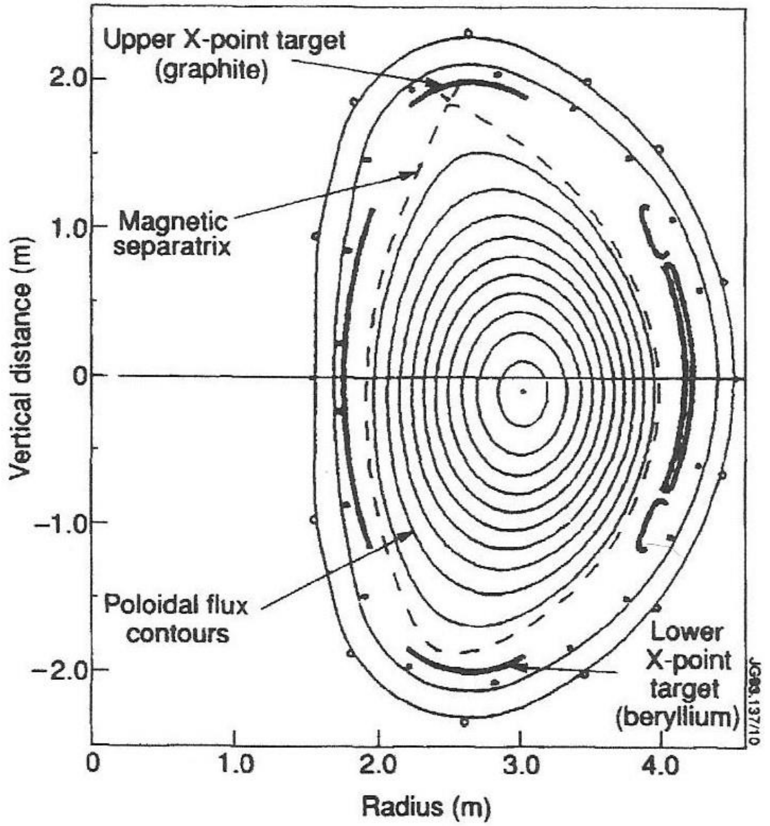
Erosion/deposition/modelling in JET

J Paul Coad on behalf of all the scientists/technicians
that have contributed in this field

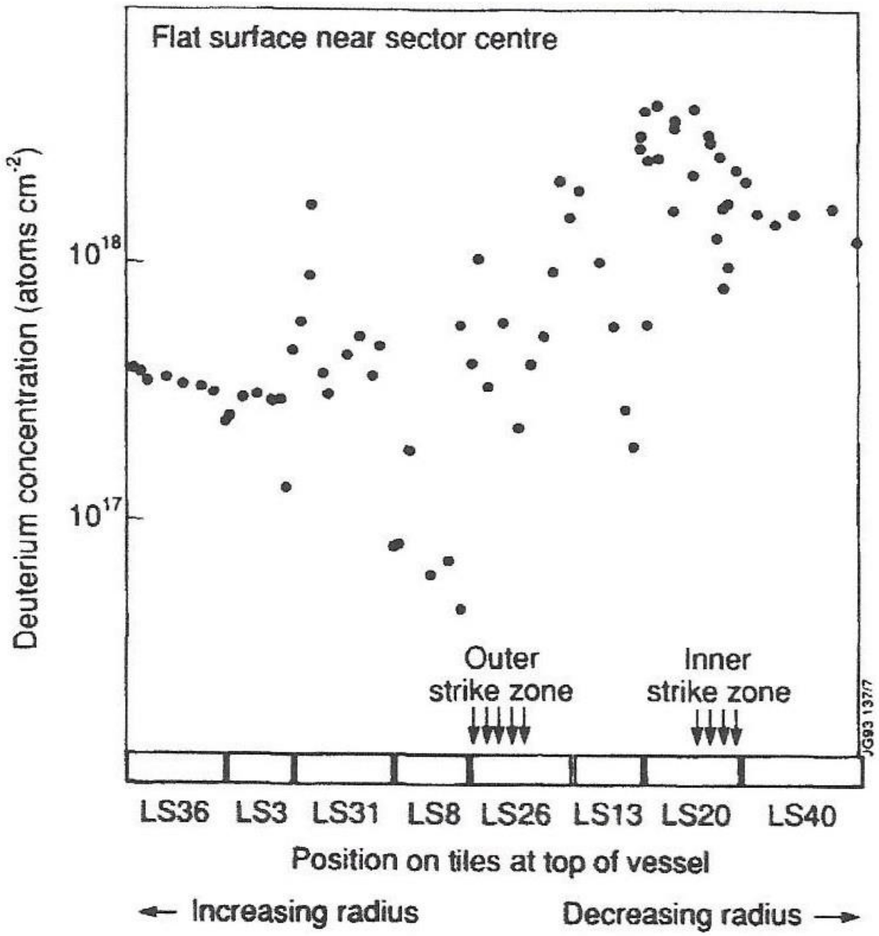
- Deposition in the JET MkI and MkIIA divertors and JET ILW campaigns
- Lessons learnt for modelling
- Don’t forget erosion! Methods of/attempts at/ measurement
- Time resolution
- Latest data

JET

Vertical X-point 1991-2



Cross-section of the JET vessel showing the principal first-wall components and a typical plasma shape for the upper X-point configuration.



A plot of deuterium versus position on the target tiles, along a radial line across all eight rings of tiles at the centre of the sector (where the tiles are each flat).

