Review of previous characterization of collected dust particles from different machines

Marek Rubel

With very important contributions from nearly 70 colleagues coworking on the topic for over 40 years

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B. Emmoth†, H. Bergsåker, N. Almqvist, J.R. Drake, J. Malmberg, M. Cecconello, D. Hasselbrunner†, H. Ferm, A. Hedqvist, P. Sundelin, P. Petersson, D. Ivanova, A. Weckmann, P. Ström, A. Garcia-Carrasco, S.W. Moon, L. Dittrich, E. Pitthan, D. Primetzhofer, D. Gautan

P. Wienhold, M. Freisinger, H. Reimer, V. Philipps, G. Sergienko, A. Huber, E. Wessel, H. Penkalla, M. Rödig, W. Biel, J. Linke, S. Brezinsek

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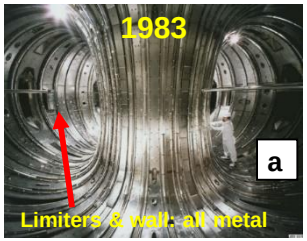
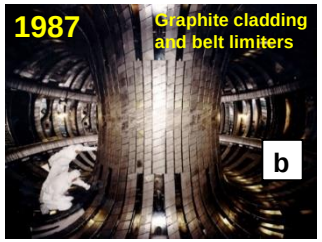
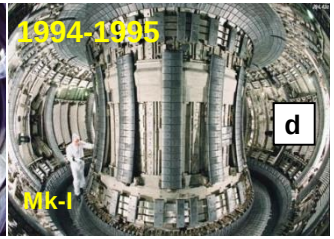
L. Dittrich, C.P. Dhard

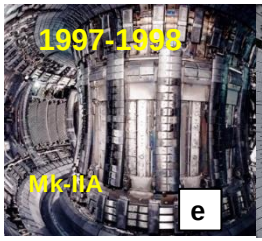
Studies over the years 1984 - 2025: The devices

JET

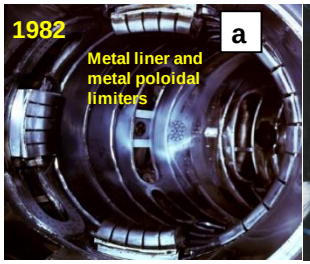


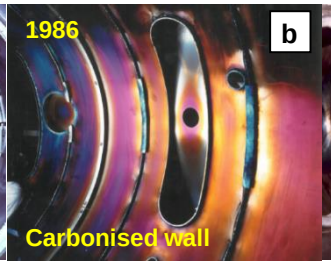


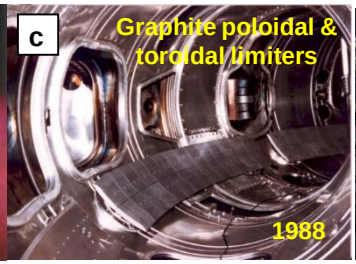




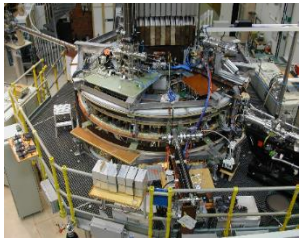
TEXTOR



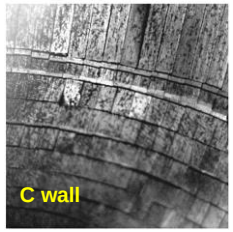




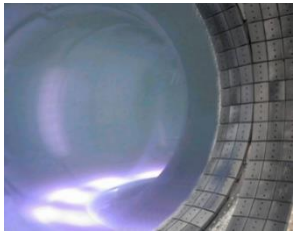
EXTRAP-T2



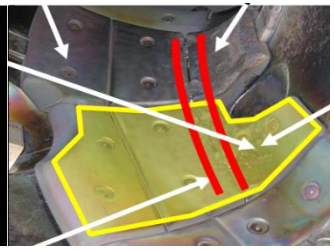
#14043



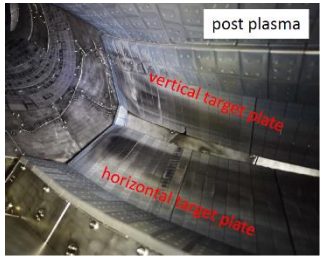
Tore Supra



COMPASS



W7-X



Interest in Dust

Driving force in studies: Safety & economy of reactor operation

- **Safety hazard:** ***ignition, H_2 generation, Be, tritiated matter***
- **Impact on operation:**
  - ***mobilization (disruptions),***
  - ***degradation of optical diagnostics,***
  - ***impact on pumping systems.***

