Dust production in JET and efforts in addressing dust production in B-W environment

Yevhen Zayachuk

WP JET1, WP JET2, WP PWIE, WP TE, EU-Japan Broader Approach contributors

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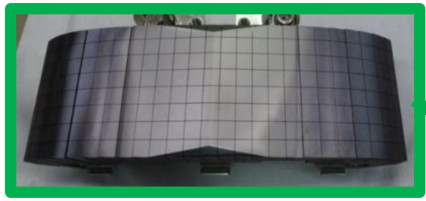
Joint WPTE-PWIE workshop on PWI in full-W fusion devices

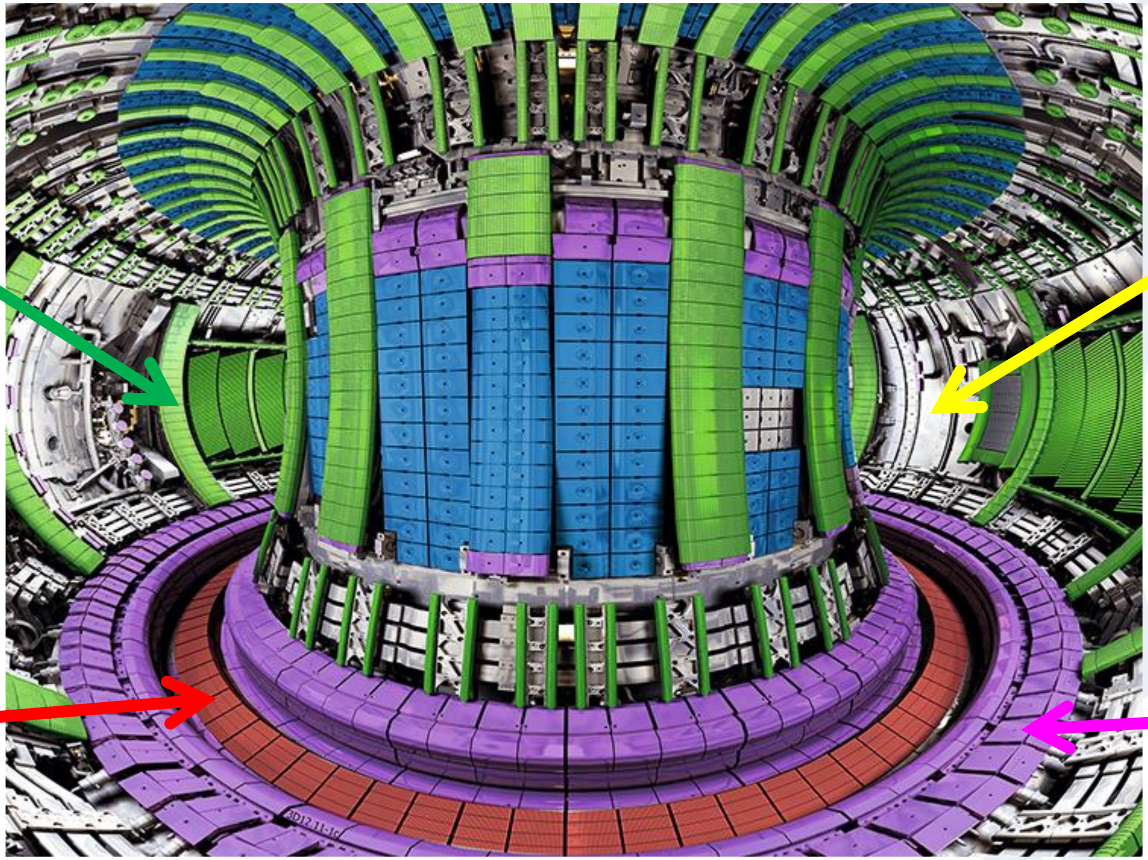
Aix-en-Provence, France | 17-19.09.2024

All-metal JET in-vessel materials

Bulk beryllium (Be)
Castellated structure



Bulk tungsten (W)
Lamellae structure



Tungsten (W) coating on carbon-fibre composite (CFC) tile

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

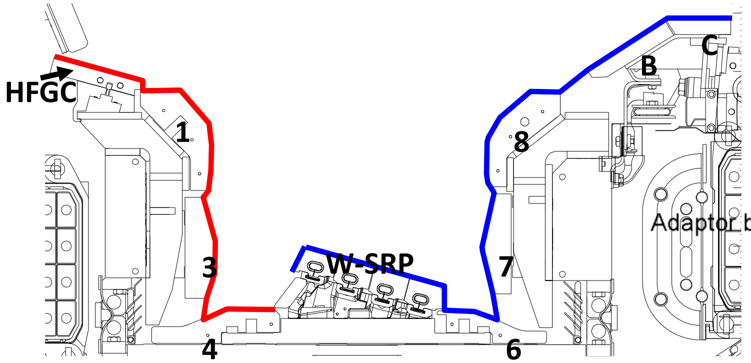
What can we learn from JET operational experience?

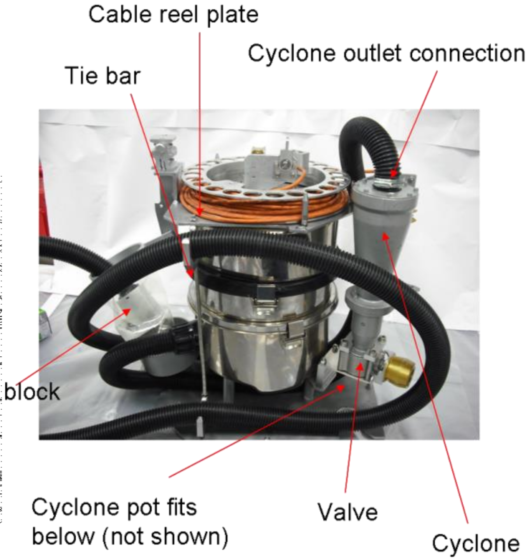
Although JET dust is dominated by beryllium there are still areas of lessons learned:

- Dust collection methods and limitations;
- Dust generation mechanisms;
- Characterisation methods for evaluation of dust quantity, composition, retention;
- Knowledge gaps and need for extrapolation to tungsten machines.

Dust collection methods in JET: overview

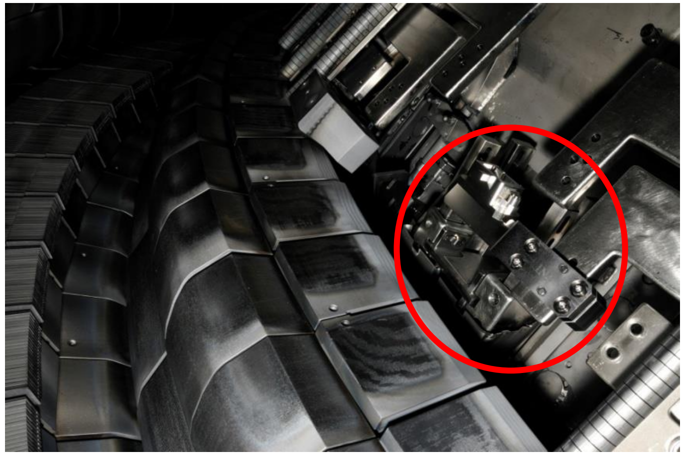
In-vessel vacuuming of divertor tile surfaces



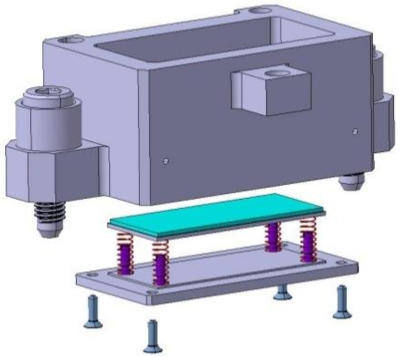


Adhesive pad on divertor/main chamber tile surfaces

Dust collectors at inner and outer recessed wall above divertor

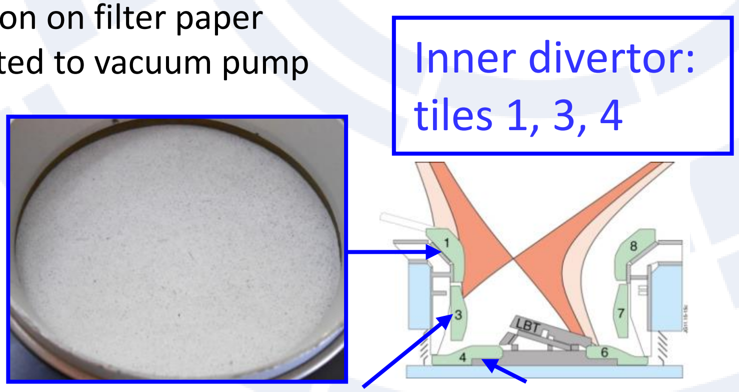


Dust collected on Si substrate.



Brushing divertor tiles

- Brushing divertor tile surface
- Collection on filter paper connected to vacuum pump



Dust collection methods in JET: sampling characteristics and limitations

In-vessel vacuuming

- Sample: Divertor and main chamber.
- Area: Divertor surface – **large surface area** + **non-specific location.**
- Form: Loose dust/flakes/debris collected in pots.
- ➢ *Mass of dust, fuel inventory, characterization of particles.*

- Size: **Small particles not collected in pot**.
- Samples of loose dust handled in **only few laboratories**.