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MkI divertor 1994-5

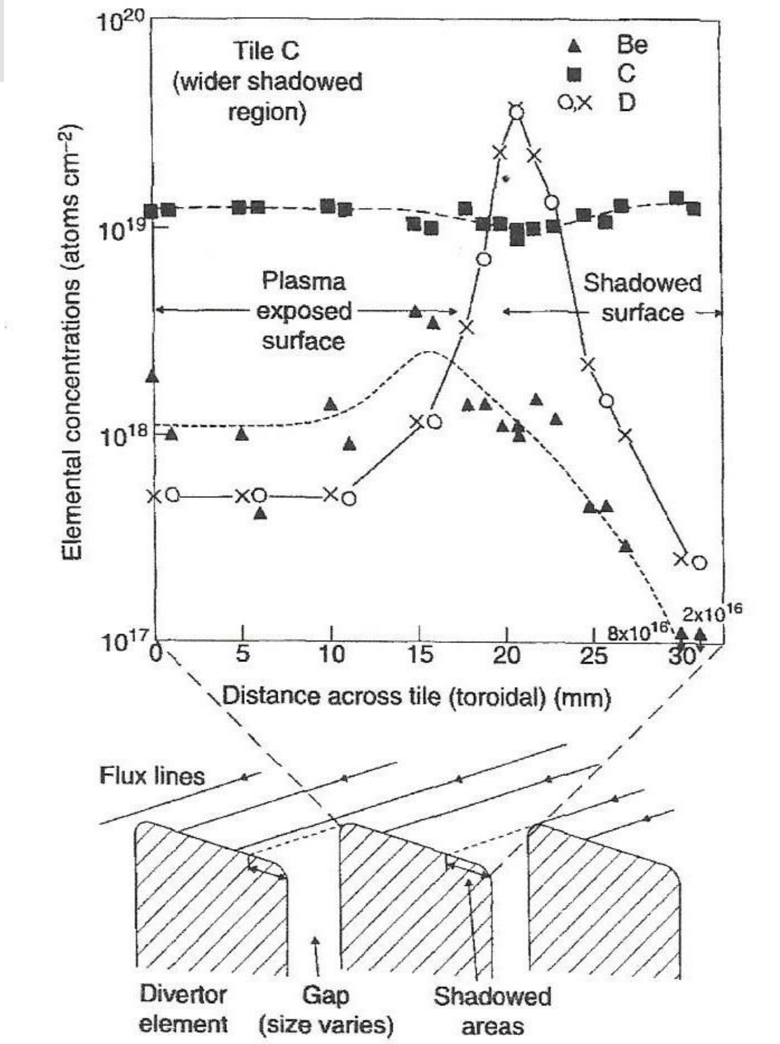

Fig. 2. Upper part: C, Be and D analyses by NRA along two adjacent lines across (toroidally) graphite tile 12 A. (D results for one line indicated by crosses, the other by circles.) Lower part: a schematic toroidal cross-section of some divertor tiles to show the shadowing of part of each tile by its neighbour.

J.P. Coad et al. / Journal of Nuclear Materials 241–243 (1997) 408–413

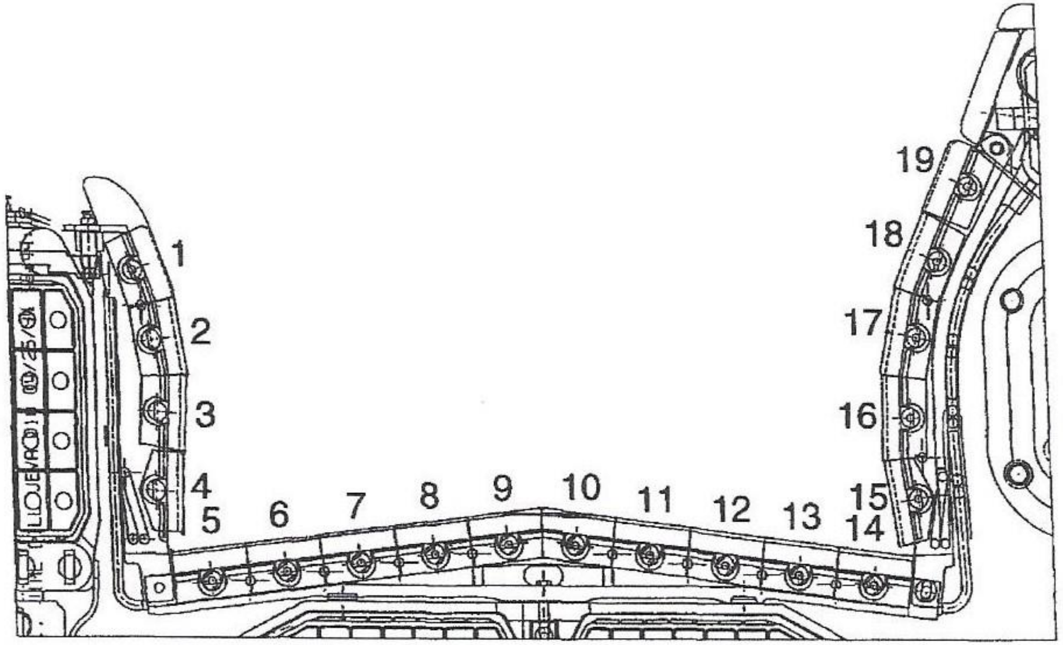

Fig. 1. Radial cross-section of the JET Mark I divertor in use during 1994 and 1995.

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Conclusions from MkI divertor phases

1. Most deposition occurs at the inner divertor.
2. Most of the deposited material has come from erosion in the main chamber, as during the Be divertor phase the deposition is still predominantly C.
3. Deposition occurs in the shadowed areas of the divertor base tiles at both inner and outer strike points
4. At the inner divertor corner the deposition extended all the way down the sides of the tiles into the gaps between them (leading to the sub-divertor).

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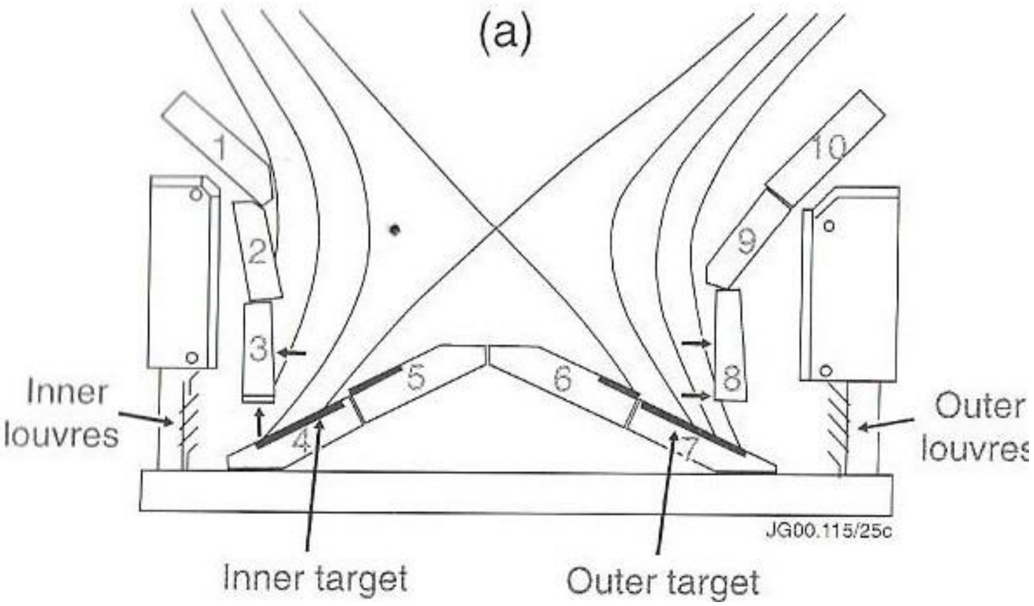
The MkIIA divertor 1996-8

1. The MkII divertor structure featured solid water-cooled side and base plates, with channels to the sub-divertor pumps only at the inner and outer corners. The carbon tiles were mounted on structures attached to these plates.
2. In 1996 heavy deposition was observed at the inner divertor corner, with films up to 40 m thick on the tiles and on the louvres beyond the opening (Peacock 1999)
3. Following the DTE1 campaign in 1997 154g of dust/flakes were collected from the inner corner containing 520mg tritium, with a further 1kg of flakes estimated to have passed through (Coad 2001).
4. Negligible deposition was found at shadowed areas on tiles within the divertor



Modelling implications

A number of additional physical properties were necessary to classical models (e.g. Brooks 1990) to explain JET data (Coad 1999).