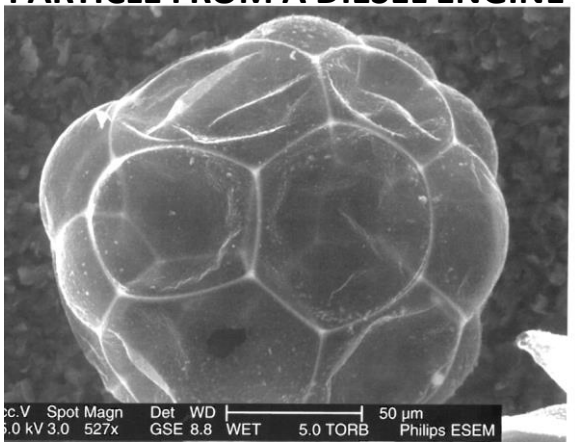
Dust/metal splashing studies started in 1984 (e.g. JET), very systematic studies since 1997 (TEXTOR, JET)

Key points:

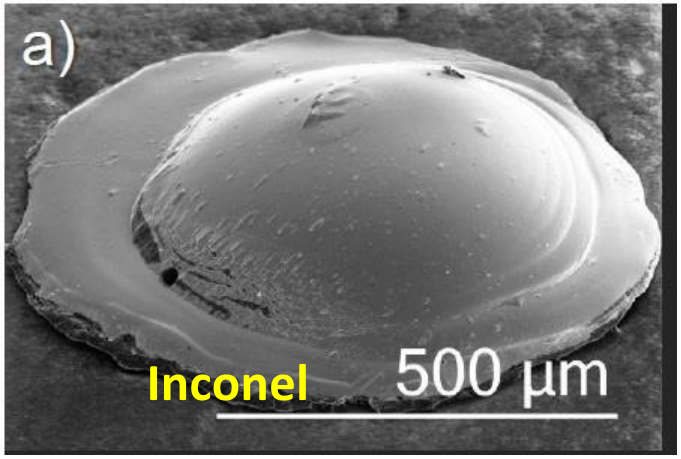
- ***quantity and fuel retention properties,***
- ***behaviour in plasma.***

