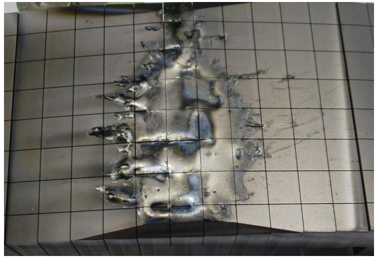


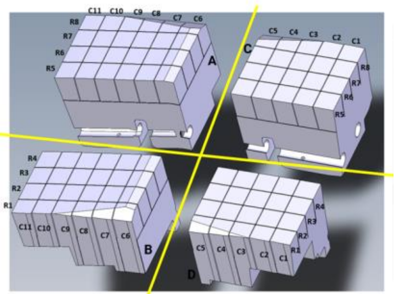


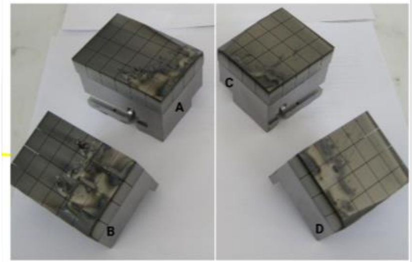


Modelling of the RE induced damage to PFC
L. Chen, R.A. Pits, M. Lehnen, C. Reux, S. Ratynskaia et al.

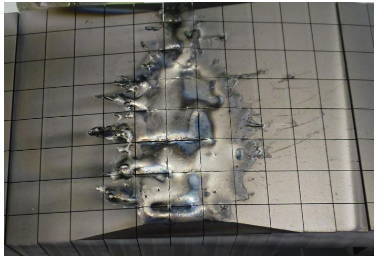
Overview – JET’s main chamber PFCs: Beryllium limiters – REs damage

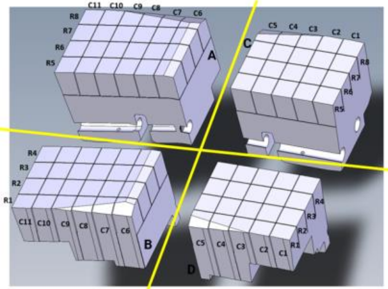


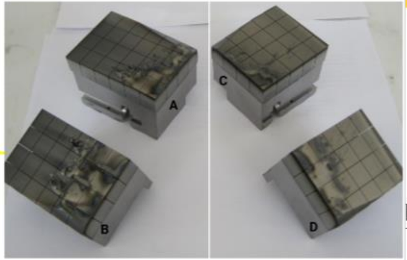




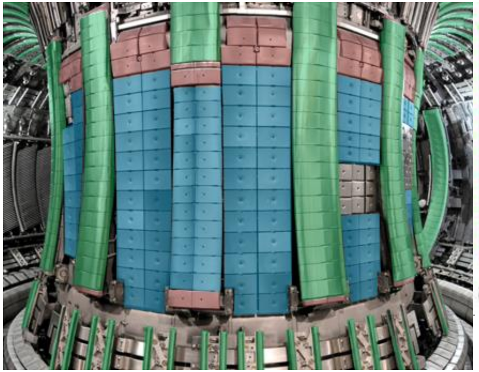
Overview – JET's main chamber PFCs: Beryllium limiters – REs damage

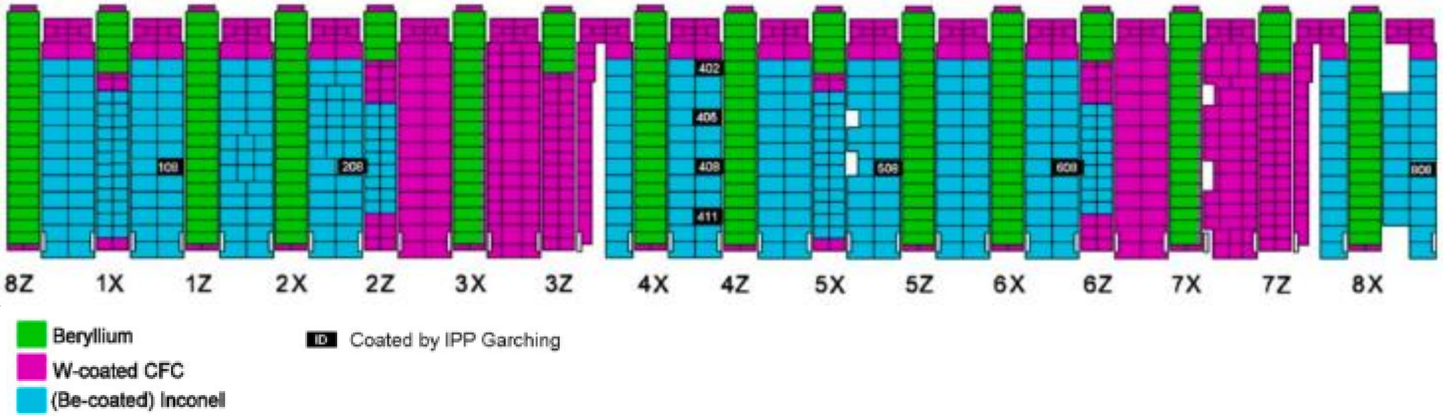






Overview – JET’s main chamber PFCs: Recessed inner wall

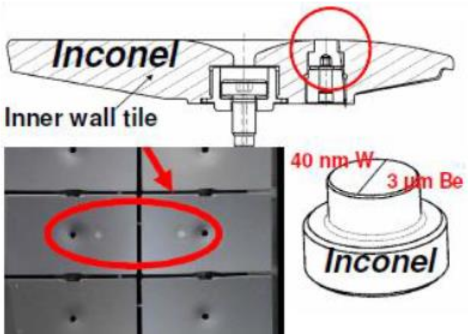




Be coated inconel

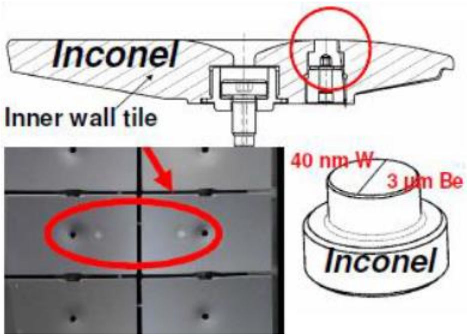
[8] S. Krat et al. Nuclear Materials and Energy 29 (2021) 101072

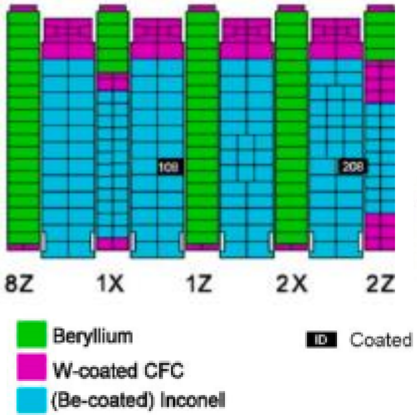
Overview – JET's main chamber PFCs: Recessed inner wall – Be/W wall inserts