1. Drift in the scrape-off layer (SOL) from outboard to inboard
2. Significant interaction between the plasma and the main chamber walls
3. Different properties for deposited films in the divertor

Drift in the SOL was observed using the RCP at the top of the JET Vessel (e.g. Erents et al 1999 measured drifts up to Mach 0.35-0.6)
Measured erosion in the main chamber must be by ions as well as CXN (e.g. Mayer 1997)
High recycling coefficients have been observed from films (von Keudel 1999), in the JET divertor (Stamp 2001) and modelled (50% estimated using DIVIMP – Stangeby 2001), (Kirschner 2004)

Something is still missing to explain the nature of the ***flow*** towards the sub-divertor as will be clear from Anna's talk

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Measuring erosion/deposition in JET

Erosion is much more difficult to measure than deposition, and many methods have been tested in JET.

1. Mechanical: CNC machine whole tile limiter tiles, C^{13} implants, micrometer measurements of MkIIGB divertor tiles (Coad 2003), laser profiling
2. W stripes on CFC tiles (Lehto 2003), W interlayer with carbon overlayer
3. Whole Be tile coating with Ni + Be overlayer, W coated CFC tiles with Mo + W overlayer (Krat 2020), (combined with laser profiling - Widdowson)
4. Marker samples at the inner wall (Mayer 1999, Krat 2015)
5. Cavity collectors in shadowed areas of the divertor (Mayer 2003)

At best, these methods only give an integrated amount of erosion for an entire JET campaign (typically >3000 pulses, varying in nature).

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Time resolved deposition in JET

Two devices were designed to provide measurements of deposition in JET with an element of time resolution – in locations shadowed from the plasma (Coad 2005)

1. Quartz Microbalance (QMB). The QMB has a quartz sensing crystal behind an aperture covered by a shutter. Deposition is derived from mass change of the crystal whilst the shutter is opened (which may be for a single, or even part-, pulse) (Esser 2004)
2. Rotating collector. A cylindrical disc (C or Si) rotates behind a slit and advances after every JET pulse. A complete revolution takes ~3000 pulses – time resolution is ~20 pulses (slit width) enables correlation with discharge type (Beal 2015, **Catarino 2017**)

Phys. Scr. T170 (2017) 014059

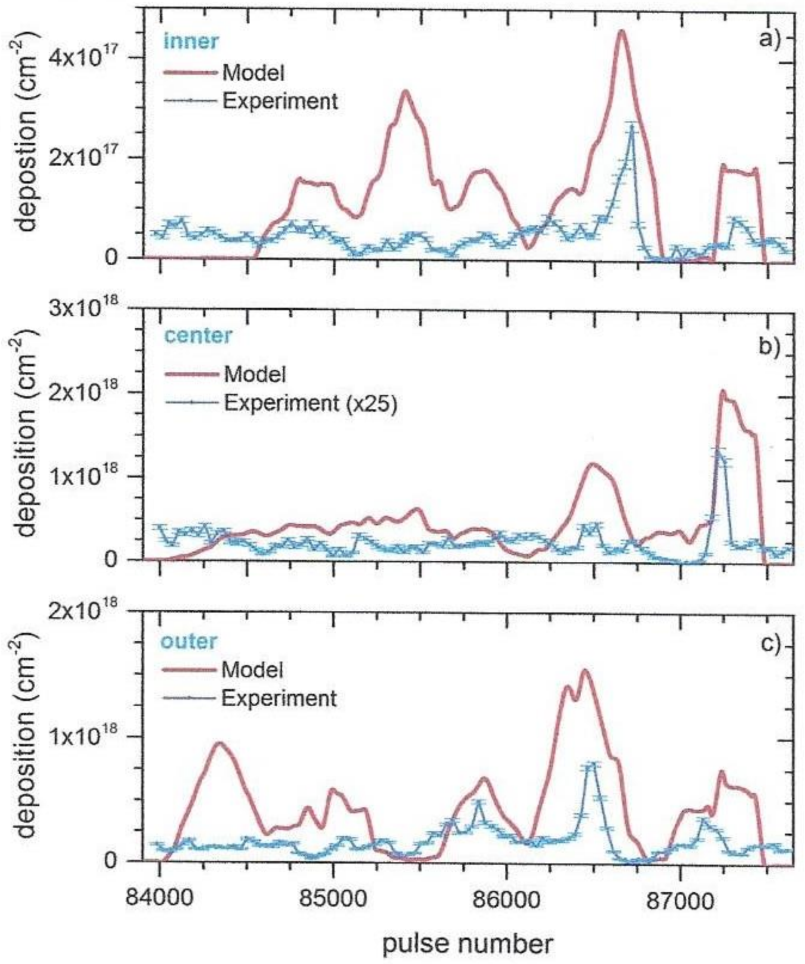


Figure 4. Beryllium deposition on the collector for 2013–14 ILW campaign operation measured by NRA (blue), and modelled (red) for the inner RC (a), central RC (b) and outer RC (c). The NRA error bars are the Poissonian error, given by $\sqrt{n}$.