Adhesive pad

- Area: Divertor /main chamber tile **surfaces-selective area** + **potentially non-representative**.
- Form: Loose dust/flakes/debris collected on pads.
- Sample: Divertor and main chamber.
- ➢ *Fuel inventory, characterization of particles.*

- Size: **Collection of larger particles dominates**.
- Can be handled in **many laboratories**.

Dust collectors

- Area: Recessed inner and outer wall collectors (behind limiters) – **selective region** + **only bottom of the vessel**.
- Form: Particles on Si substrate.
- Sample: Mobile dust in main chamber recessed areas.
- ➢ *Characterization of particles.*

- Size: **All sizes may be collected**.
- Can be handled in selection of laboratories.

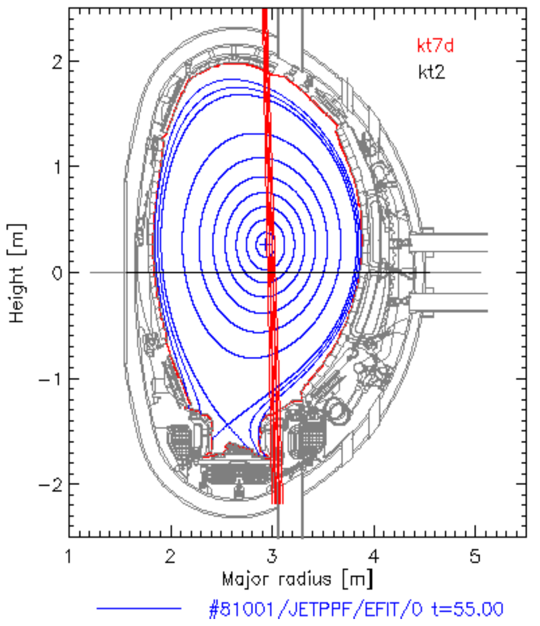
Brushing

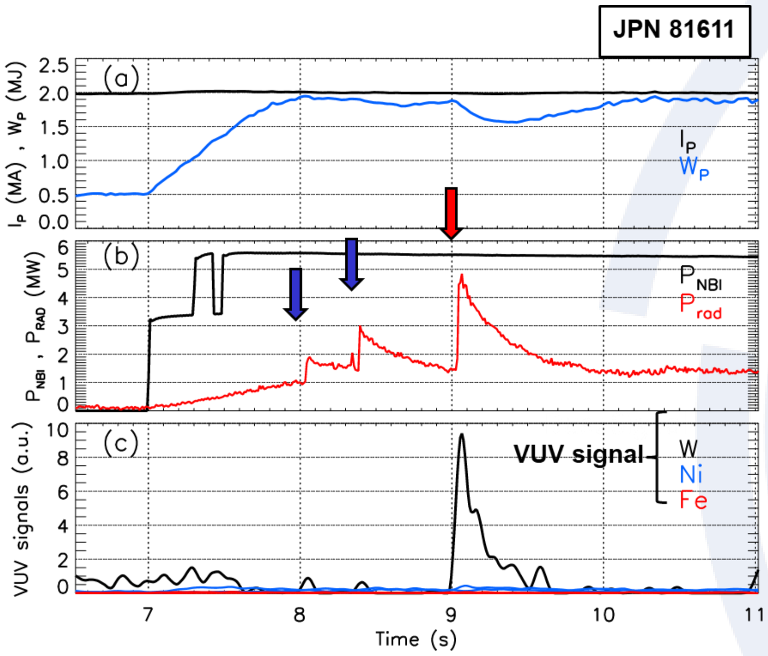
- Area: Divertor surface – **whole single tile surface** + **potentially non-representative.**
- Form: Dust on filter paper.
- Sample: Divertor and main chamber.
- ➢ *Fuel inventory, characterization of particles.*

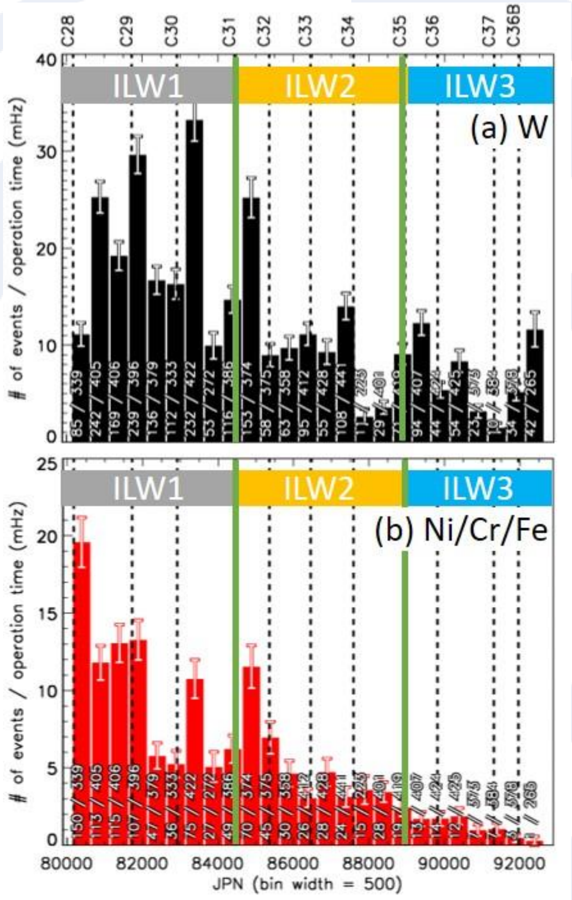
- Size: **All sizes may be collected**.
- Can be handled in selection of laboratories.

In-vessel dust detection

Transient Impurity Events (TIEs):







TIE monitoring in JET-ILW

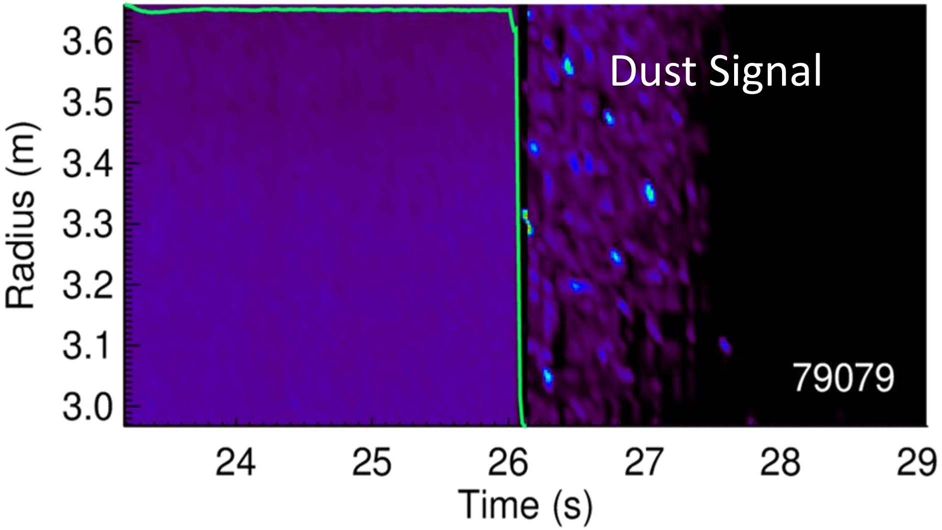
- TIEs are radiation spikes in the radiated power.
- Elemental origin can be identified by VUV spectroscopy.
- Ejected W particles detected *in-situ*.

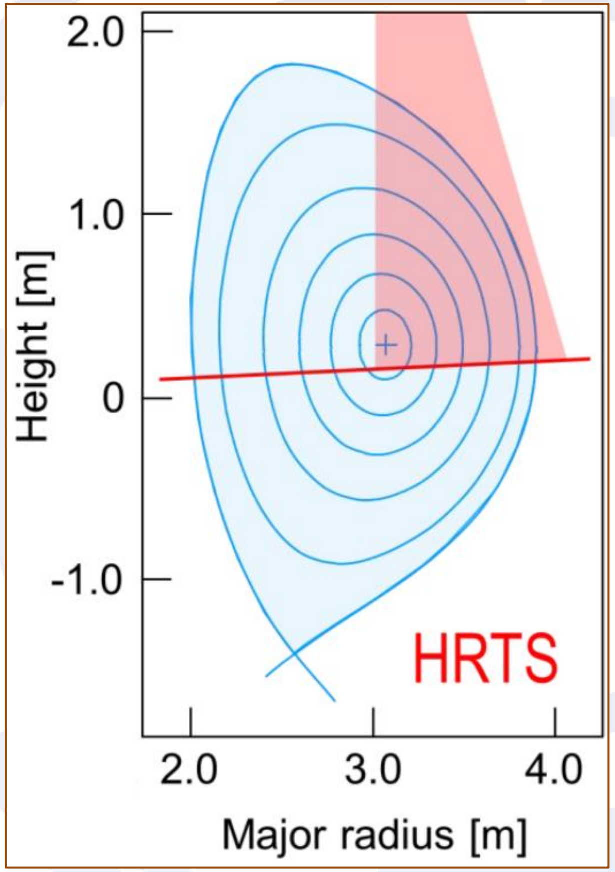
Widdowson, A., et al. (2019) *Nuclear Materials and Energy*, *19*, 218–224.
https://doi.org/10.1016/J.NME.2018.12.024