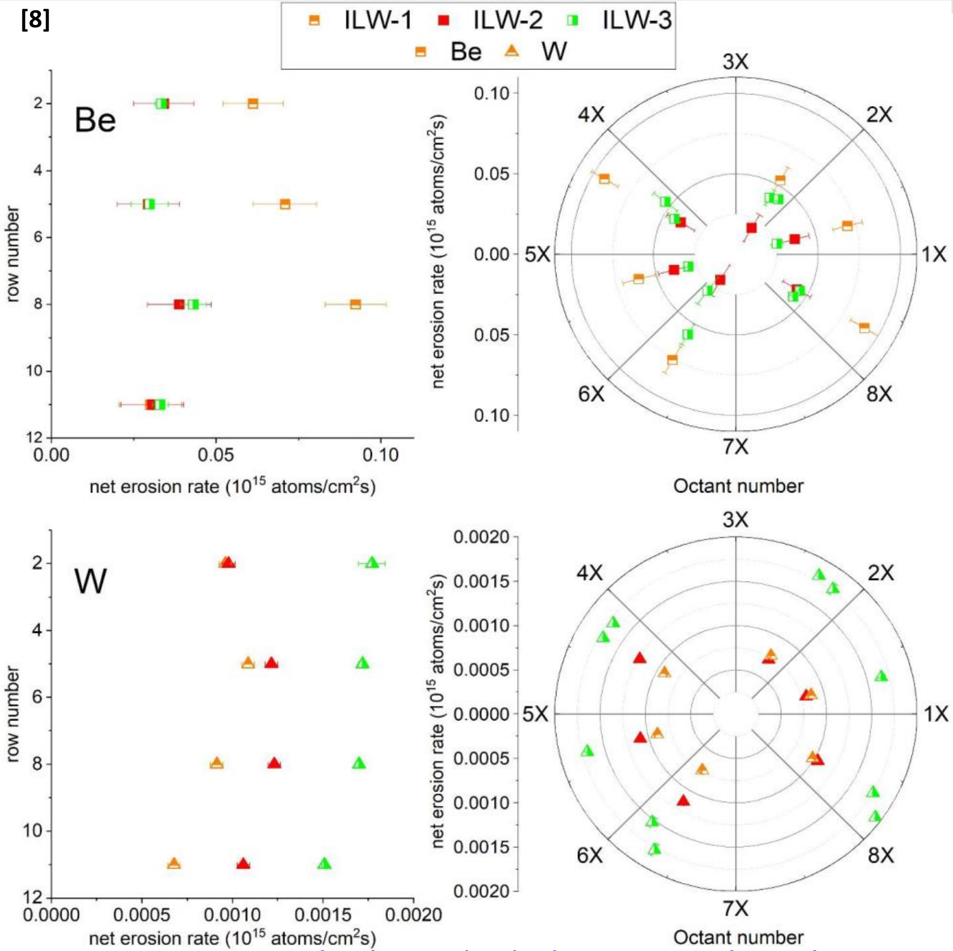
Be coated inconel

[8] S. Krat et al. Nuclear Materials and Energy 29 (2021) 101072





Be coated inconel

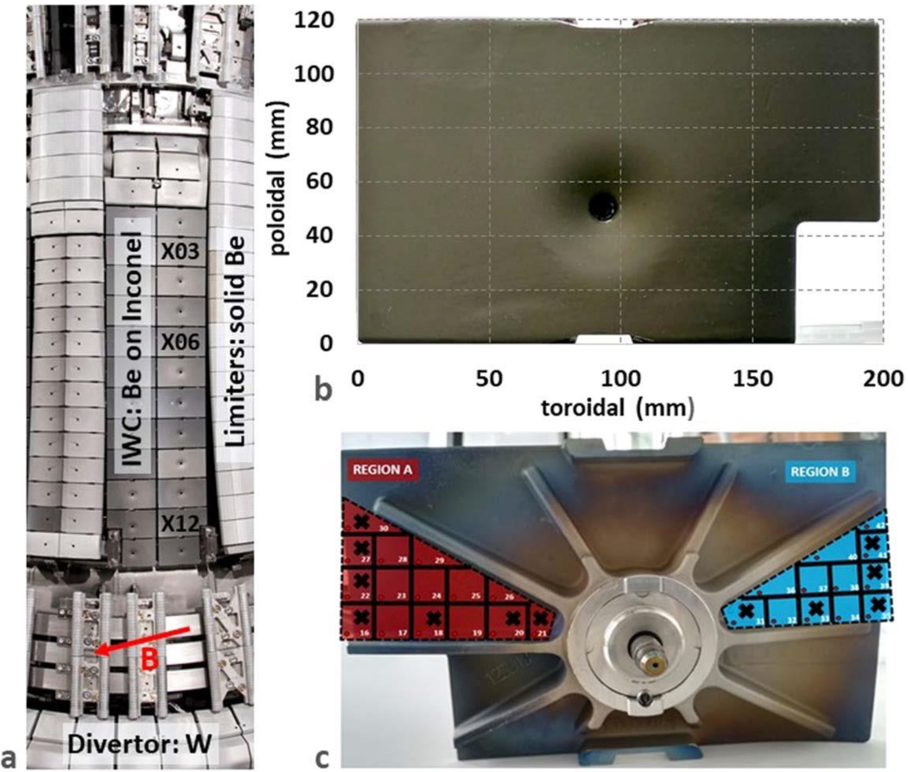


Results

- Fairly homogeneous erosion rate in toroidal and poloidal directions, both for Be & W.
- Variation of erosion rate within factor 2 for all 3 ILW campaigns
- Very small erosion rate for W < 0.3 pm/s

[8] S. Krat et al. Nuclear Materials and Energy 29 (2021) 101072

[9]



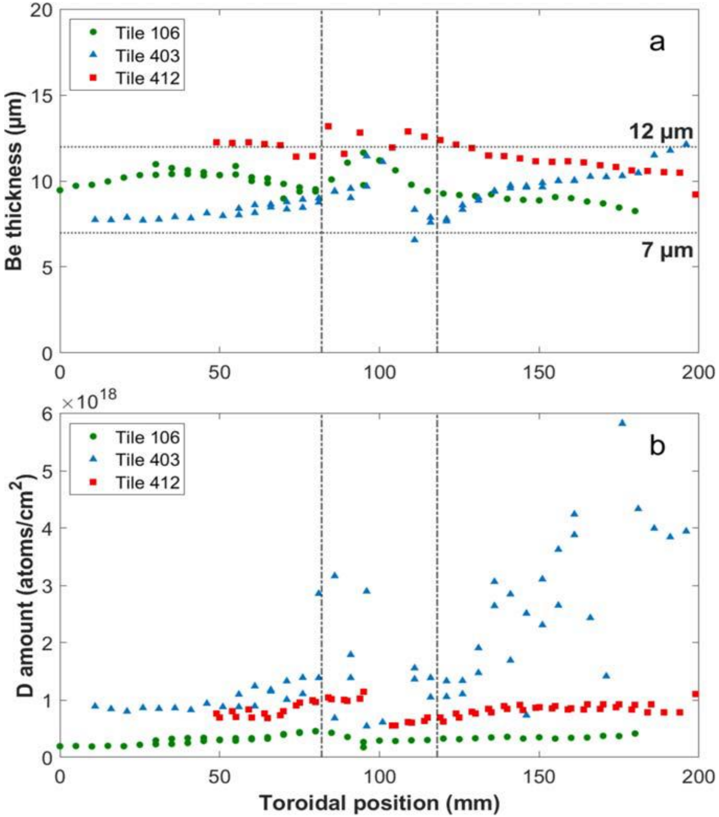
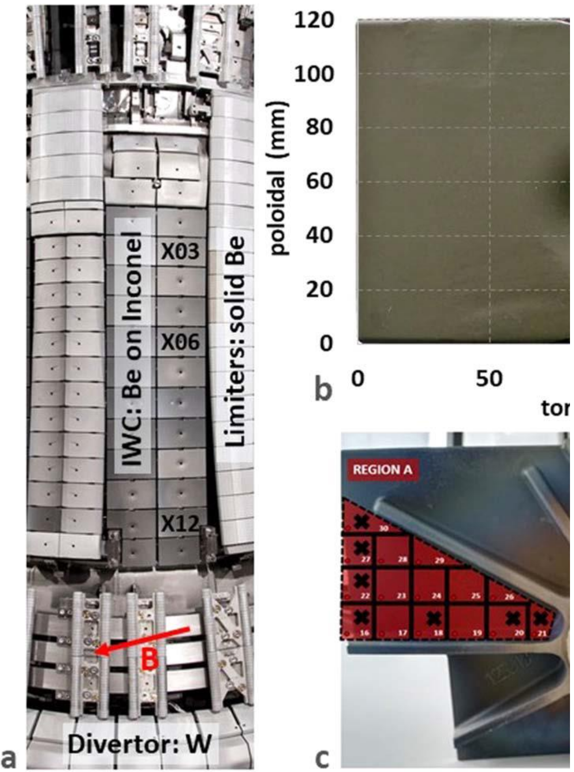