Latest measurements in the JET divertor (1)

ILW2 (2012-4)
Mayer 2017

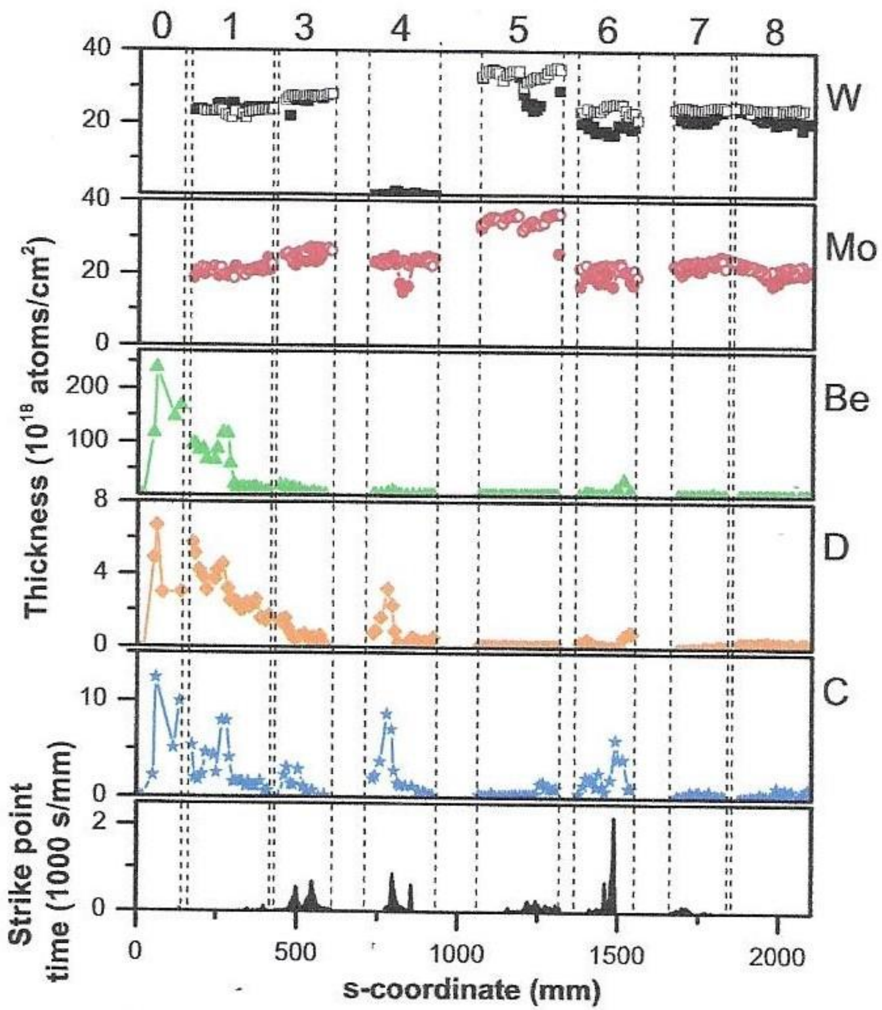


Figure 3. Thicknesses of the W and Mo marker layers before and after exposure during the ILW-2 campaign 2013–2014 and total deposition of Be, C and D on the marker tiles. Hollow points: before exposure; solid points: after exposure. The distribution of strike point positions is shown in the lowest figure. Numbers are divertor tile numbers, see figure 1. Massive deposition of Be, D and C is observed on tiles 0 and 1, some deposition of C together with D is also observed on tiles 4 and 6. Erosion of W is observed on tiles 5 and 6.

Phys. Scr. **T170** (2017) 014058

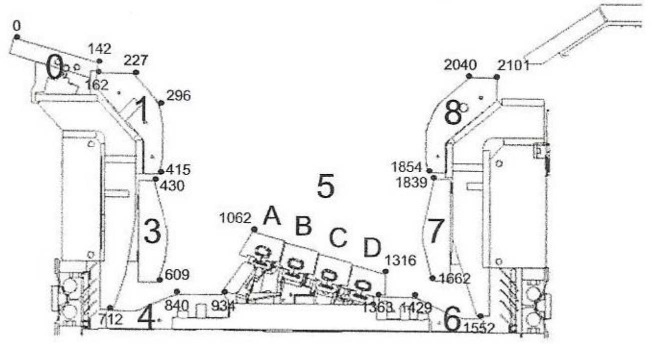


Figure 1. The JET divertor during the ILW-1 and ILW-2 campaigns. Numbers in large font size are tile numbers. Tile 5 consists of rows of tungsten lamellae ordered in stacks A–D, see figure 5 for more details. The s-coordinate (in mm) is indicated for a few characteristic points in small font size.

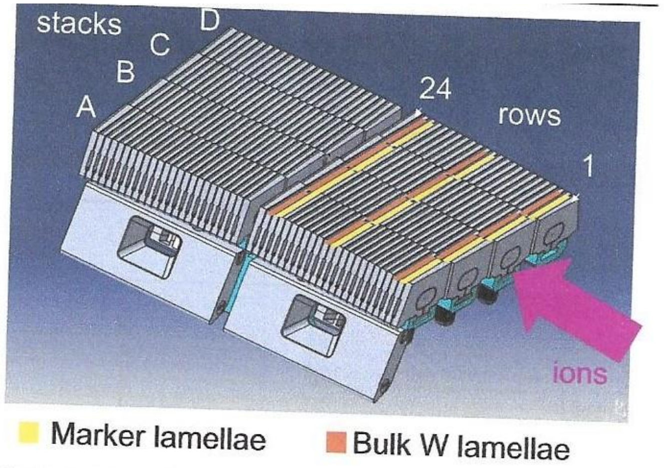
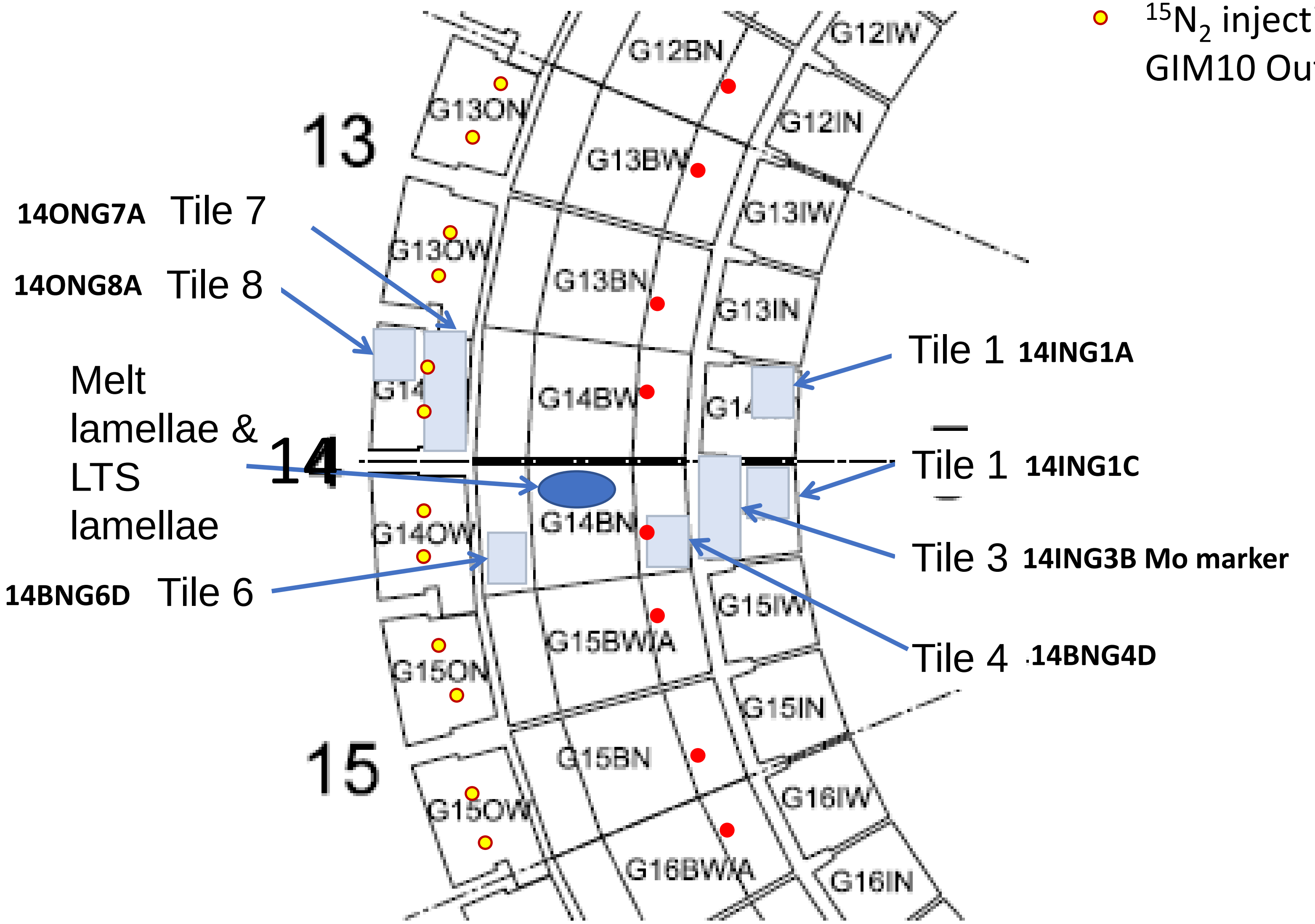