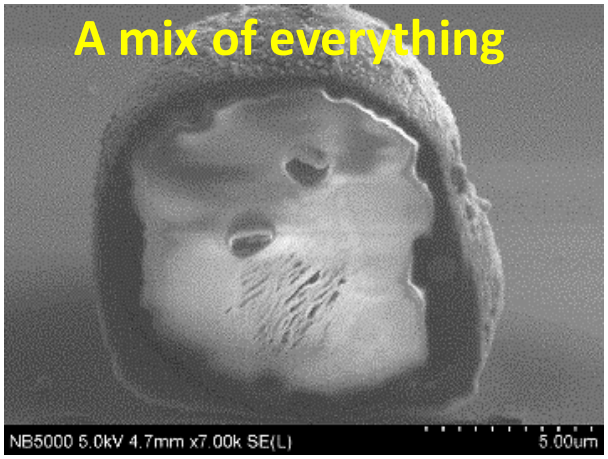
Dust is fascinating

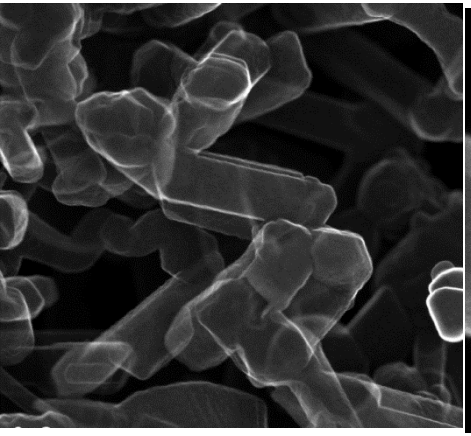
PARTICLE FROM A DIESEL ENGINE

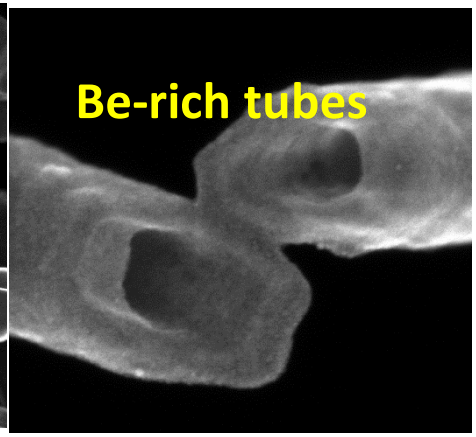


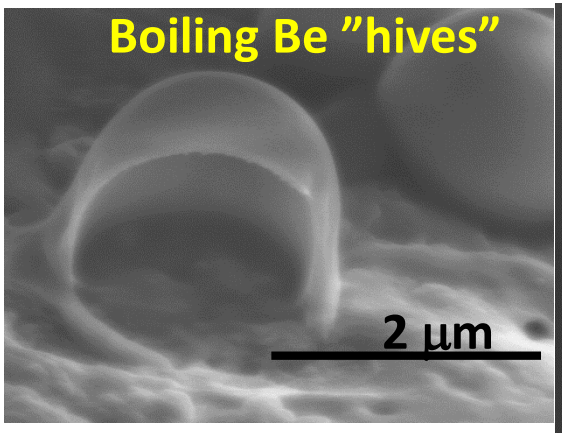
Dr. Tricard, ELF Acquitaine, France

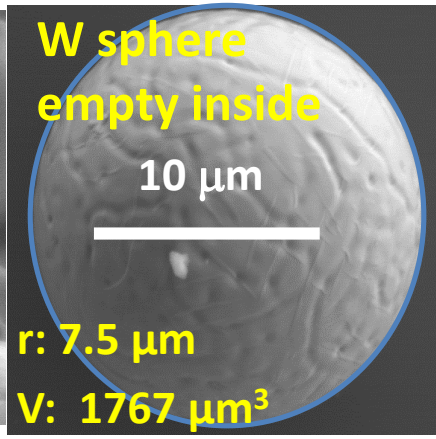








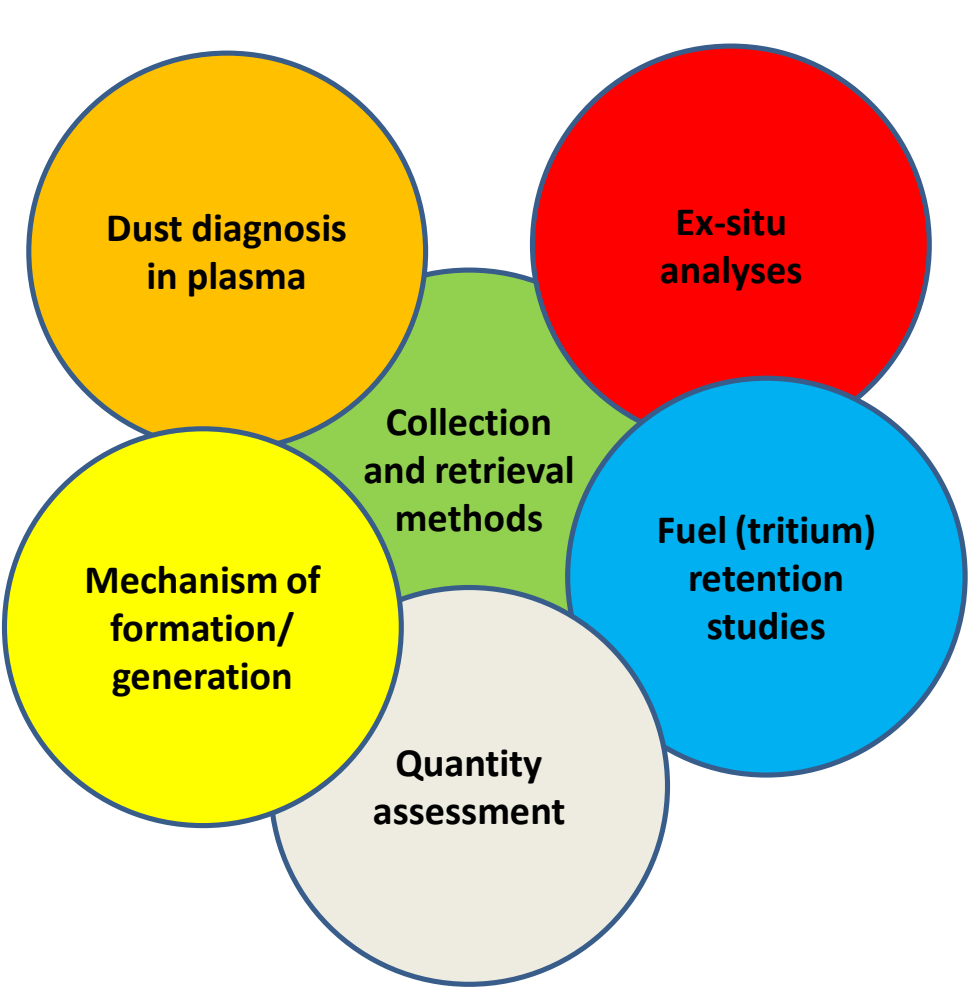


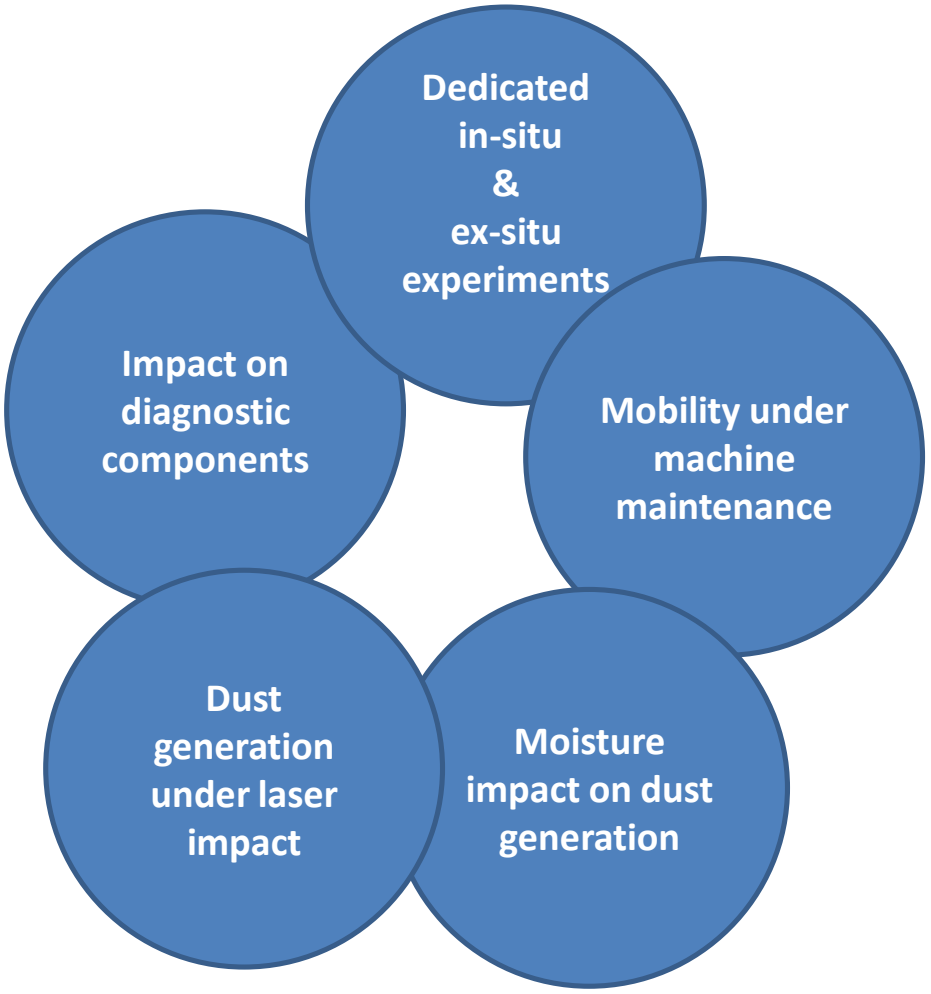


There will be many pictures, but this work is far beyond ”picturology”.

Dust is unpleasant, difficult in handling, in many cases just dangereous.

Integrated / Holistic Approach

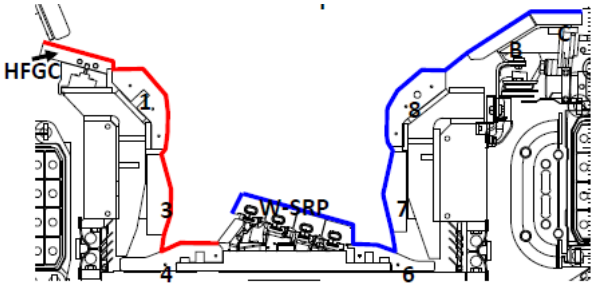





IR Cameras
Fast Cameras
In-Vessel
HR Imaging
Optical
spectroscopy
Performance of Optical
Components:
Mirrors
Windows
Long Distance
Microsccopy
Magnetic
Diagnostics
Marker
Techniques
Thermocouples

Dust Collection: *Facts, Advantages, Drawbacks*

Vacuum cleaning: 360 °



Message:

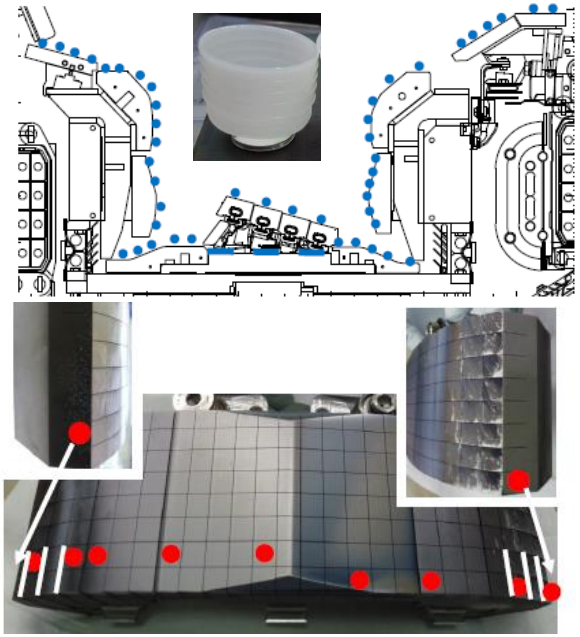
Around 1 g found after each campaign (20 h of plasma)

Drawbacks:

Composition: a mix of all particles.

Not possible to associate dust morphology with a place of collection.

Local sampling: sticky pads



Messages:

- ***Fairly small amount sampled.***
- ***Good adherence of particles to tiles***

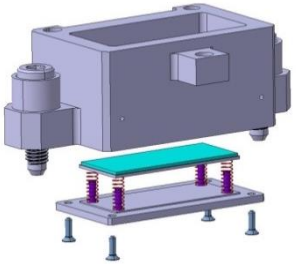
Advantage: *Detailed local analyses.*

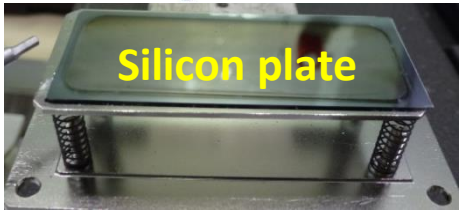
Drawbacks:

The top layer of samples represents the bottom of deposits.

Force is applied during the collection; more than just dust may be collected.

Dust monitors





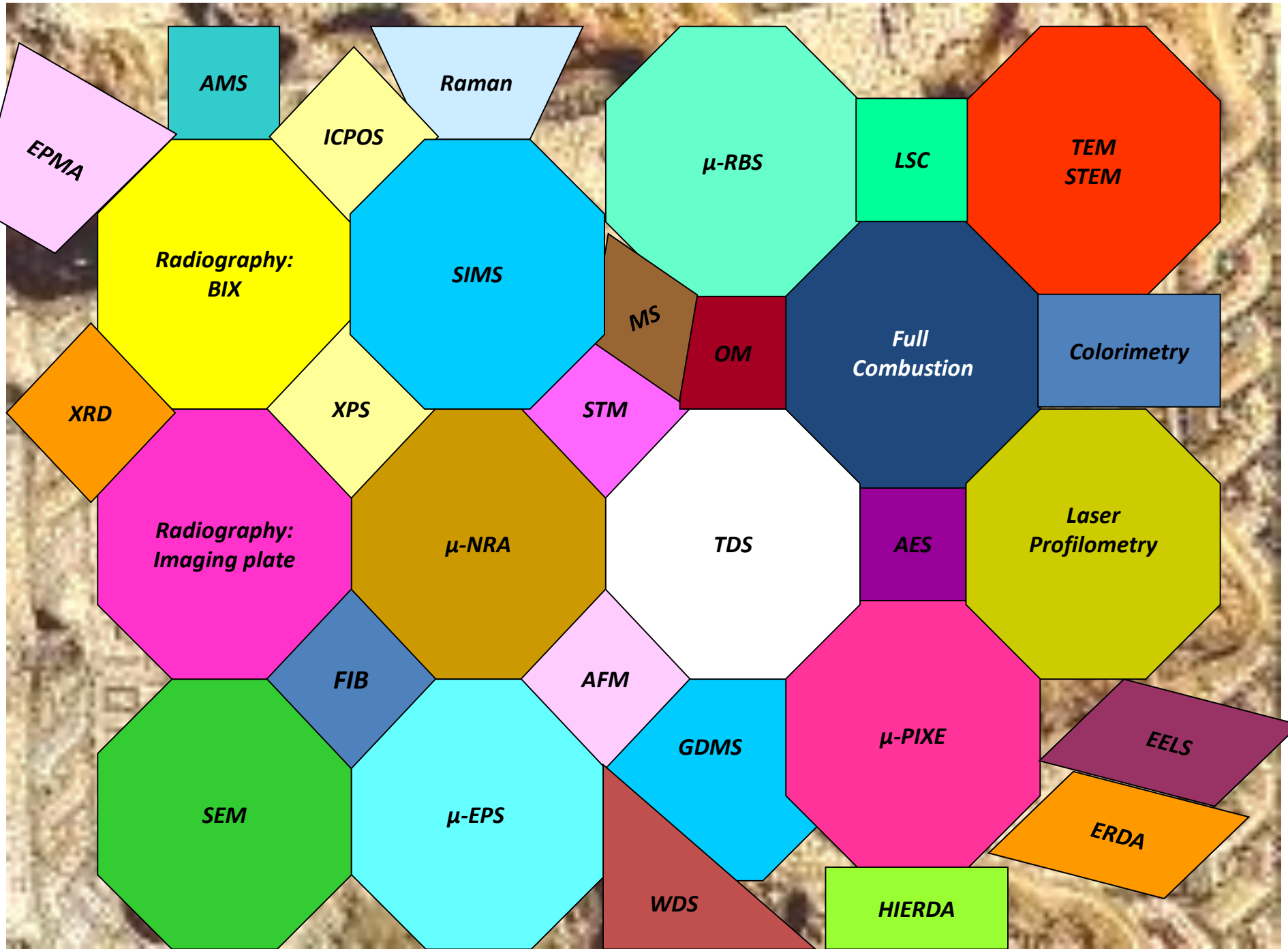
Message:

Tiny amount collected.

Advantages:

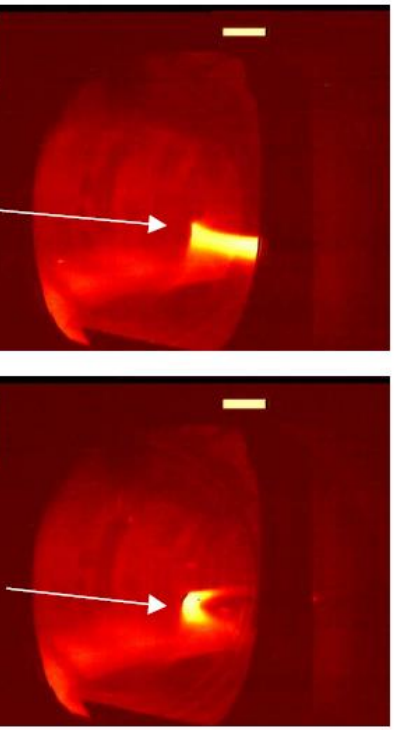
Collection of undisturbed mobilized particles.

Precise analyses.

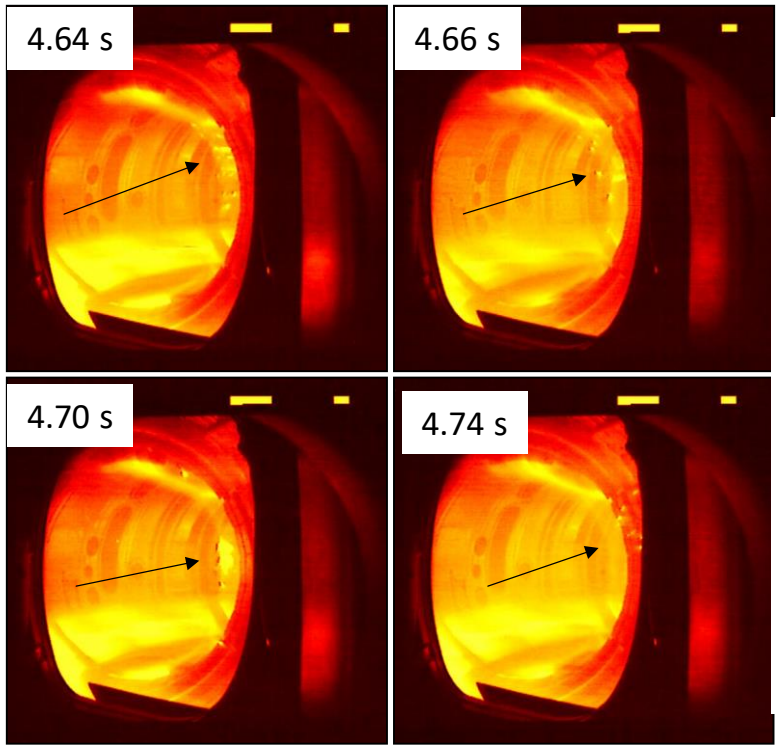

AMS
Raman
EPMA
ICPOS
μ-RBS
LSC
TEM
STEM
Radiography:
BIX
SIMS
MS
OM
Full
Combustion
Colorimetry
XRD
XPS
STM
Radiography:
Imaging plate
μ-NRA
TDS
AES
Laser
Profilometry
FIB
AFM
GDMS
μ-PIXE
EELS
SEM
μ-EPS
ERDA
WDS
HIERDA