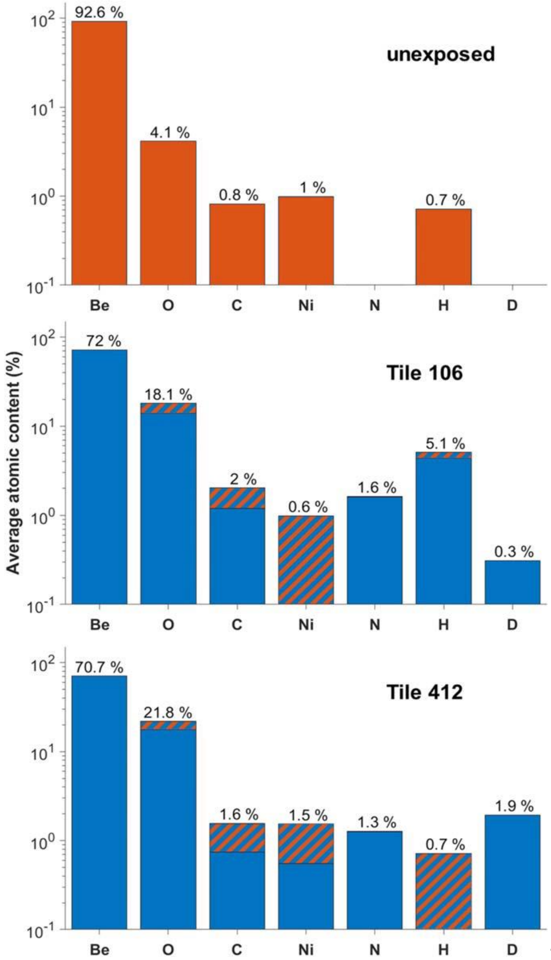
Figure 2. Toroidal profiles of (a) beryllium layer thickness and (b) deuterium retention on the IWC tiles, measured with a 2.3 MeV $^{3}He^{+}$ and H^{+} beam. The Be layer thickness is given for an assumed material density of $1.85\frac{g}{cm^3}$.

[9] L. Dittrich et al. Phys. Scr. 96 (2021) 124071

Overview – JET's main chamber PFCs: Recessed inner wall – Be-coated Inconel (ERDA and ^{3}He-NRA)

[9]



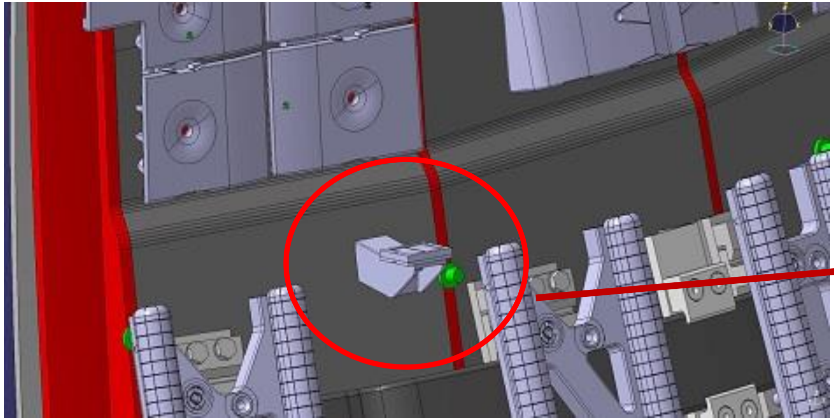


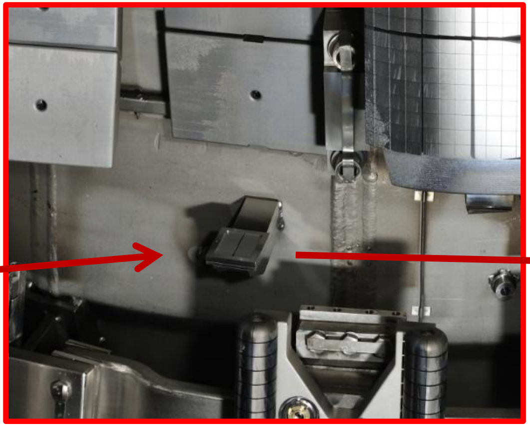
Results

- Total D retention amounts to 5.3×10^{22}Datoms (176mg) in the entire IWC beryllium coating for ILW 1–3 (equal to the sum ofDatoms on IWGL and OPL, as assessed after ILW1–3 and it is five times smaller than determined for the divertor);
- The Be layer thickness on the exposed tiles is not uniform, but in neither place it is less than 7 µm thick;
- There are no signs of complete erosion. This proves good long-term adherence to the Inconel substrate;
- No material mixing with the substrate components has been identified.

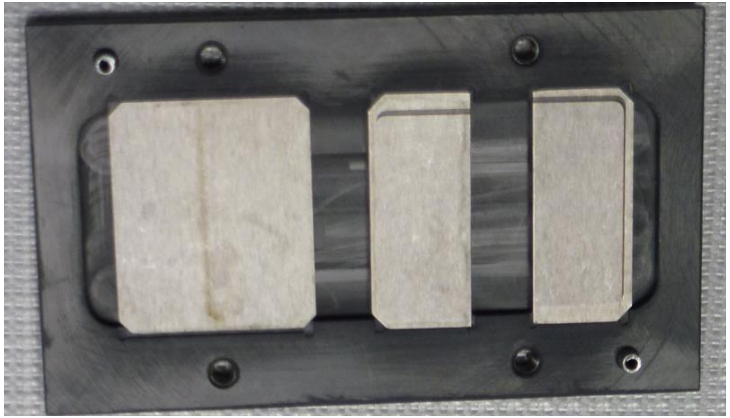
[9] L. Dittrich et al. Phys. Scr. 96 (2021) 124071