Figure 5. View of two modules of tile 5. Each module consists of 24 rows of bulk tungsten lamellae in toroidal direction arranged in 4 stacks in poloidal direction; see figure 1 for a cross-sectional view. Lamellae with markers are marked in yellow, analyzed regular bulk W lamellae are marked in orange. The direction of plasma ions is indicated by the arrow.

Octant 5: Gas injection and tiles removed

- $^{18}O_2$, CH_4 injection point GIM11 inner base ring
- $^{15}N_2$ injection points GIM10 Outer SOL



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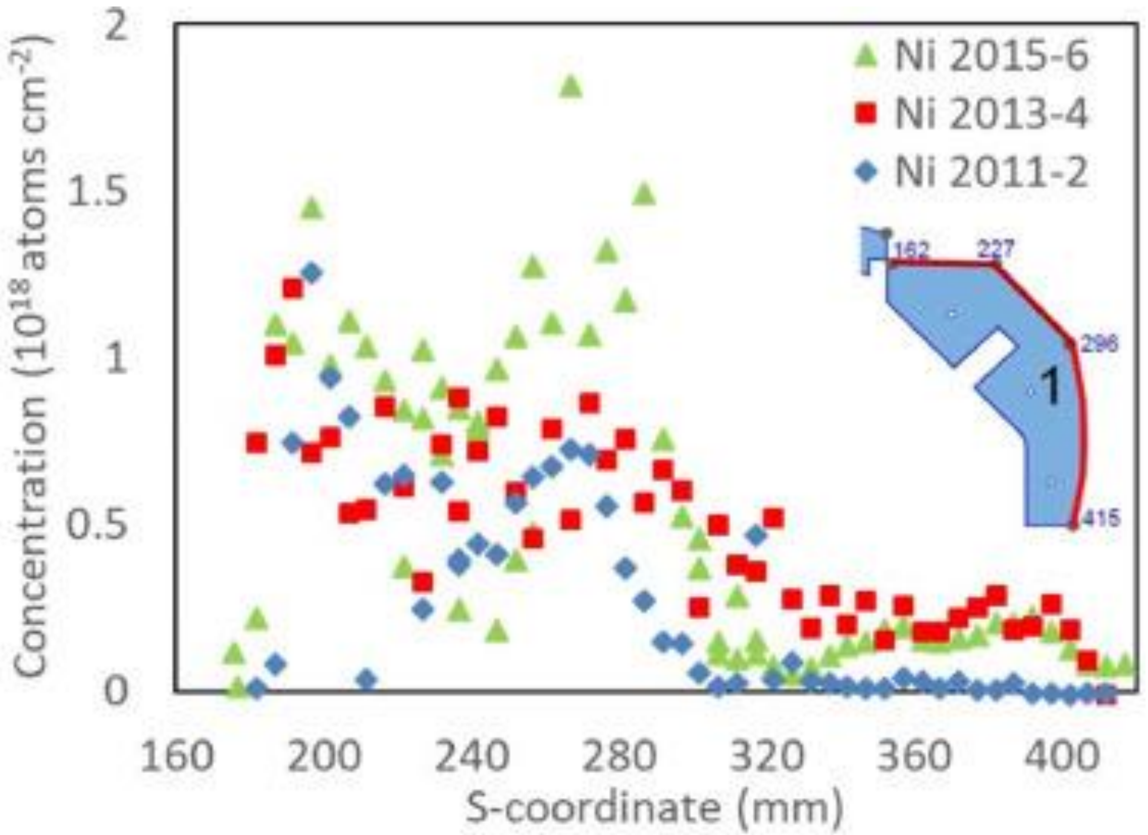
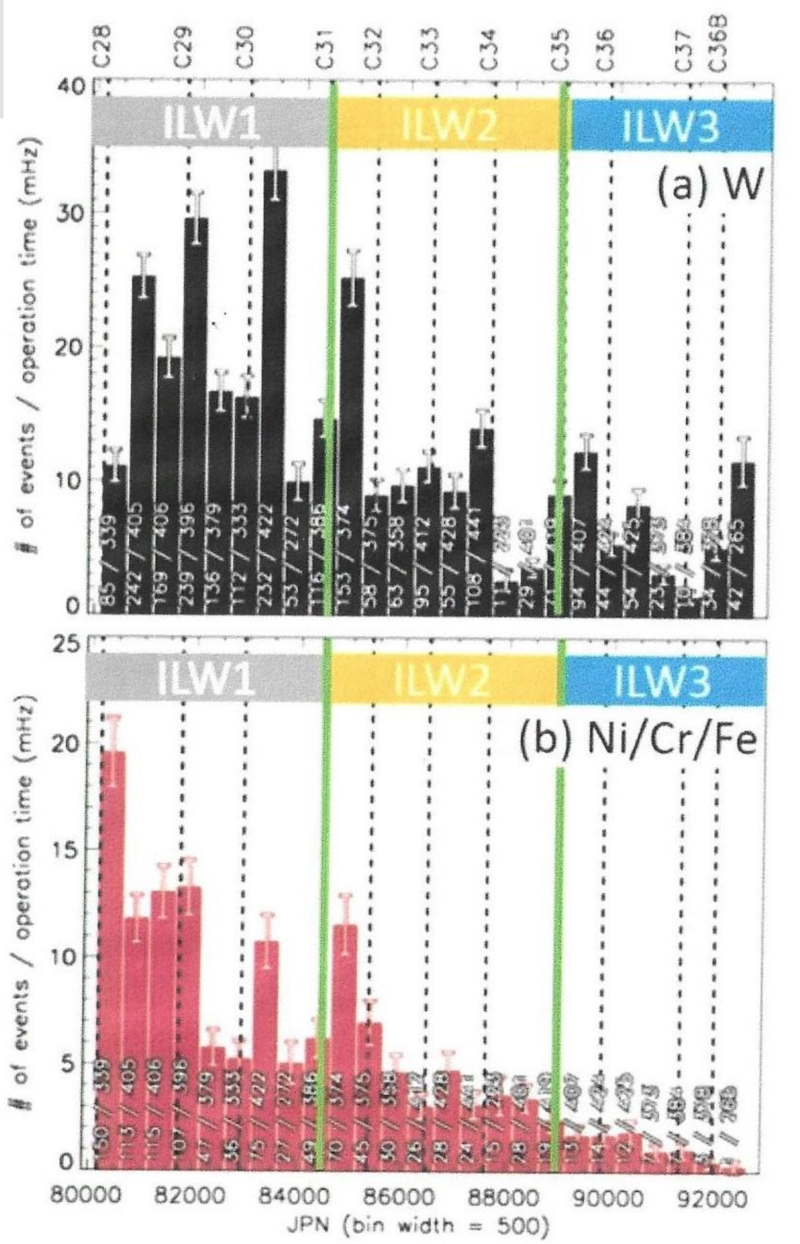
A Widdowson et al, Nuclear Materials and Energy, 19 (2019) pp218-224