In-vessel dust detection

Dust after disruptions detected by HRTS:

- HRTS: Measures Te and ne from Thomson scattered light
- Does not stop after a disruption
- Light from dust particles seen as anomalous spikes
- Provides an indication of dust mobilized/created after a disruption

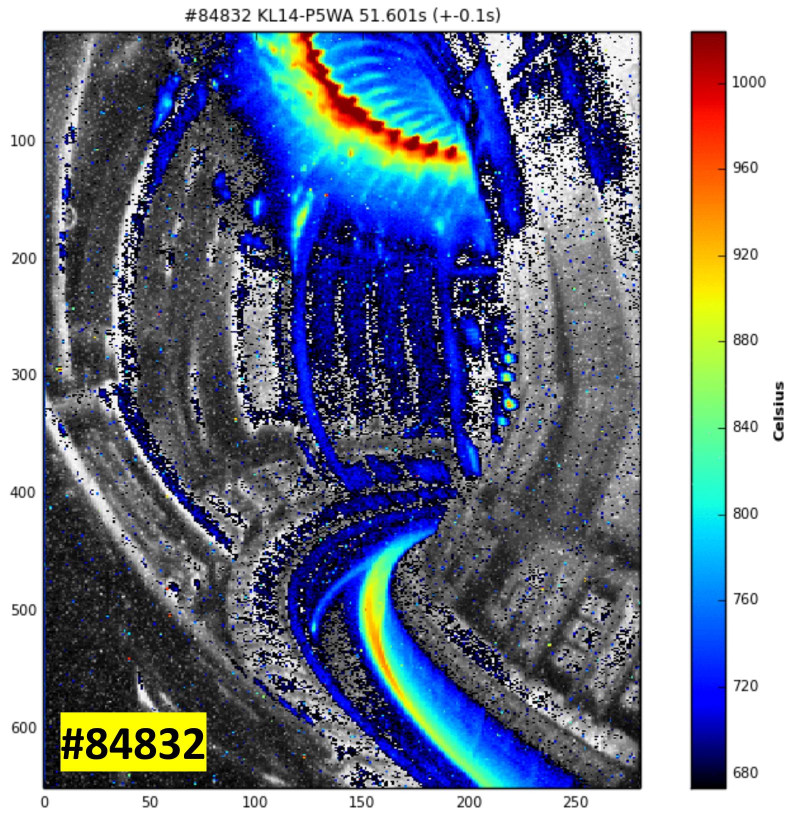




Flanagan, J. C., et al (2015). *Plasma Physics and Controlled Fusion*, *57*(1), 014037.
https://doi.org/10.1088/0741-3335/57/1/014037

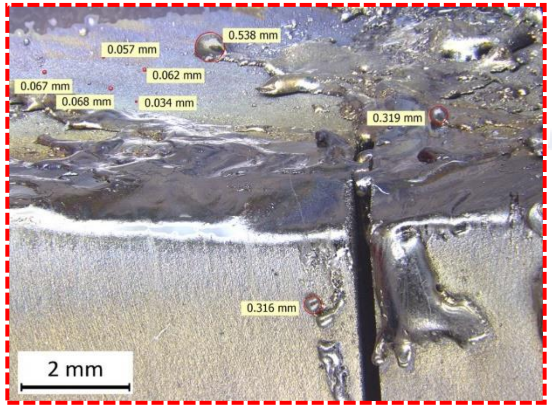
Dust generation mechanisms: melting

Source of molten beryllium droplets

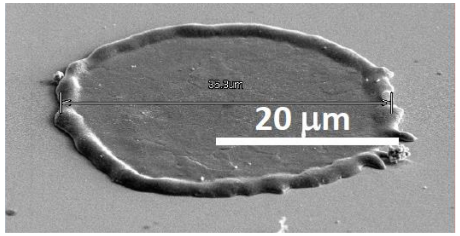


Jepu, I., et al (2024). *Nuclear Fusion*. https://doi.org/10.1088/1741-4326/AD6614

Melting along dump plate due to disruptions

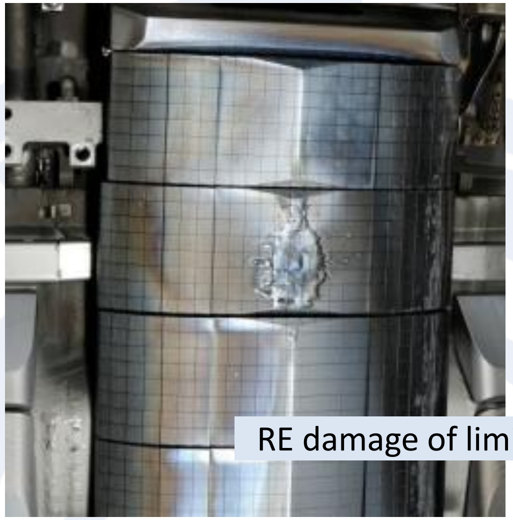


Droplets formed in molten region

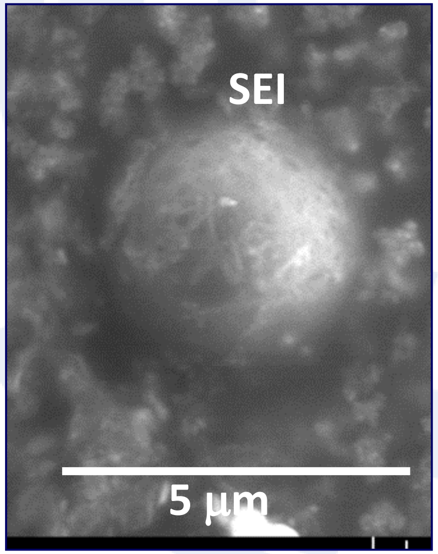


Beryllium “rain” from top of vessel following a disruption

Typical droplet on dust collector



RE damage of limiter tiles



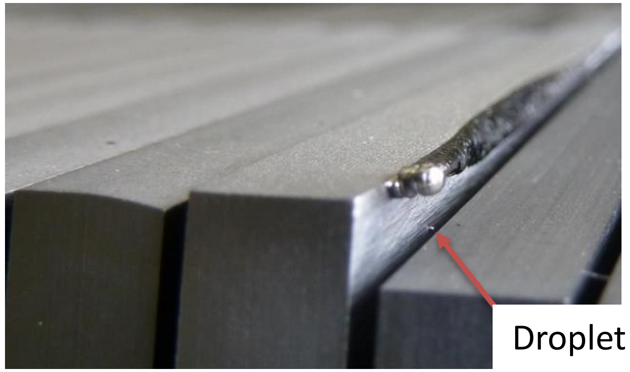
Size of identified droplets: 4 -8 µm.

Dust generation mechanisms: melting of bulk W under high heat loads

Melting of bulk tungsten plasma facing surfaces only during specific melt experiments (2013 & 2015/16)

2013 Transient tungsten melt experiment - ***leading edge***.

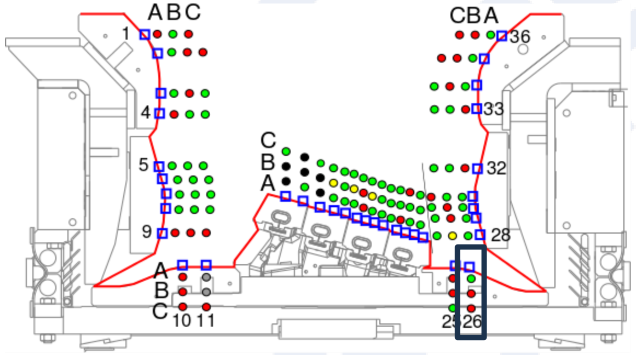
Evidence of droplets emitted during melting → including in-situ.