Overview – JET's main chamber PFCs: Recessed Inner wall – Sticking monitors

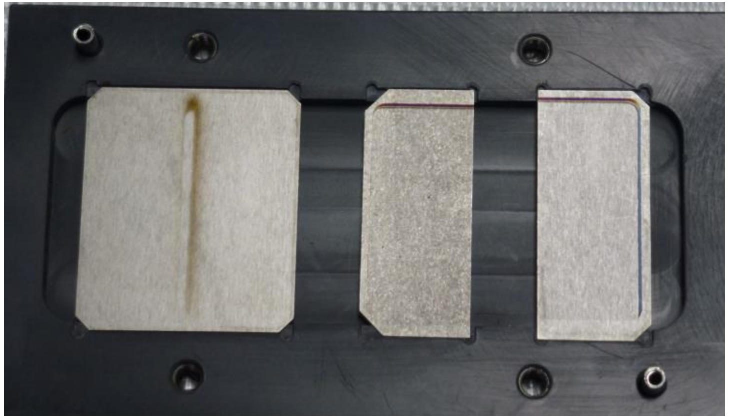




OCT3



OCT5

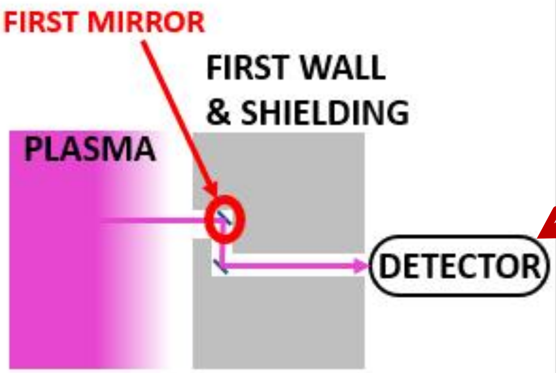


Data available: Univ. of Helsinki

Overview – JET's main chamber PFCs: <u>Recessed Outer wall</u> – Mirrors

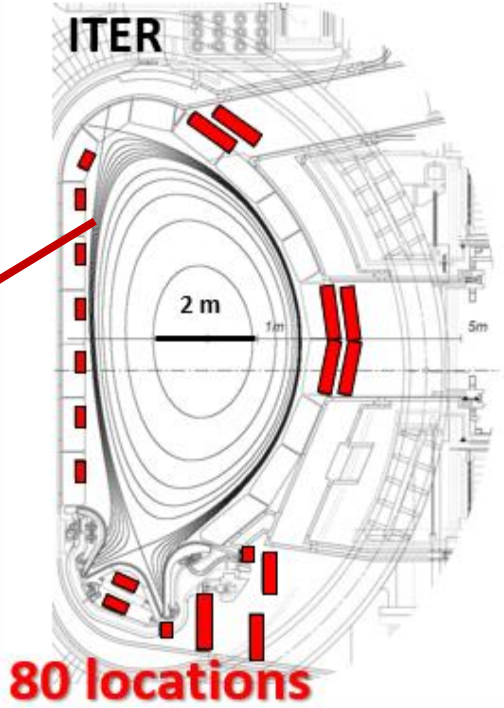
CONCEPT	PLAN	TEST

CONCEPT

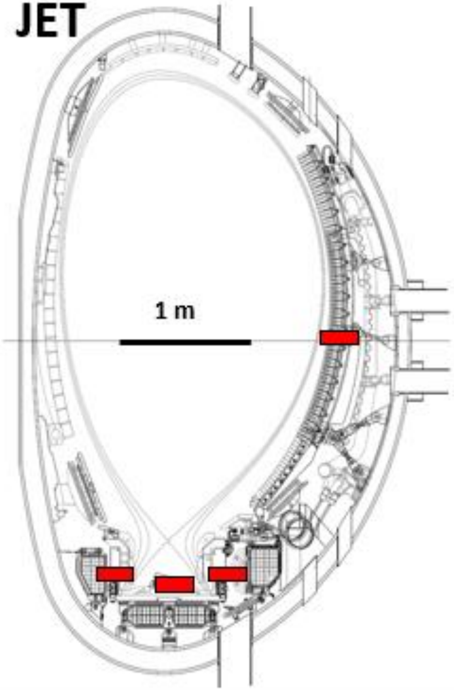


Protection against neutrons

PLAN

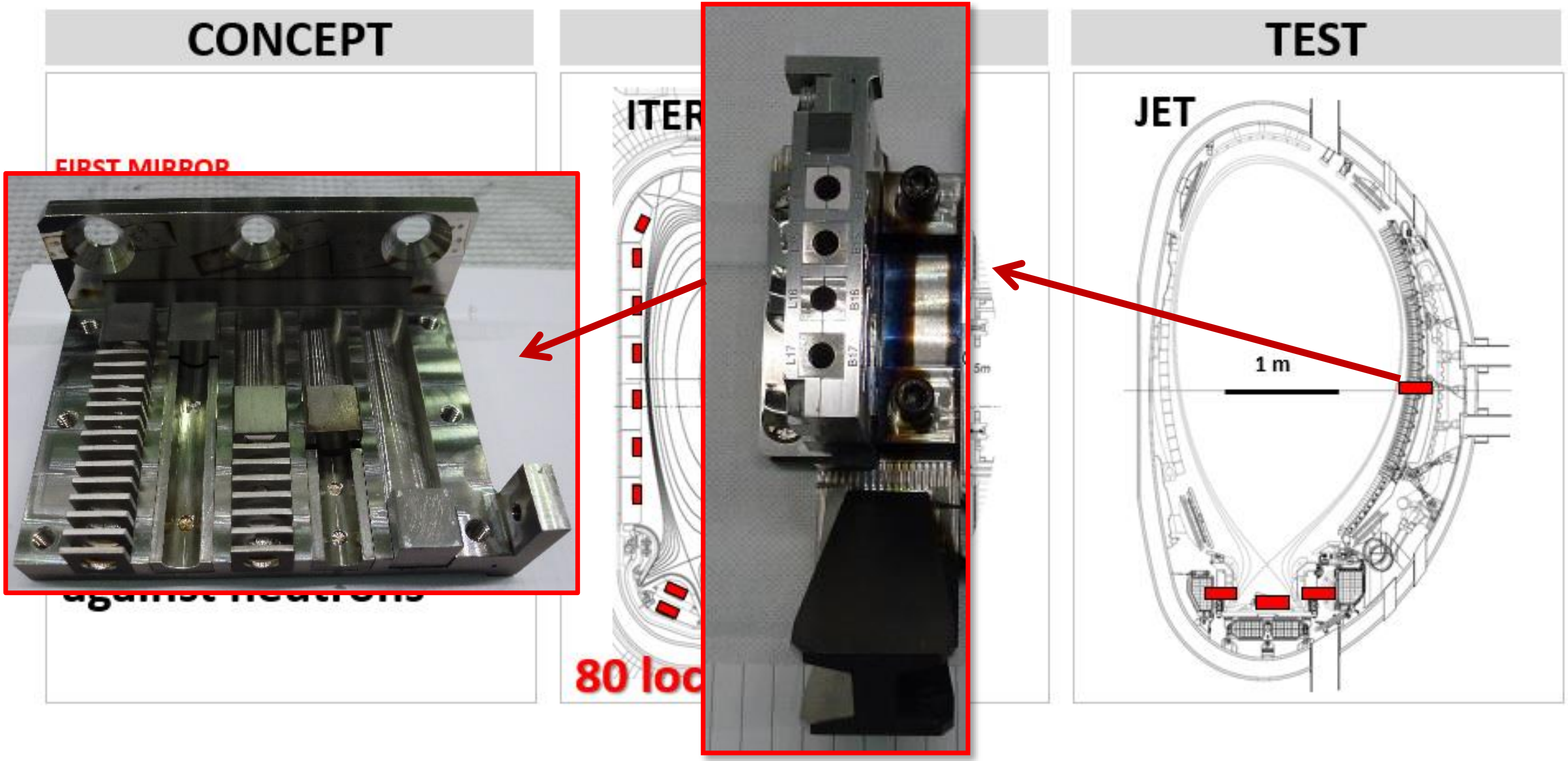


TEST



[10] S. Moon, et al. Nuclear Materials and Energy 19 (2019) 59–6

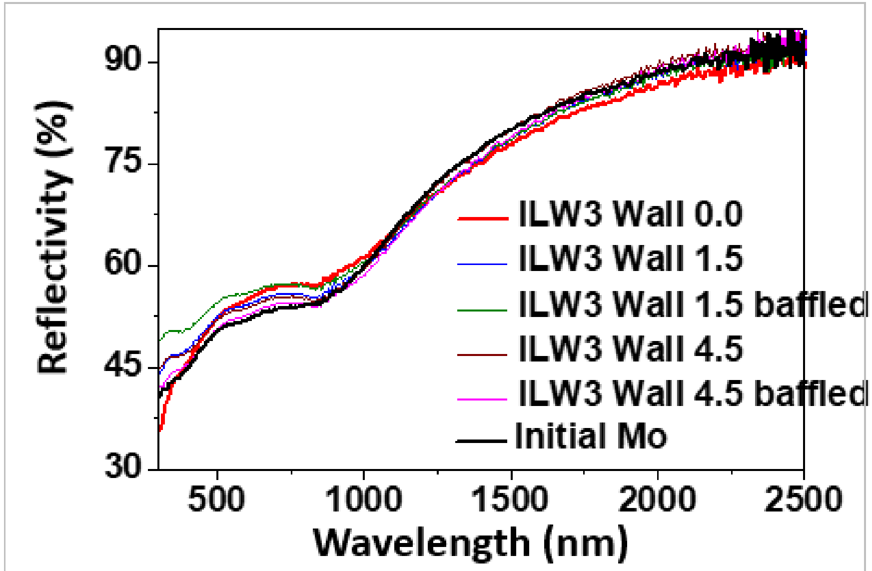
Overview – JET's main chamber PFCs: Recessed Outer wall – Mirrors