Metallic Impurities in JET





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Erosion of divertor tiles for each ILW campaign

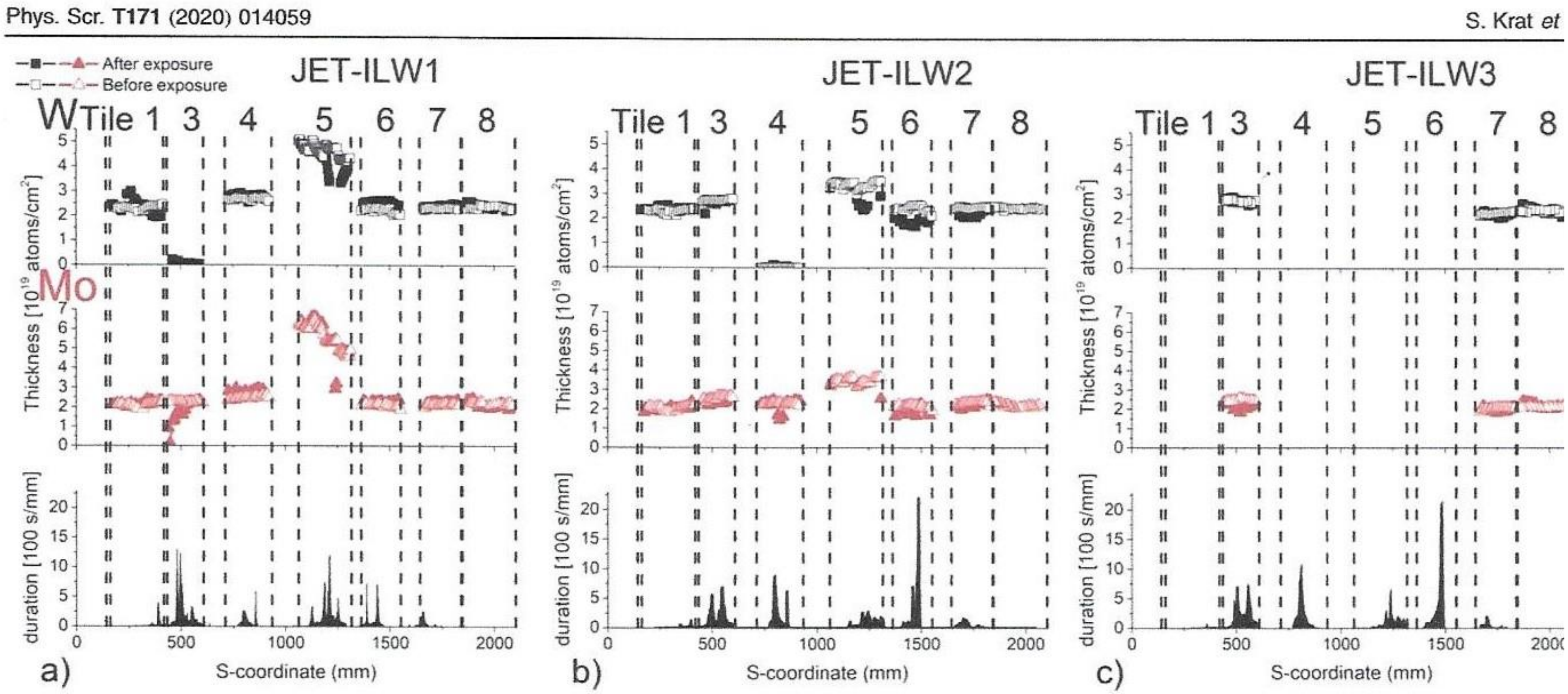

Figure 2. Top to bottom: W (black squares) and Mo (red triangles) thicknesses measured before campaigns (hollow symbols) and after campaigns (filled symbols), and strike point distribution during the campaigns for (a) JET-ILW1, (b) JET-ILW2, (c) JET-ILW3.