TEXTOR plasma: detachment of co-deposits

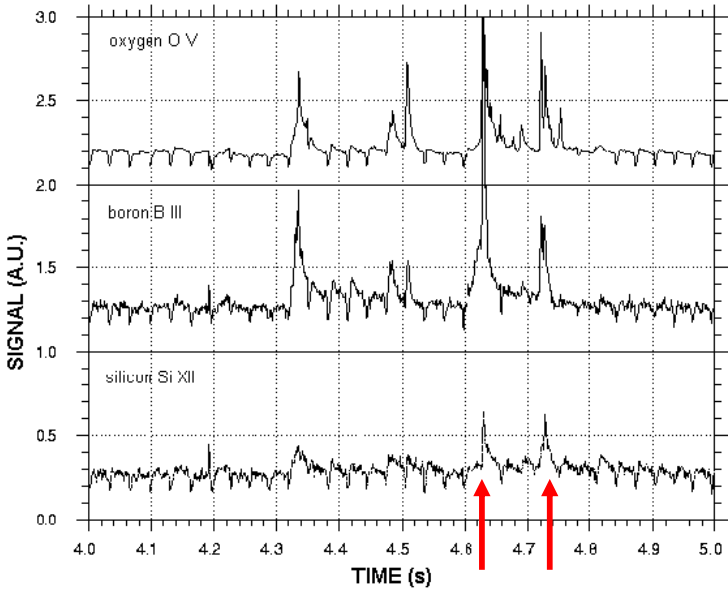
A debris motion caused by the rocket effect.



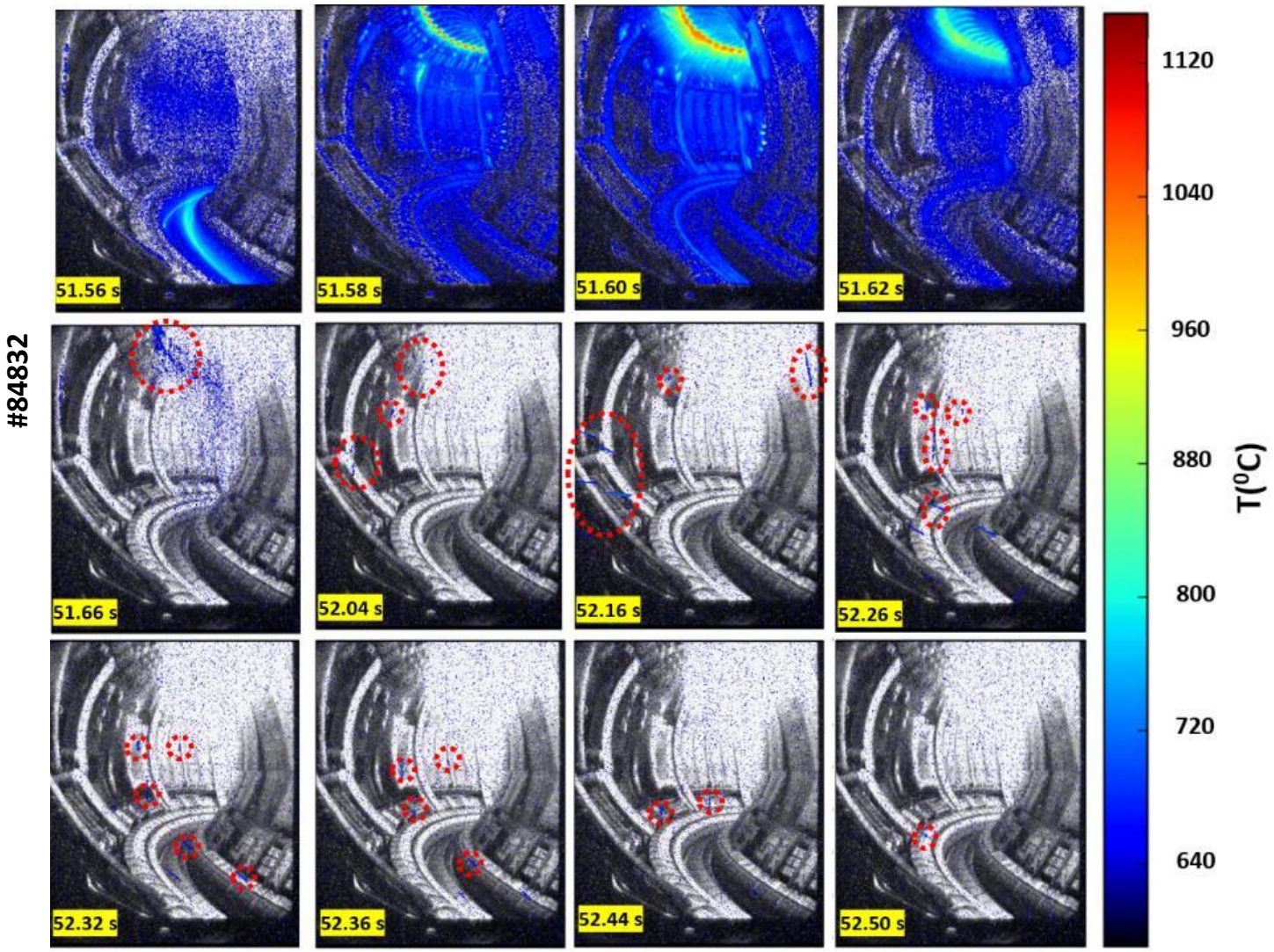
Time sequence showing a cloud of particles