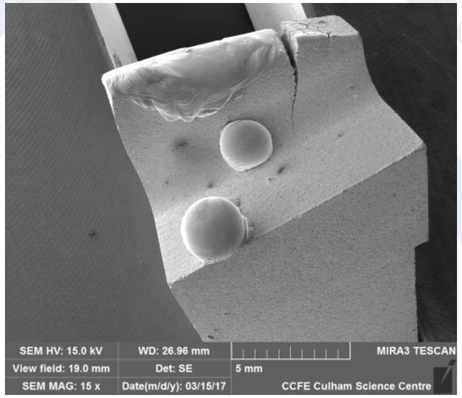


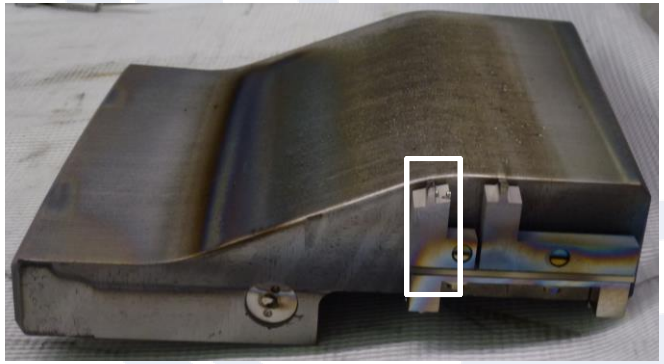
Droplet

Melting of tungsten Langmuir probe diagnostic due to misalignment

Evidence of droplet formed during melting







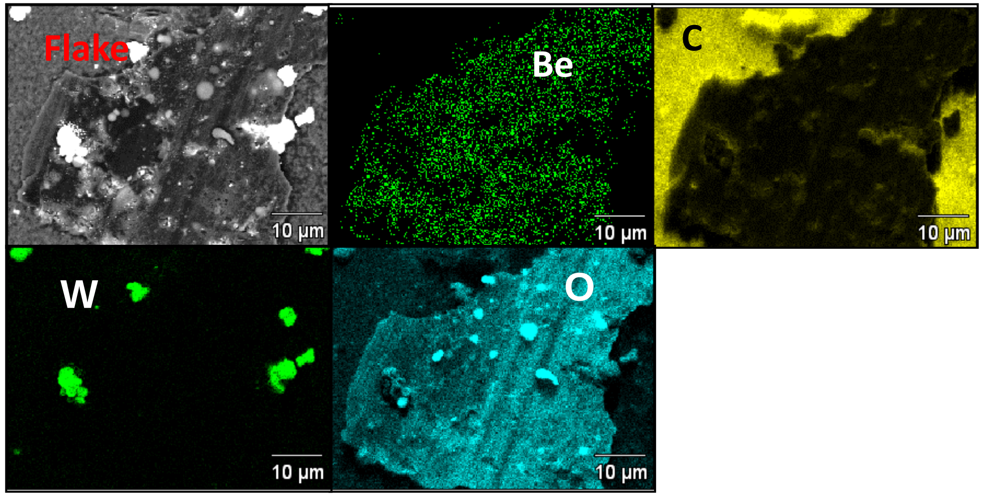
Coenen, J. W., et al. (2015). ELM-induced transient tungsten melting in the JET divertor. *Nuclear Fusion*, *55*(2), 023010. https://doi.org/10.1088/0029-5515/55/2/023010

Coenen, J. W., et al. (2017). Transient induced tungsten melting at the Joint European Torus (JET). *Physica Scripta*, *T170*, 014013. https://doi.org/10.1088/1402-4896/aa8789

Dust generation mechanisms: flaking of deposits

- Widespread in JET Carbon Wall.
- Reduced deposition in JET-ILW.
- No wide scale flaking observed.

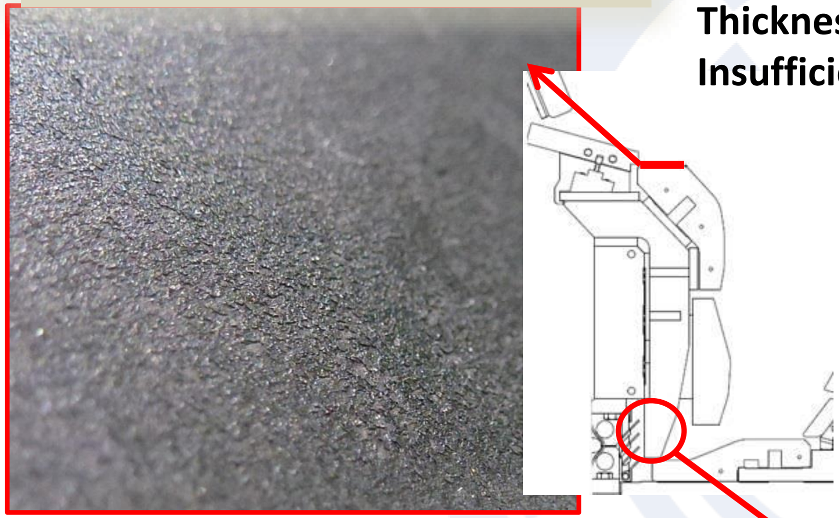
SEM & EDS analysis of adhesive pad



Beryllium flake, surface oxide and tungsten inclusions
Sizes: Few µm to 100s µm

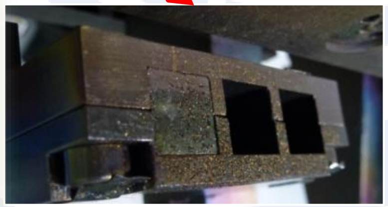
A. Baron-Wiechec et al., Nucl. Fusion 55 (2015) 113033

Deposit on top of Tile 1 well adhered, rough surface



Thickness of Be deposits ~50 µm.
Insufficient thickness for flaking.

Isolated examples of flaking deposit on metallic surfaces in remote divertor corners

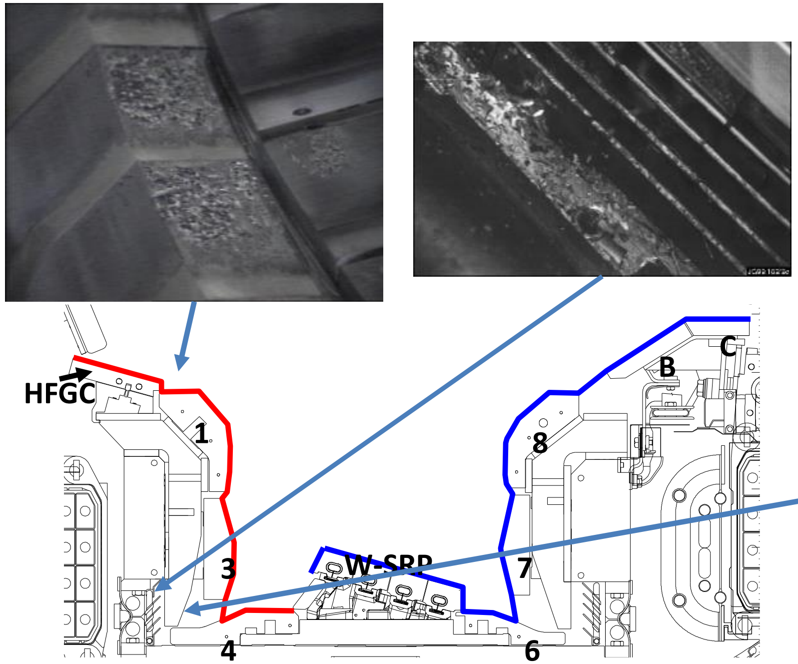


Accumulation over time in unexposed locations.

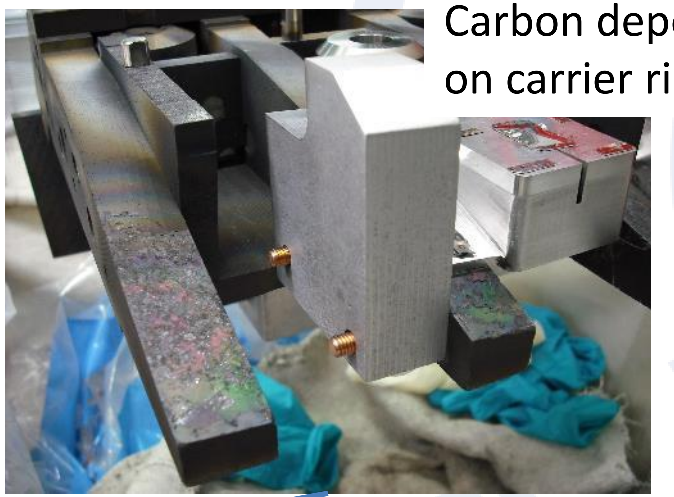
Dust generation mechanisms: flaking of deposits (carbon/historical)

JET-Carbon wall: Flaking deposit on top of Tile 1 & flakes at louvres

JET-Carbon wall: Flaking deposit on top of Tile 1 & flakes at louvres



Historic deposits - JET Specific
Potential for carbon based deposits in remote divertor corners to contaminate dust collected by vacuuming



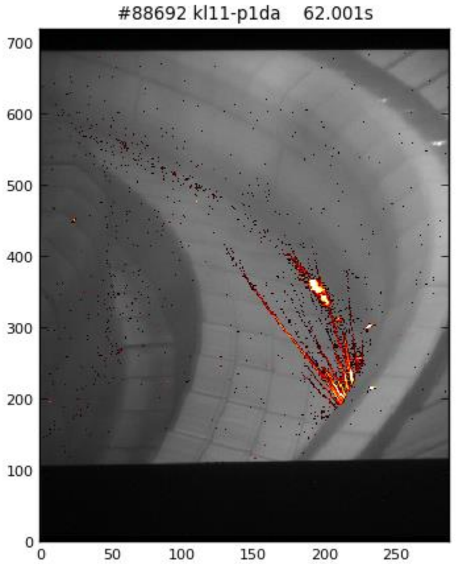
Carbon deposits on carrier ribs

Thickness of C deposits ~1 mm.
Flaking occurs if sufficient thickness is reached.
Historical accumulation in unexposed locations.