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Divertor deposition in each of the ILW campaigns

	ILW1	ILW2	ILW3
D	0.9	0.7	0.9
Be	53	60	46
C	13	7	6

Integrated deposition in the divertor per campaign (g)

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Phys. Scr. **T171** (2020) 014059 S. Krat *et al*

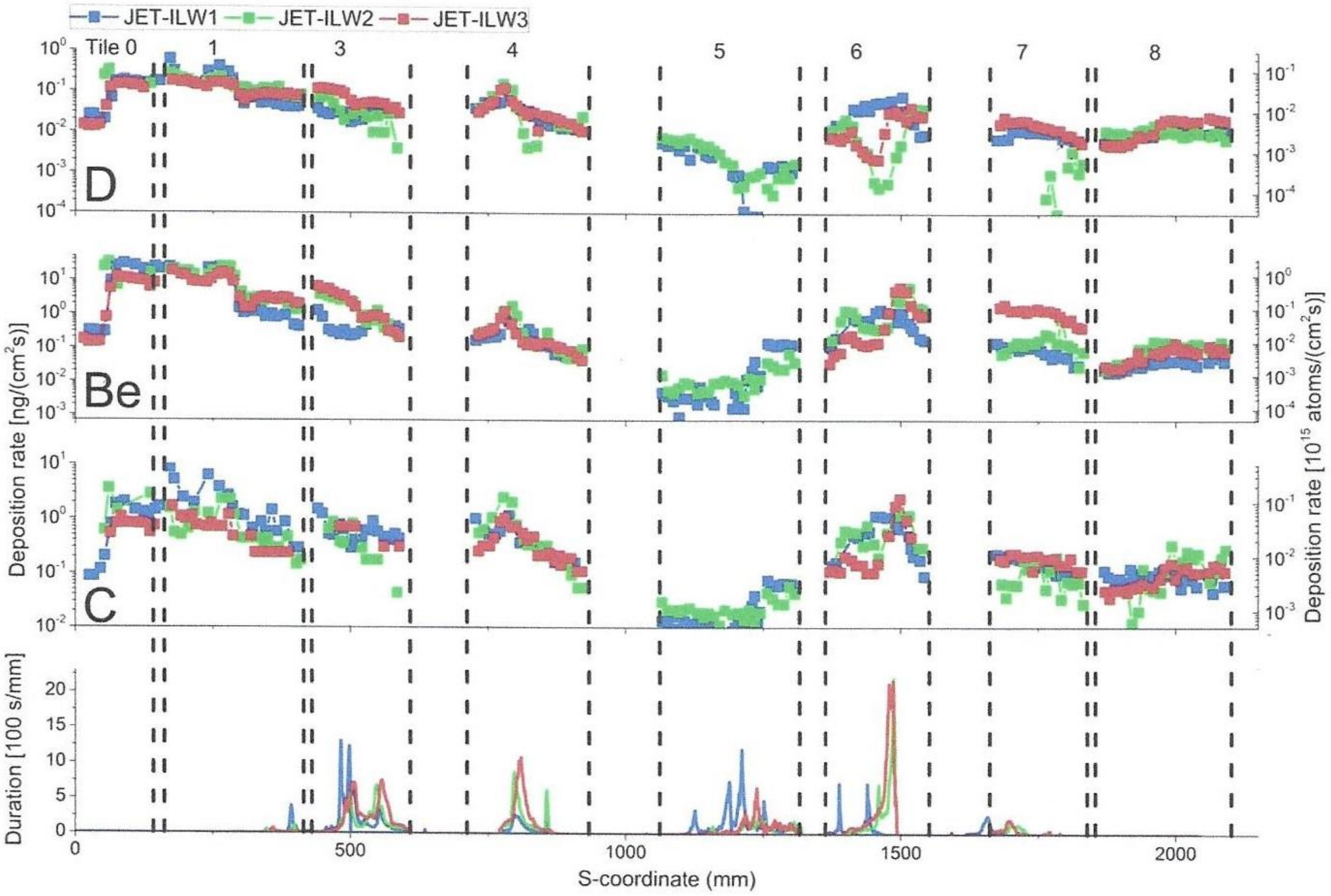
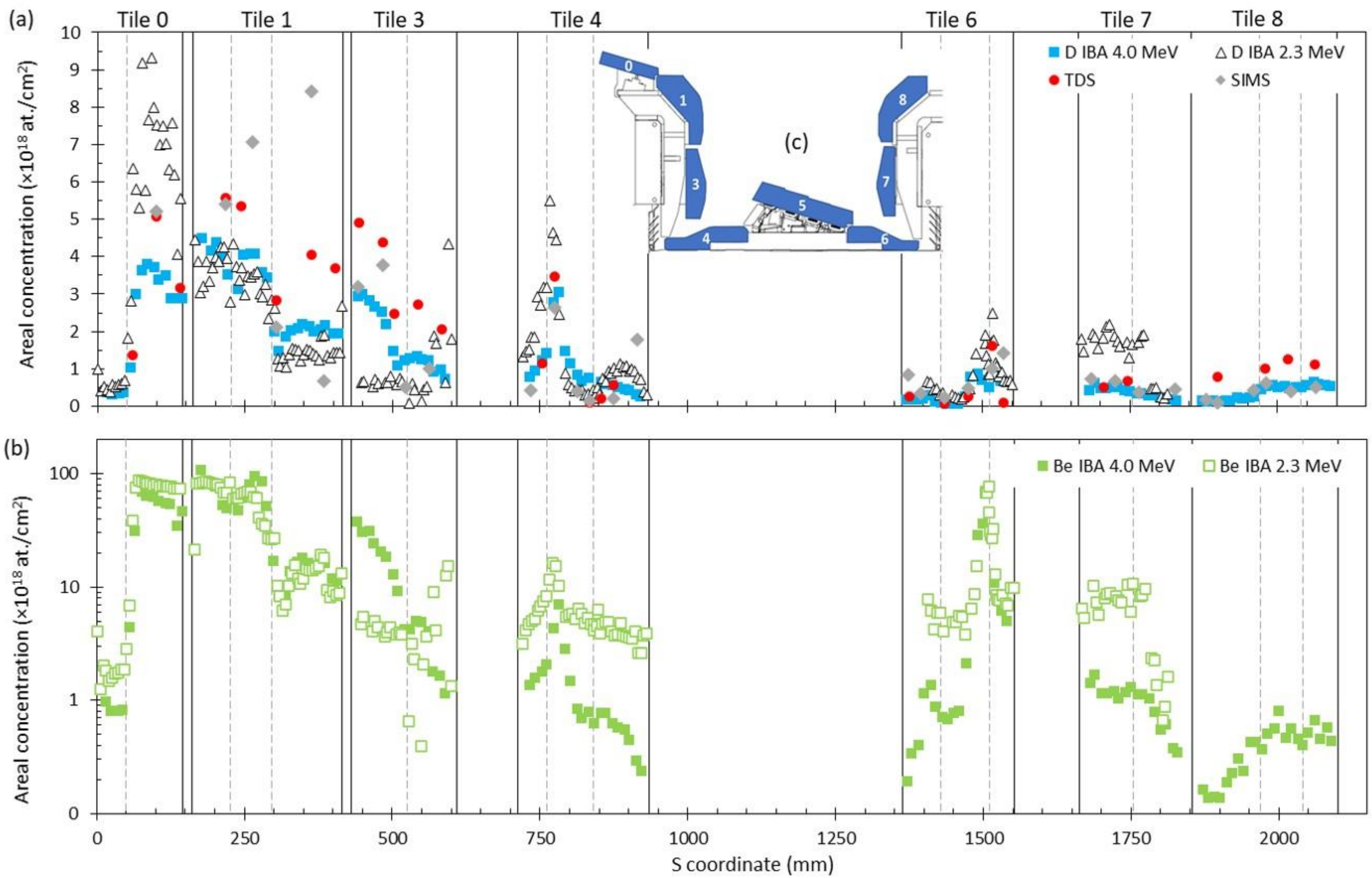