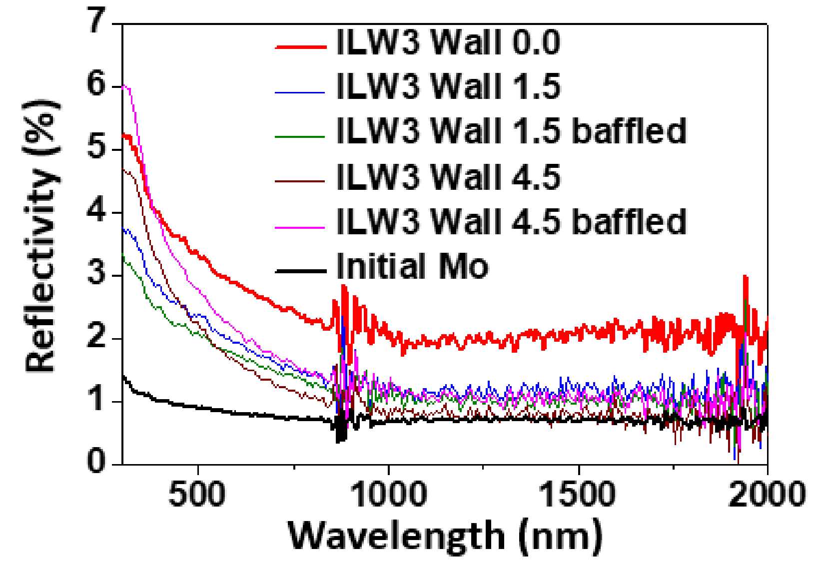
[10] S. Moon, et al. Nuclear Materials and Energy 19 (2019) 59–6

Overview – JET's main chamber PFCs: Recessed Outer wall – Mirrors - Reflectivity

TOTAL reflectivity



DIFFUSE reflectivity

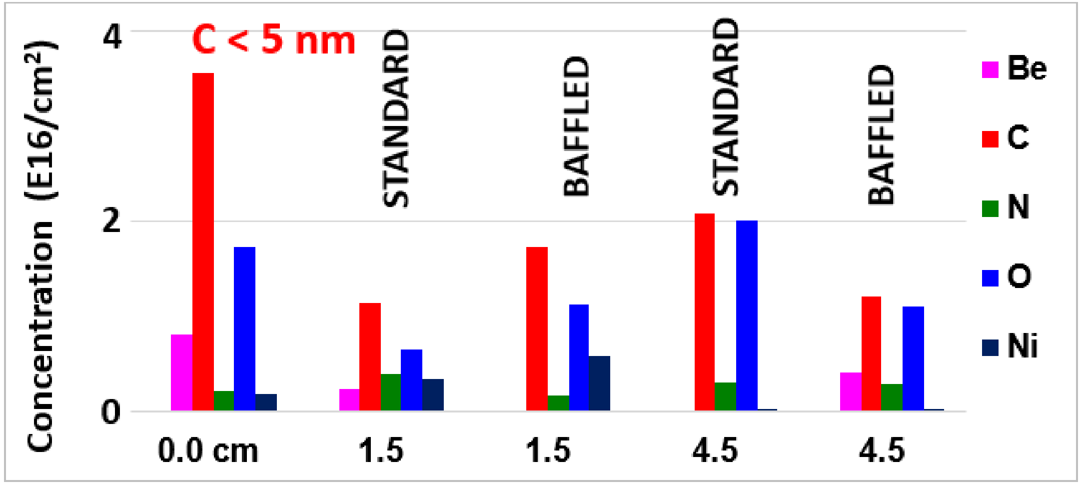


- **Small changes of total reflectivity** *(position independent)*
- **Increase of diffuse reflectivity** *(especially at the cassette mouth)*

[10] S. Moon, et al. Nuclear Materials and Energy 19 (2019) 59–6

Overview – JET's main chamber PFCs: Recessed Outer wall – Mirrors - Surface

Composition



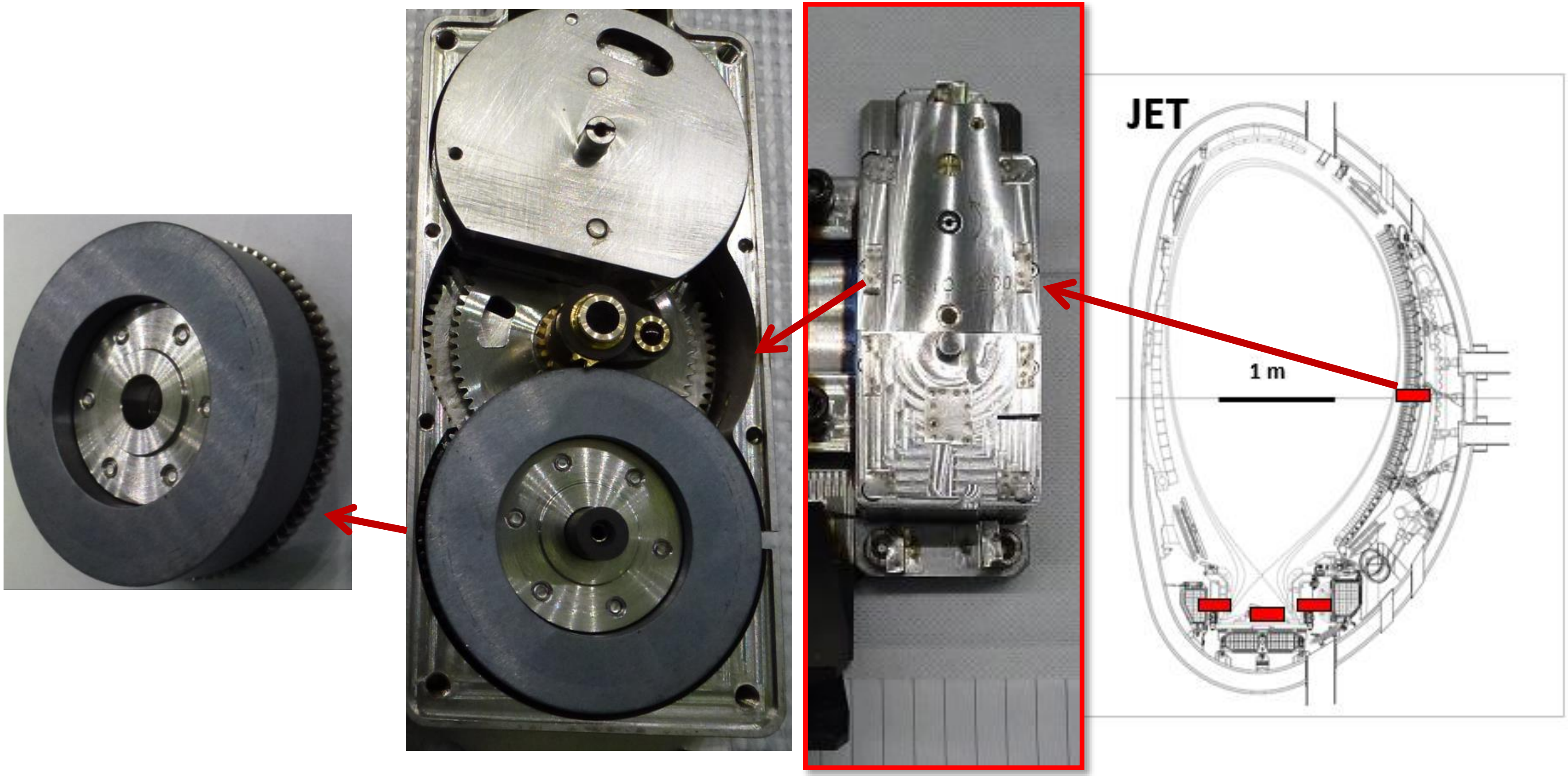
Roughness

Mirror	R_a (nm)
0.0 cm	8.48
1.5 cm	5.77
1.5 cm baffled	6.20
4.5 cm	4.87
4.5 cm baffled	4.72

- Composition: very small quantities of C, N, O, Be, Ni.
- Nitrogen is detected on all mirrors (and on all analysed PFC).
- No difference in deposition between standard and baffled channels.