Dust generation mechanisms: flaking of coatings

Coating degradation - JET specific

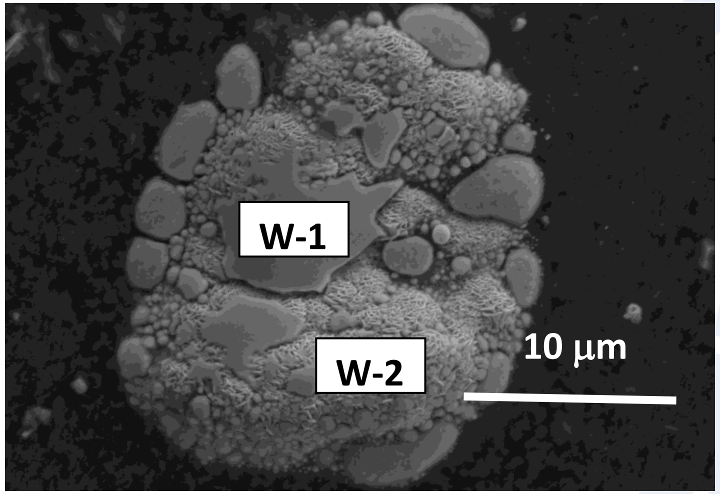
Tungsten coatings on CFC tiles in main chamber and divertor

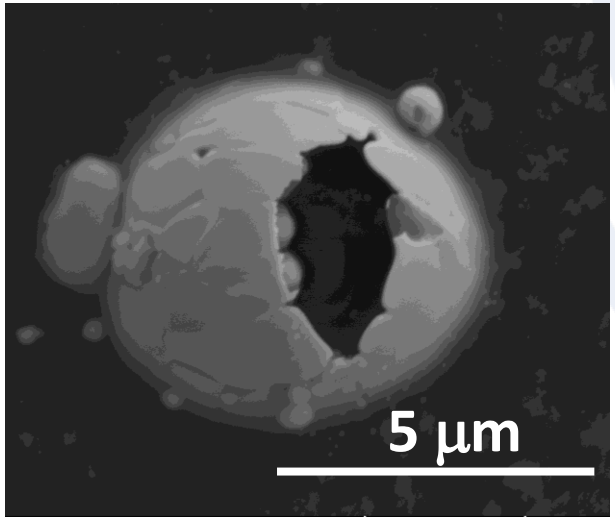


IR camera image showing ejection of particulates from localised divertor area

Outer limiter Side protection tiles

SEM & EDS analysis of adhesive pad at IPPLM





Tungsten and Mo-W flakes

Flakes originate from W/CFC tile coatings.

Two phases:

- *Amorphous (W-1) – metallic glass, fast cooling.*
- *Crystalline (W-2) – original coating.*

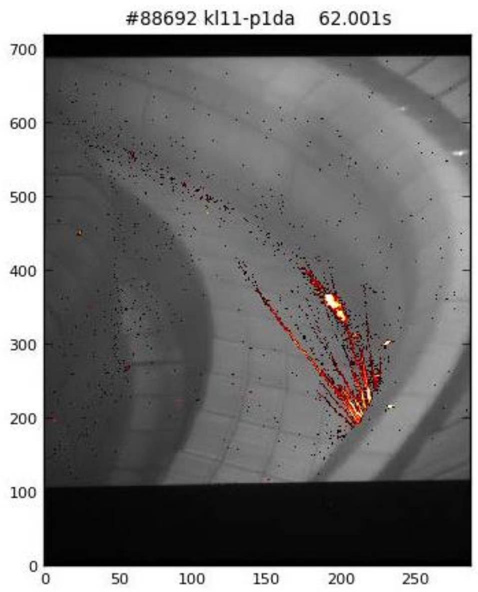
Flakes of W coating → W droplets.

- Formation in the scrape-off layer – i.e., hollow ball.

Baron-Wiechec, A., et al. (2015). *Nuclear Fusion*, *55*(11), 113033. https://doi.org/10.1088/0029-5515/55/11/113033

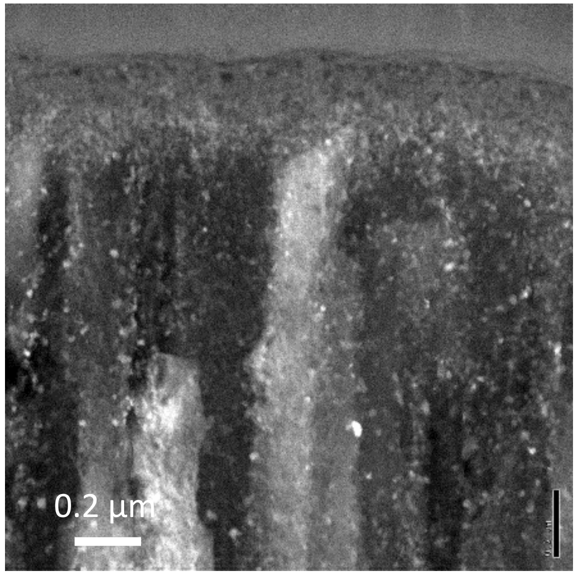
Interaction of W and Be

Tungsten particles in beryllium deposit

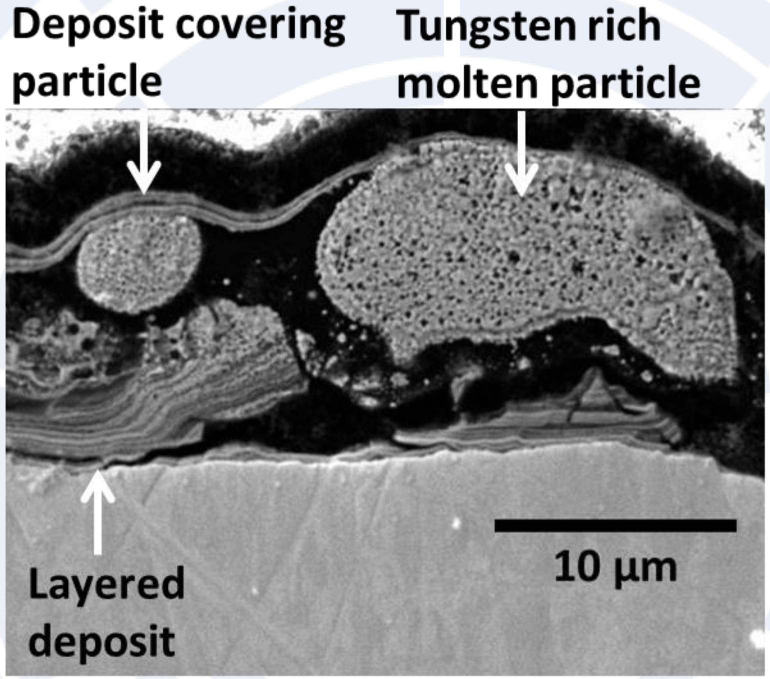


Infrared camera view showing particle shower

FIB/TEM at IFERC



White particles are tungsten flakes immobilised in divertor deposit*



Mobile particles covered by deposit and immobilized.
Reduction of mobilizable dust content over time.

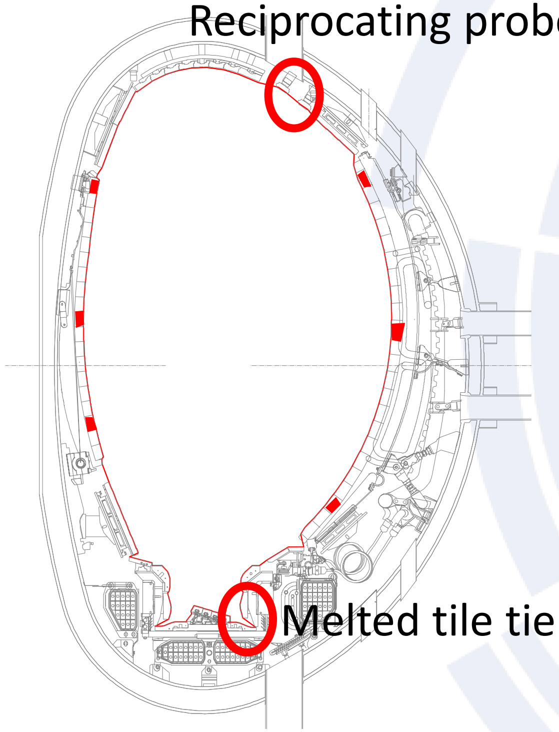
*M. Rubel et al., Fusion Eng. Des. (2018). doi:10.1016/j.fusengdes.2018.03.027
Widdowson, A., (2017) *Nuclear Materials and Energy*, *12*, 499–505 https://doi.org/10.1016/j.nme.2016.12.008

Dust generation mechanisms: damage of in-vessel components

In vessel Components

Operation of the reciprocating probe made of boron nitride associated with release of BN particles.