Figure 4. Top to bottom: distributions of D, Be and C deposition rates (in logarithmic scale), and distribution of strike point positions (linear scale) in the first three JET-ILW campaigns. Blue—JET-ILW1, green—JET-ILW2, red—JET-ILW3. Vertical dashed lines indicate borders of the divertor tiles. Black numbers on top of the figure—numbers of the tiles. For tile 5, data is shown for the lamellae in row 13.

Be and D deposition in ILW3

A Widdowson et al, (2021) *Phys. Scr* **96** (12) 124075



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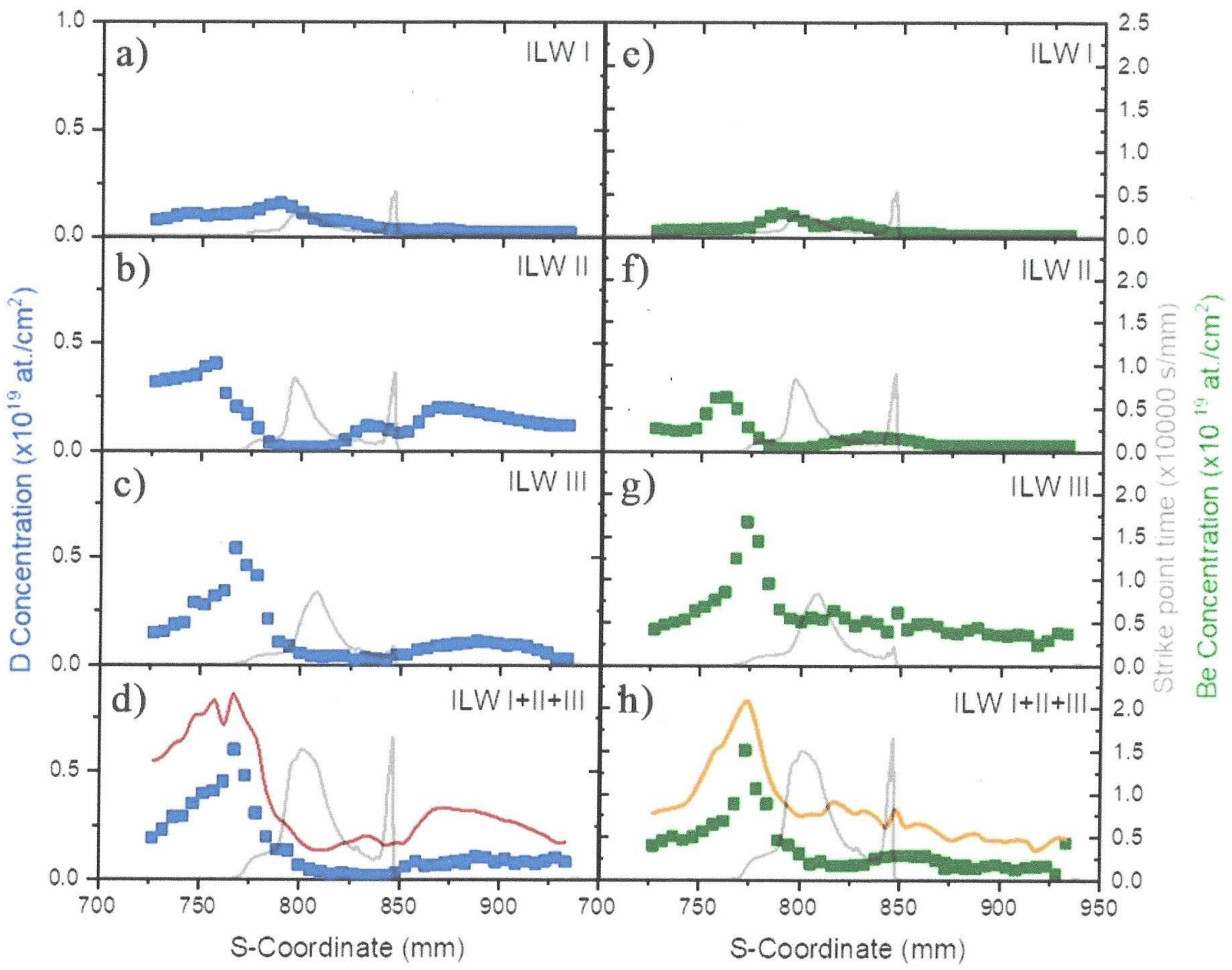
Deposition after exposure to all ILW may be less than sum of individual campaigns

Catarino et al (2020) *Phys Scr* **T171** 014044



Deposition of D (blue) and Be (green) on Tile 4

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Conclusions

Experimental data from JET have transformed the requirements for modelling over the years:

- Drift in the SOL
- Main chamber interactions
- Recycling properties

and may continue to do so:

- Transport/flow into pumping channels
- Physical properties of deposits
- Behaviour of T relative to D

These talks/referenced papers just give snapshots. For more details/numbers it is necessary to talk to the JET group and co-workers throughout Europe.