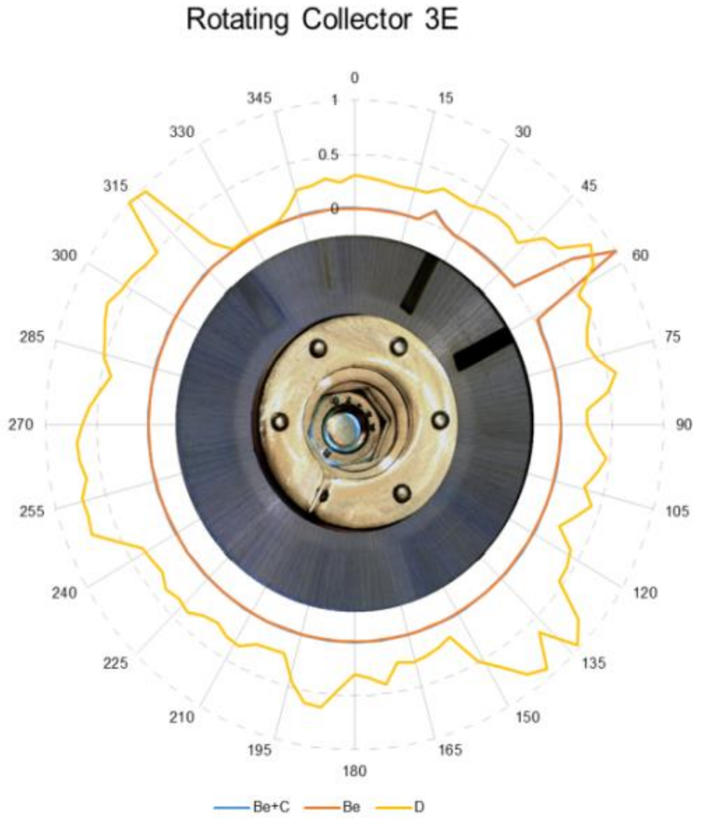
[10] S. Moon, et al. Nuclear Materials and Energy 19 (2019) 59–6

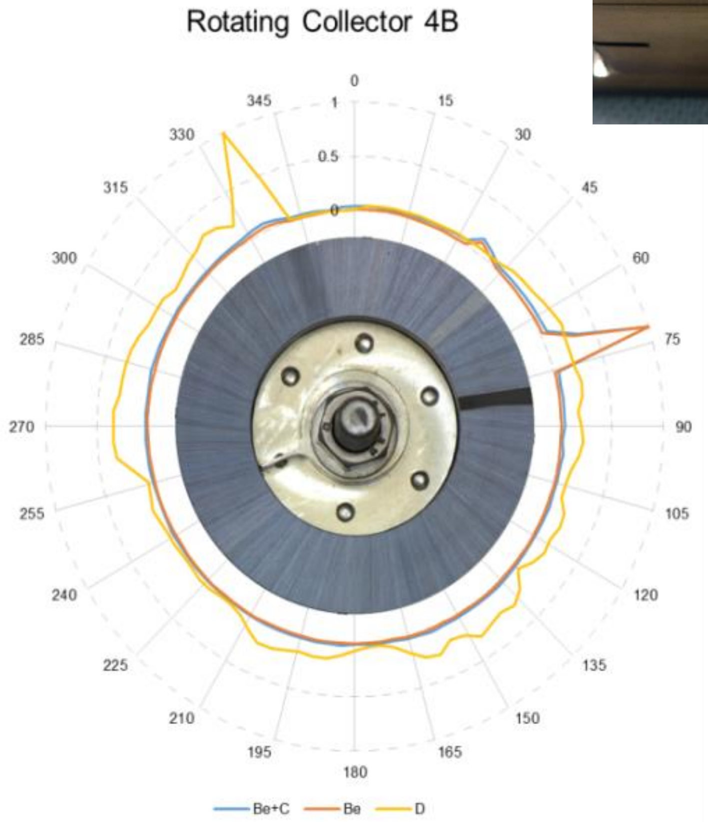
Overview – JET's main chamber PFCs: <u>Recessed Outer wall</u> – Rotating Collectors