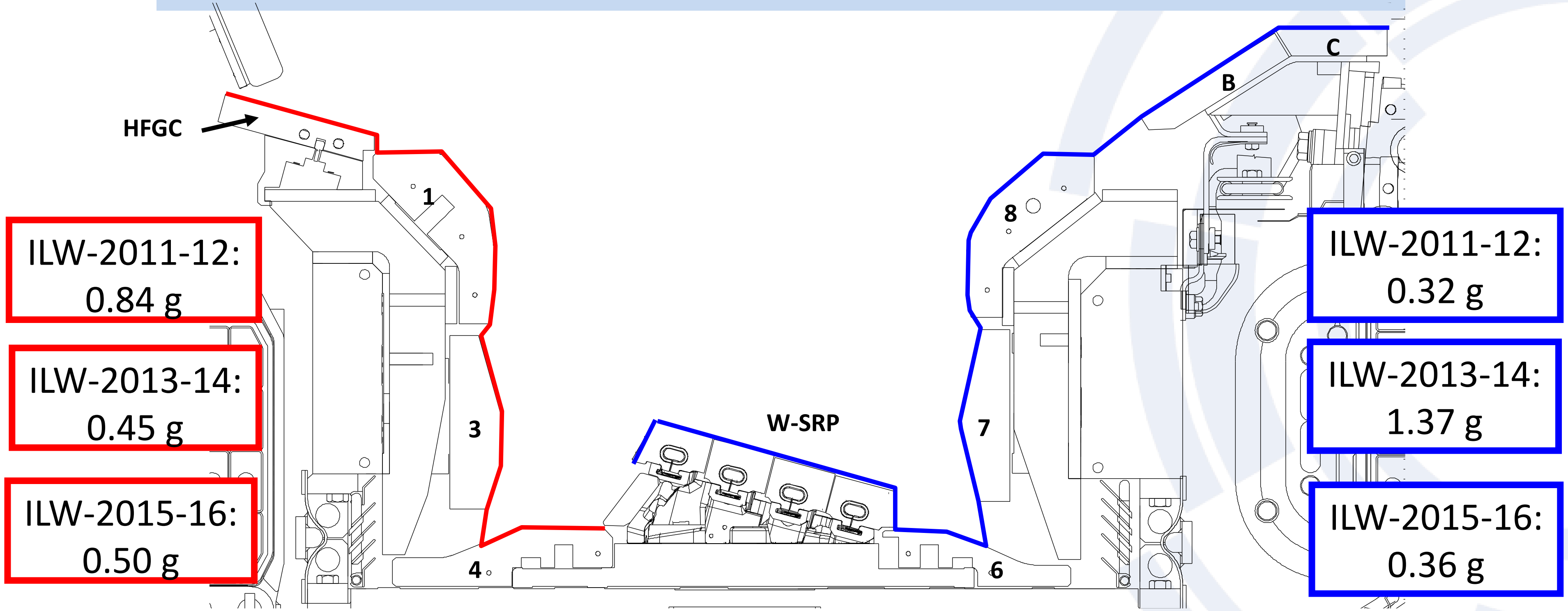
Ni, Cr, Fe based – molten Inconel



Potential of non-PFCs for dust generation.

Dust – collected amount

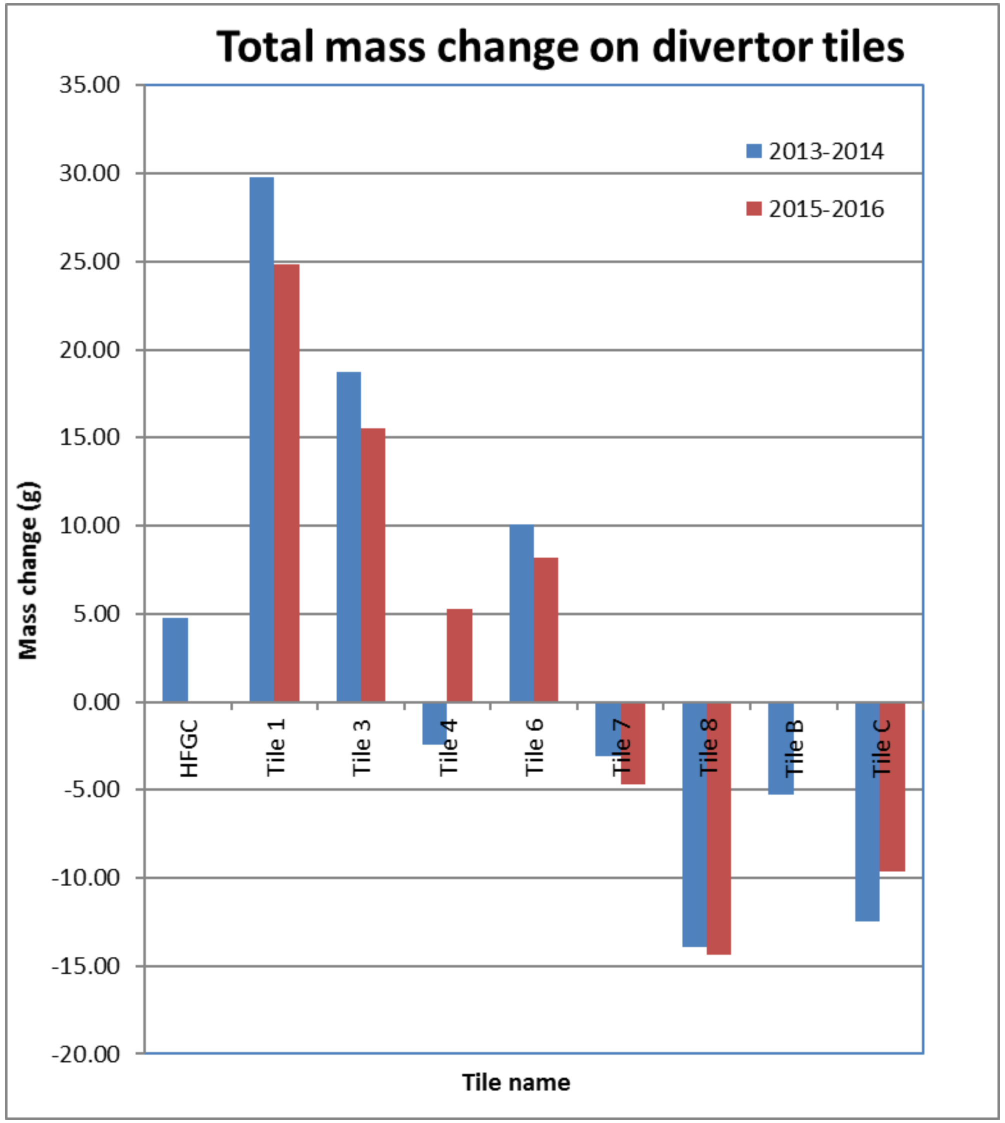
Collection <2g for JET-ILW 2011-12, 2013-14, 2015-16
Significantly lower than in JET carbon wall ~ 300 g



2 vacuuming stages: Red = inner divertor, Blue = outer divertor

A. Widdowson et al, Nucl. Mater. Energy (2016) http://dx.doi.org/10.1016/j.nme.2016.12.008
A. Widdowson, et al, Phys. Scr. T159 (2014) 014010 http://dx.doi.org/10.1088/0031-8949/2014/T159/014010

Dust conversion factor



Based on erosion/deposition material balance & dust production mechanism of flaking of deposits

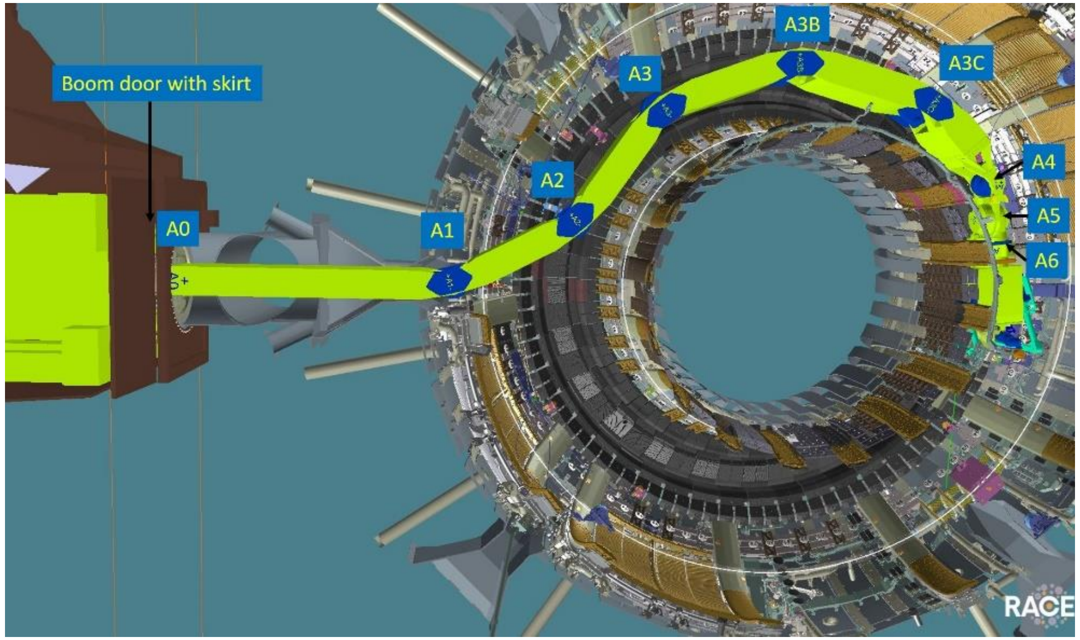
Gross increase in mass in divertor:-
- 2013-14 = 63 g
- 2015-16 = 54 g

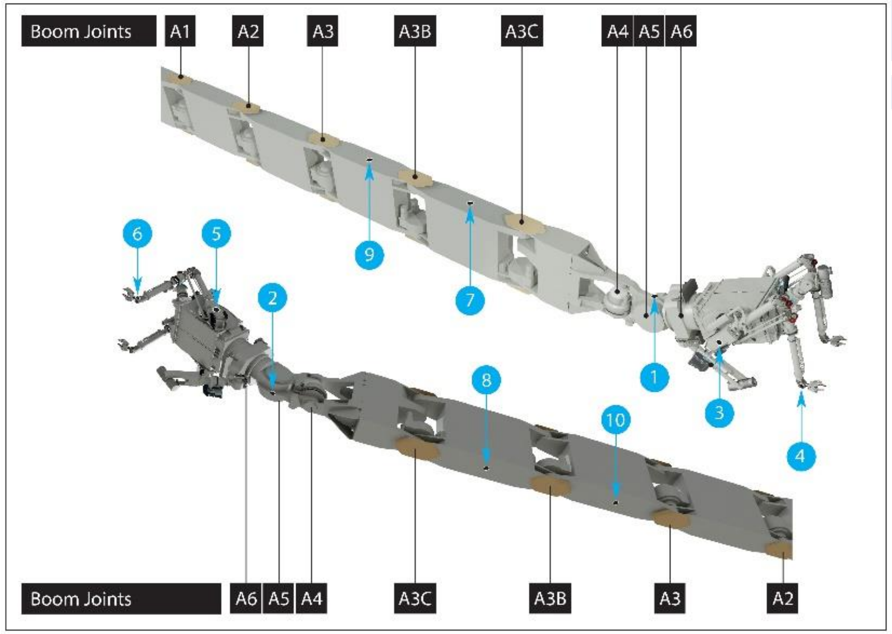
Assuming dominant dust production process is break-up of deposits:
Conversion factor ⇒ 2 - 4%

NOTES: -
- Net erosion/deposition values from weighing
- What fraction is dust from flakes or droplets?

Carbon wall dust conversion factor 43%
Likonen et al. JNM 463 (2016) 842

Dust mobilisation during remote maintenance

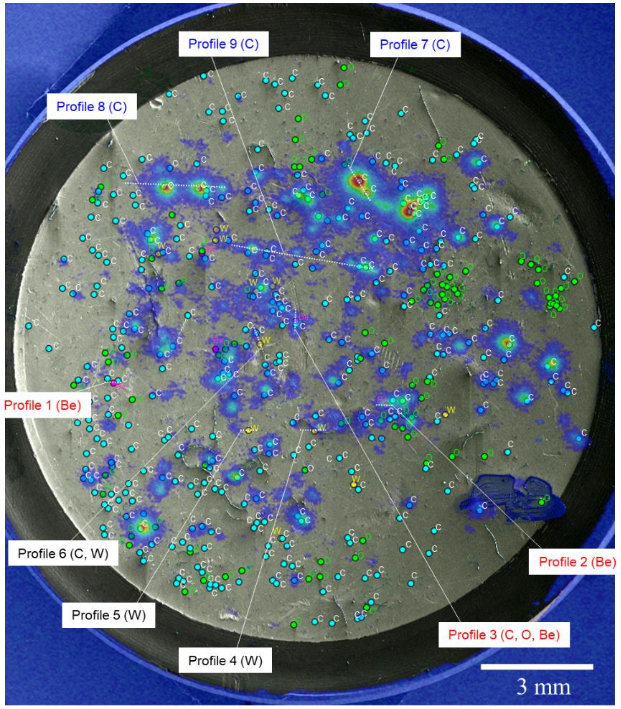




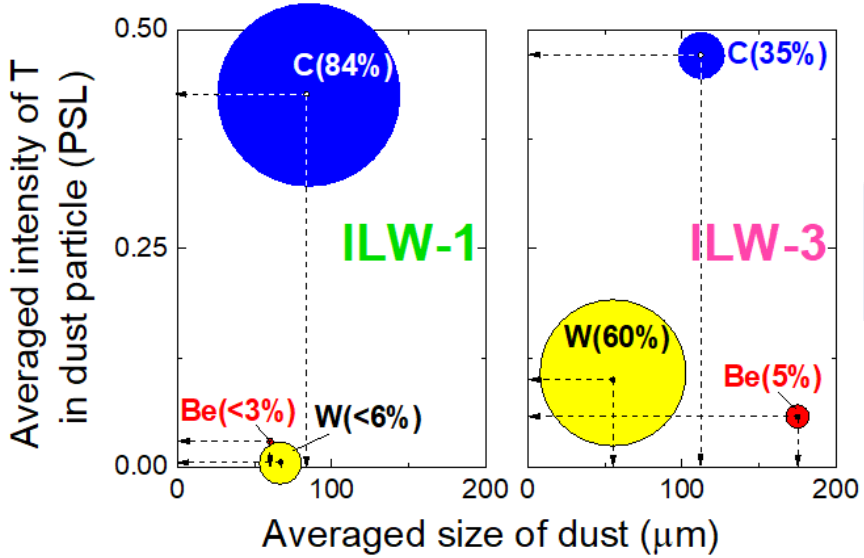
- Sampling of dust on JET remote handling boom during intervention:
  - ➢ Only one relevant Be flake observed on 10 samples.
  - ➢ **Low dust mobilisation.**

Rubel, M., (2020) *Physica Scripta*, *T171*(T171), 014048. https://doi.org/10.1088/1402-4896/ab4fcf

Dust – retained fuel



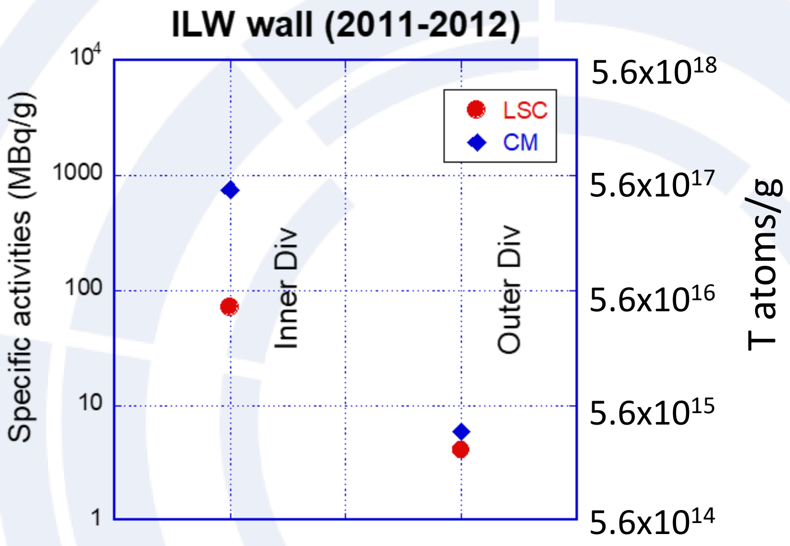
Superposition EPMA & TIPT
Electron Probe Micro Analysis & Tritium Image Plate Technique



Courtesy T. Otsuka PFMC-18 2021
Otsuka, T. et al. 2021 NME 17 279–283

Fuel (tritium) retention highest in carbon particles (JET carbon wall)

Tritium retention in divertor dust



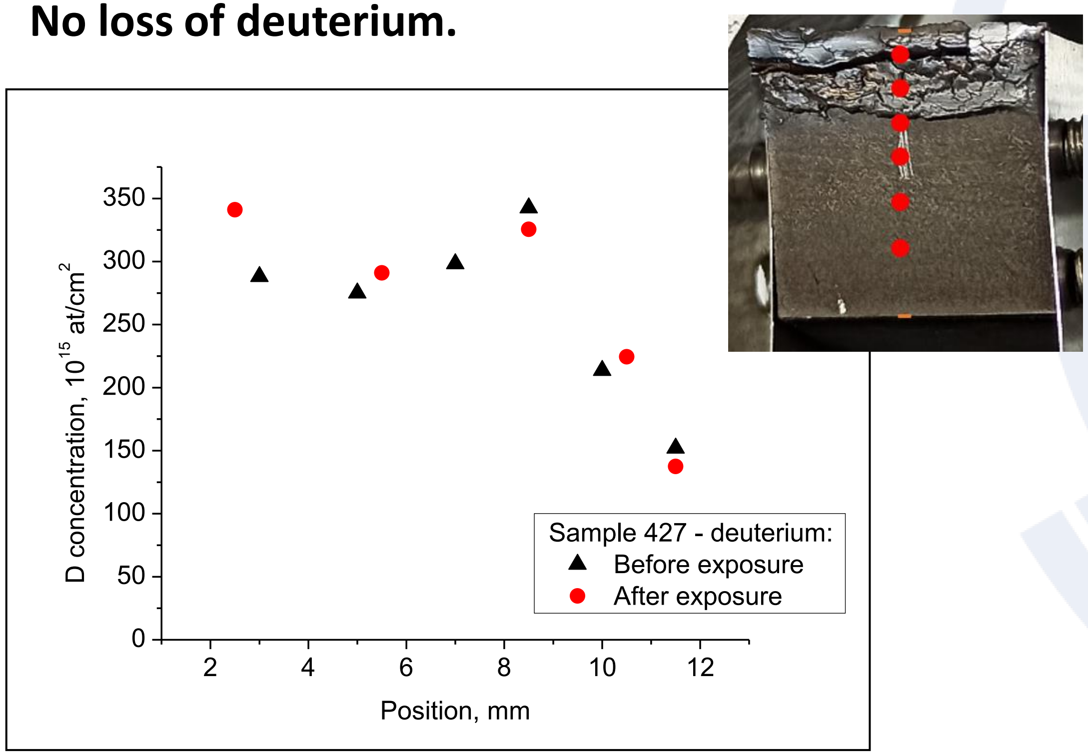
Deuterium retention in divertor dust
1.2 x 10^{21} D atoms/g dust (TDS at IFERC)

→ Dust in divertor contributes <1 % to global fuel retention

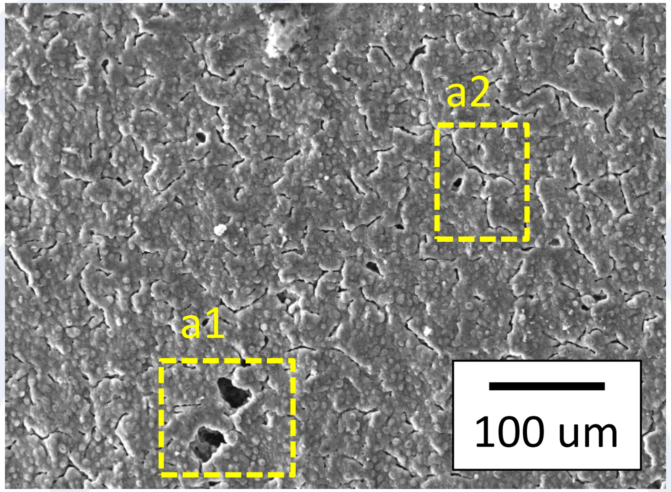
Water exposure experiments

- Simulation of water ingress accident scenario.
- Individual castellations with deposits or cracks exposed to boiling water ex-situ.