Overview – JET's main chamber PFCs: Recessed Outer wall – Rotating Collectors

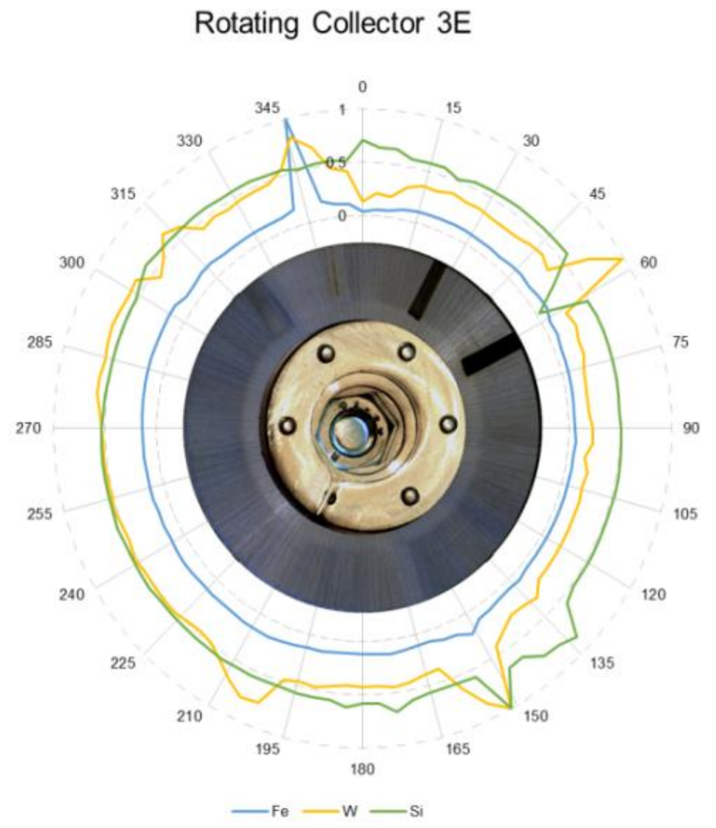
ILW-2

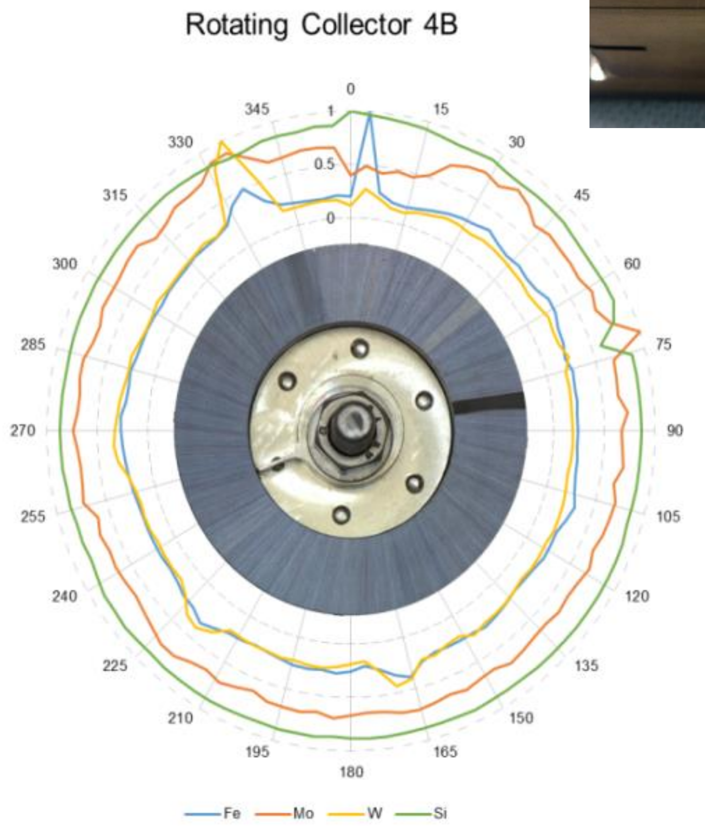




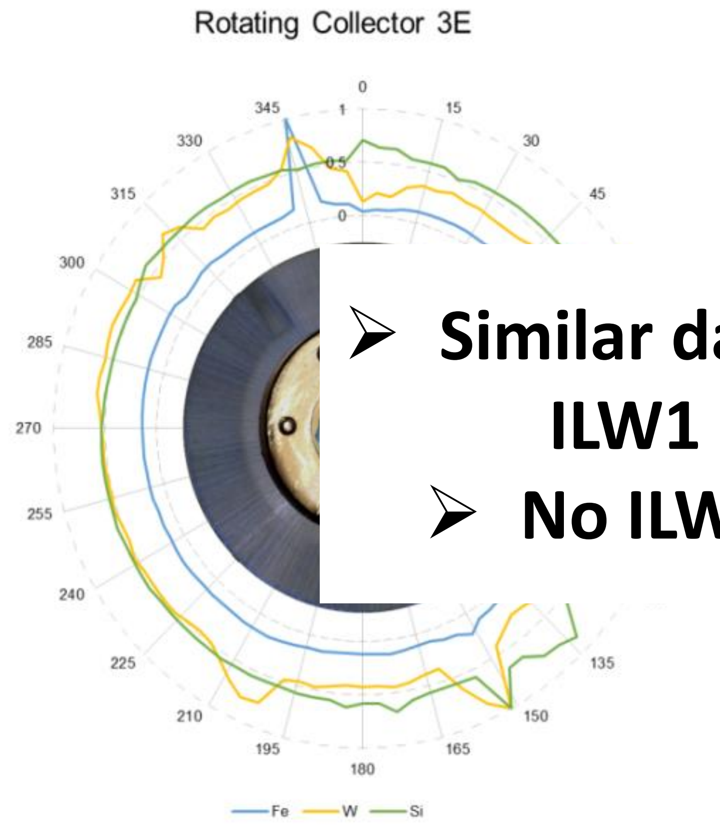
Overview – JET's main chamber PFCs: Recessed Outer wall – Rotating Collectors

ILW-2





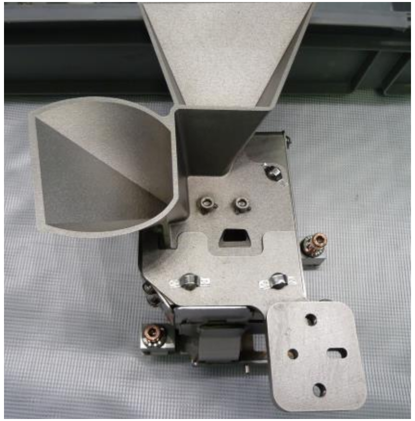
Overview – JET's main chamber PFCs: Recessed Outer wall – Rotating Collectors

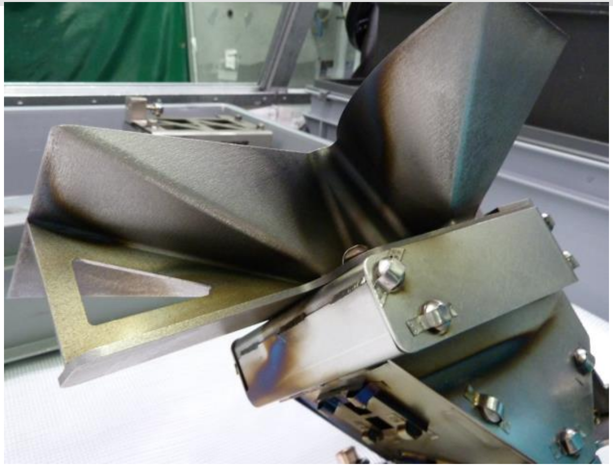


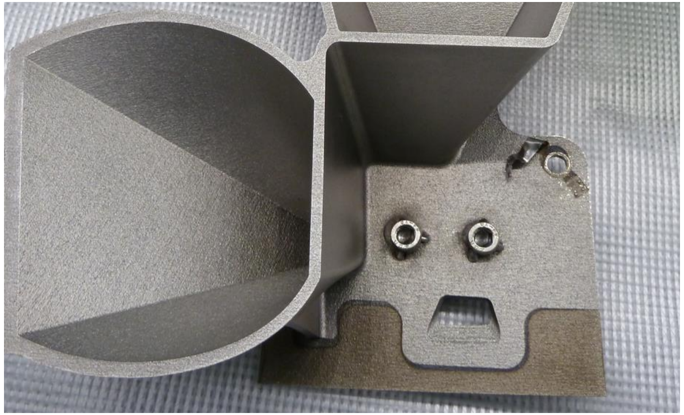
- ➢ **Similar data available for ILW1 RCs (3E&4B)**
- ➢ **No ILW3 data on 4B**

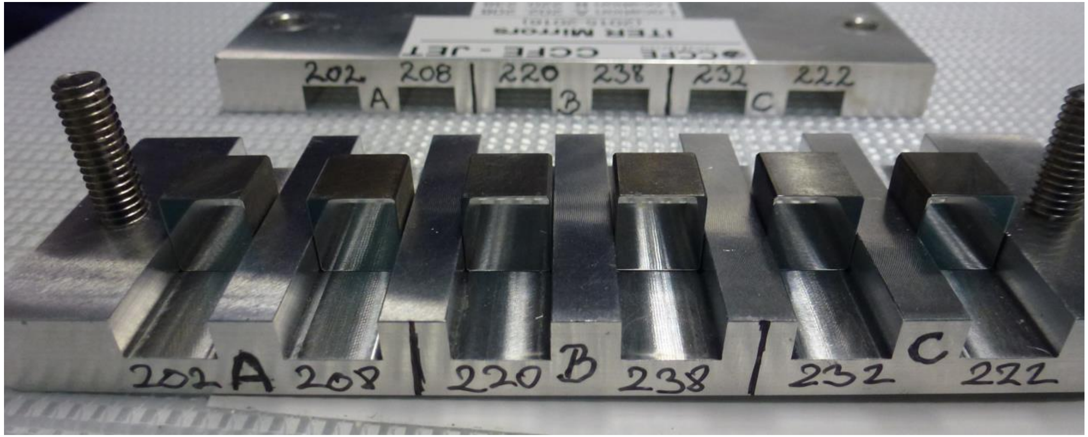
N. Catarino, E. Alves, IST, Portugal

Overview – JET’s main chamber PFCs: Recessed Outer wall – ITER mirror assembly









Overview – JET's main chamber PFCs: Fuel retention and material migration in gaps of Be tiles

IOP Publishing | International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion 57 (2017) 066027 (7pp) https://doi.org/10.1088/1741-4326/aa6864

Fuel inventory and deposition in castellated structures in JET-ILW

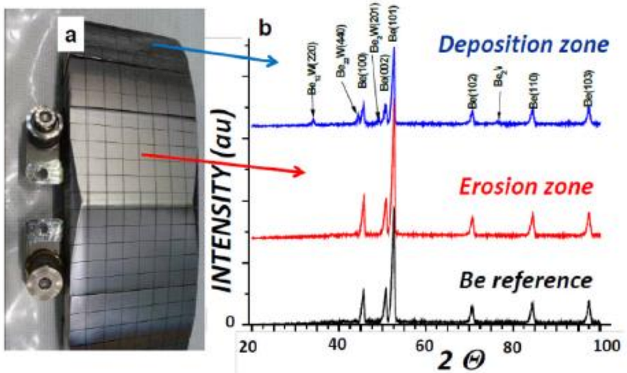


Figure 2. Castellated beryllium limiter tile from JET-ILW (*a*); x-ray diffractograms recorded for the initial limiter surface, erosion and deposition zones (*b*).