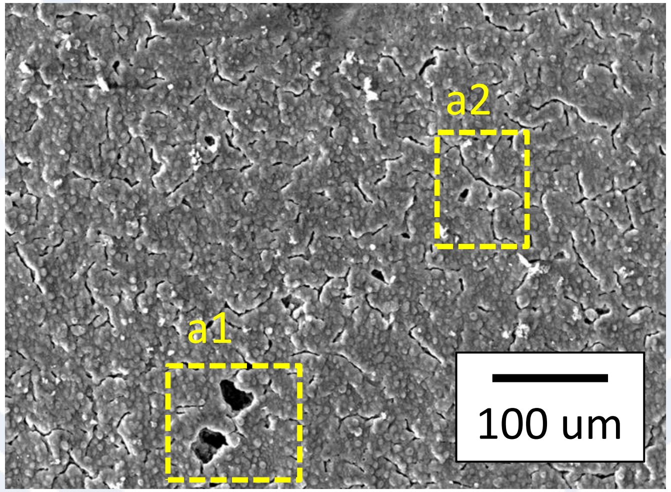
- **No dust generation by exposure to boiling water.**
- **No loss of deuterium.**



Before



After



Zayachuk, Y., (2023). *Nuclear Materials and Energy*, *35*, 101437. https://doi.org/10.1016/j.nme.2023.101437

Lessons learnt

Sources of dust in JET:

- Be melting, tungsten divertor coatings, beryllium deposits, failure and melting of non-plasma facing component elements.

Quantity:

- < 2 g dust vacuumed per operating period (~20 hr plasma/~200GJ input energy).

Potential for mobilization:

- Deposition immobilises dust.
- Low mobilisation during remote maintenance.

Production factors:

- ~2-4 %, from erosion/deposition material balance and deposit delamination.

Fuel inventory:

- <1% of global fuel retention.

Knowledge gaps

- How well is the true size and composition distribution is known (collection method bias)?

- How strong is the adhesion of molten particles to the underlying PFC surfaces → potential for mobilization?

- At what point in thickness the deposits begin to flake?
- What are the stresses induced by thermal cycling in the deposit layers?
- What are mechanical properties of deposits?

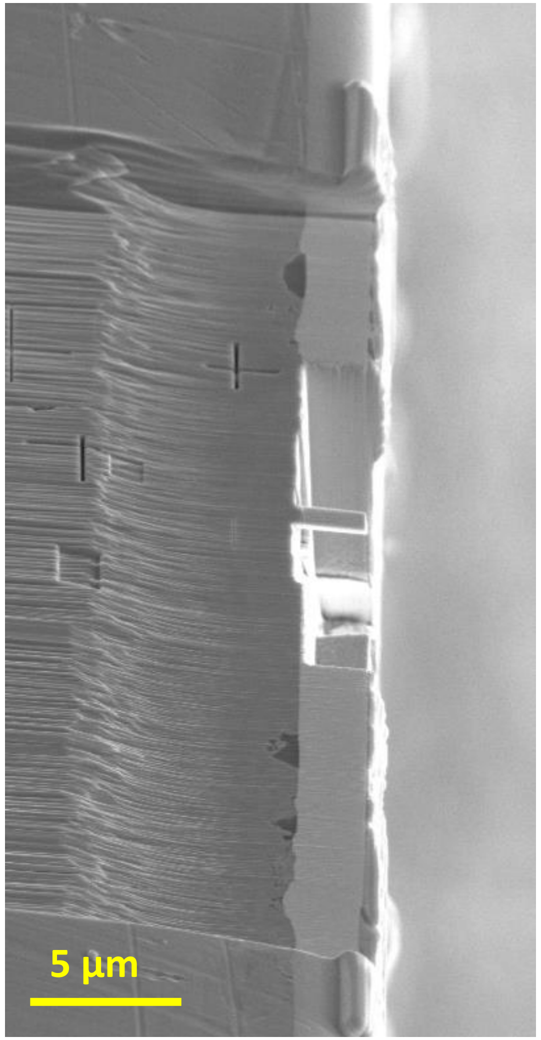
- What are the relative contributions of different mechanisms of dust generation?
- How these contributions change over time?

- Lack of understanding of relevant dust production mechanisms and scaling criteria required for extrapolation to full-W environment.
- Potential for oxidation and explosion in the event of air ingress?

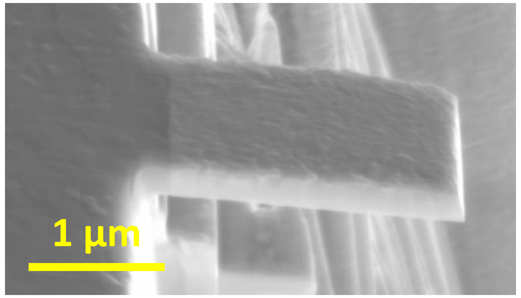
Planned dust studies

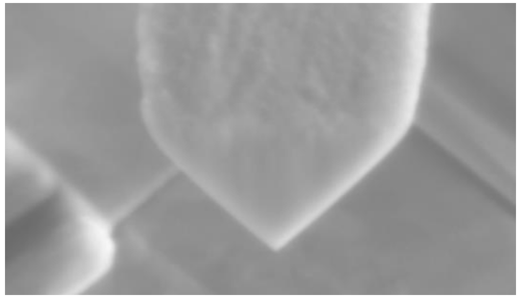
- Intervention is imminent/ongoing.
- Vacuuming in a few days → full divertor sample.
- Start of component removal in ~October → outer wall deposition monitor.
- Results from post-ILW3 (2015-2016) operational period, including DTE2 (2021) and DTE3 (2023).

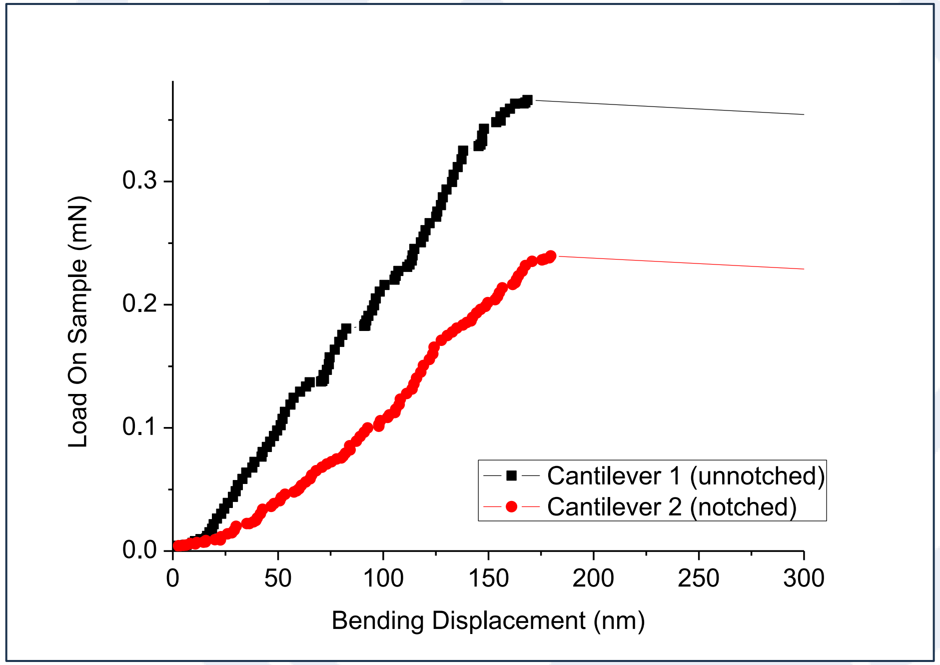
Bridging the gap to B-W environment



- Apply micromechanical testing tools to characterize deposit layers:
  - Interfacial strength and toughness.
  - Bulk deposit strength and toughness.
- Method development stage → applied to W-Mo reference samples.







- B-coated W substrates procured (IAP).
- Different roughness → study the difference in mechanical properties.