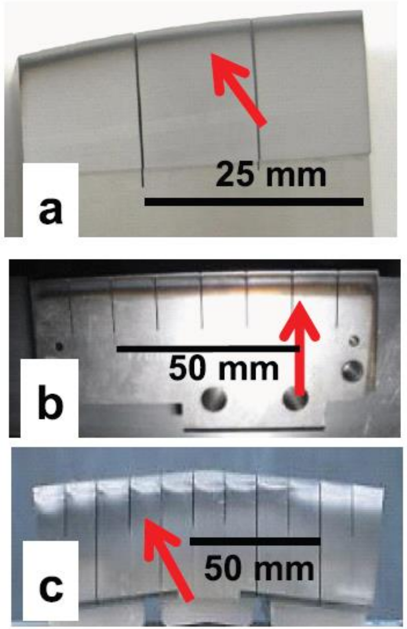


Figure 3. Deposition in the castellated groove (*a*); deposits of different width on the side surfaces of the tiles, in the gaps between the tiles (*b*) and (*c*).

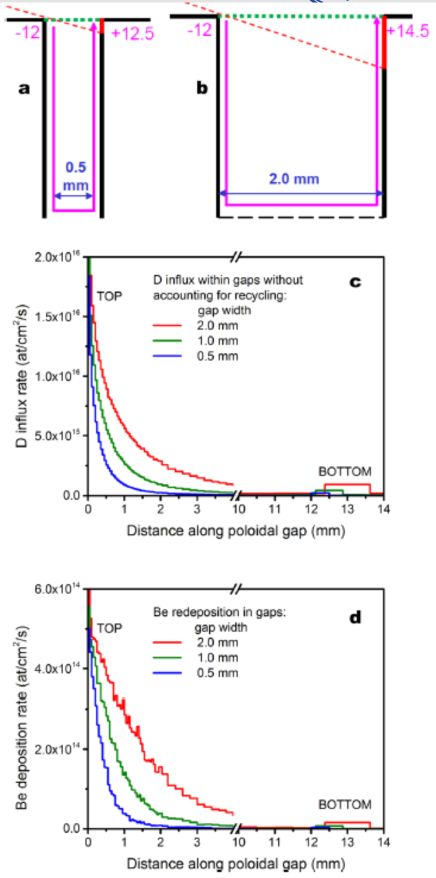


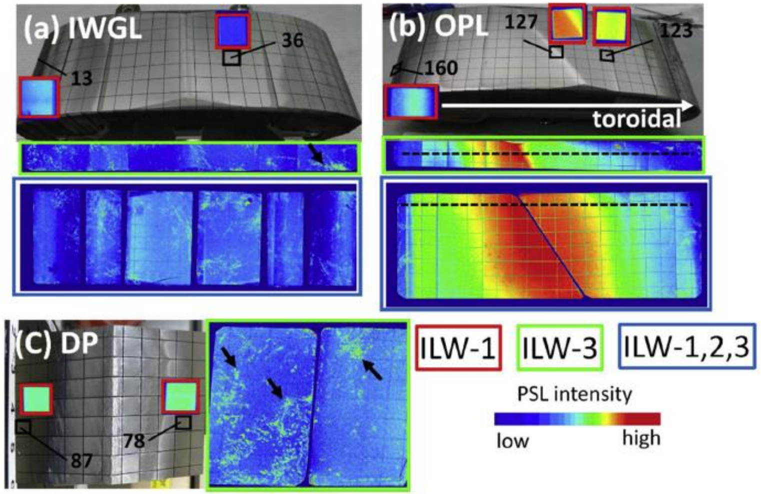
Figure 8. Modelling of deposition in the castellation: geometry of the gaps (*a*) and (*b*); simulated deposition profiles of deuterium (*c*) and beryllium (*d*) in the gaps of various widths.

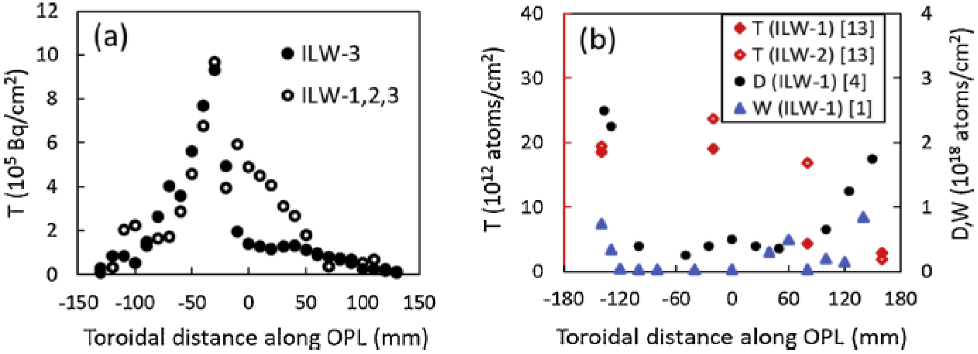
- Very shallow deuterium deposition is measured in the castellation: 0.5–1.5 mm deep into the groove
- Small quantities of D are found in the castellation both in the erosion and deposition zones. No difference is observed between the poloidal and toroidal gaps
- No dust accumulation was detected inside the castellation

[11] M. Rubel et al. Nucl. Fusion 57 (2017) 066027 (7pp)

Overview – JET's main chamber PFCs: Fuel retention→ difference between D and T in limiter tiles

Tritium distribution analysis of Be limiter tiles from JET-ITER like wall campaigns using imaging plate technique and β-ray induced X-ray spectrometry





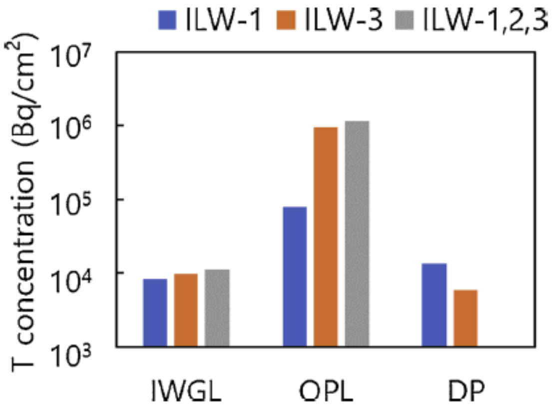


Fig. 6. Concentration of T evaluated from PSL intensity obtained by IP measurement. The regions with the highest PSL intensity were selected.

- ➢ **The observed T distributions on PFSs showed no systematic correlation with those of metallic impurities and D**
- ➢ **The highest T concentration was observed at the centre of OPL where the concentrations of D and metallic impurities showed the minimum values**
- ➢ **This difference in distributions indicated different deposition and retention mechanisms between T and D.**

[12] S.E.Lee et al. Fusion Engineering and Design 160 (2020) 111959

Conclusions

Be limiters

- IBA data for IL, OL and DP covering toroidal (throughout the “length” of entire tile) and poloidal distribution (bottom, mid and top part of JET vessel) for D and impurities (W, Ni, Cr, Fe) distribution for individual and combined campaigns available;
- Similar D distribution available via TDS analysis (not presented here)
- T assessment via IP measurements → different behaviour as compared with D distribution;
- D and impurities assessment in gaps available
- Melting due to VDEs and REs, splashes, material distribution around main chamber data available
- Microscopy, SEM, EDX, XRD, roughness available for pretty much all limiters (not presented here)

Recessed inner and outer walls

- Results from Inconel inserts available;
- Results from Be coated Inconel tile samples;
- RC results available.

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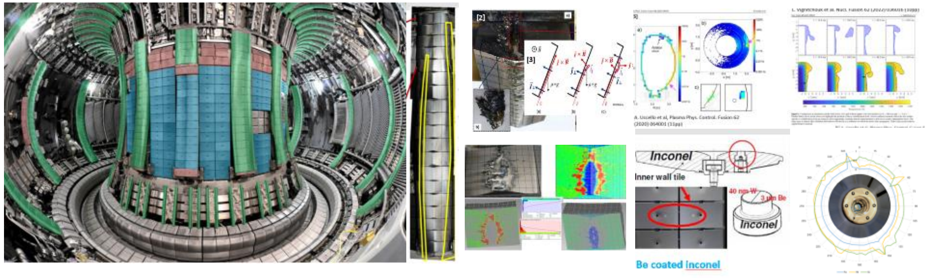

Thank you for your attention!