Dust release is immediately detected by spectroscopy.

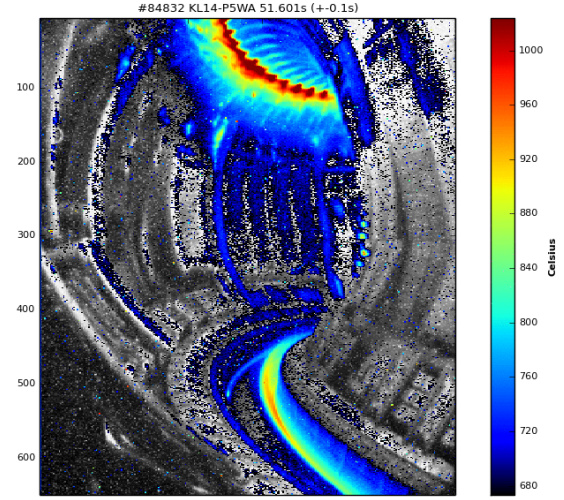


JET-ILW: Beryllium melting and splashing. A rain of droplets from the upper limiters



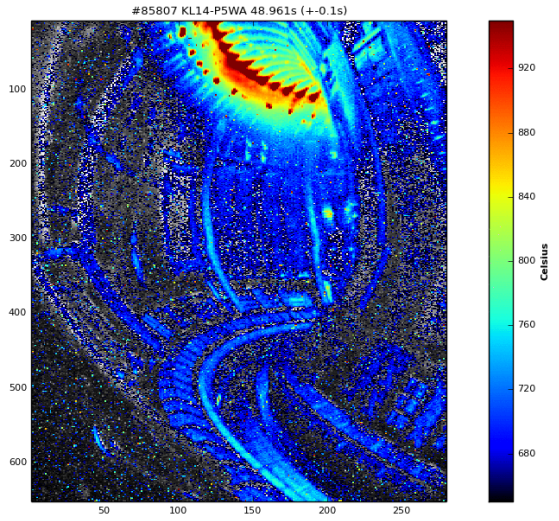
Beryllium splashes

#84832 KL14-P5WA 51.601s (+-0.1s)

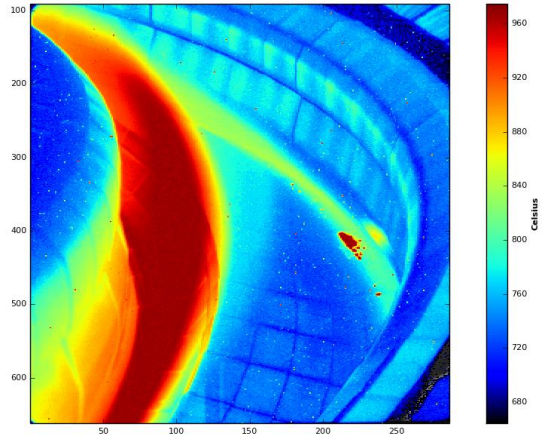


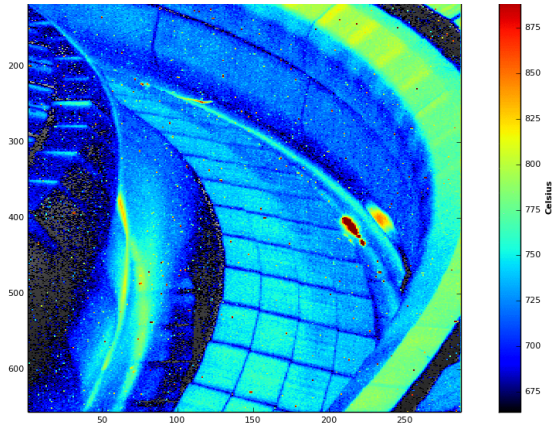
#85807

#85807 KL14-P5WA 48.961s (+-0.1s)

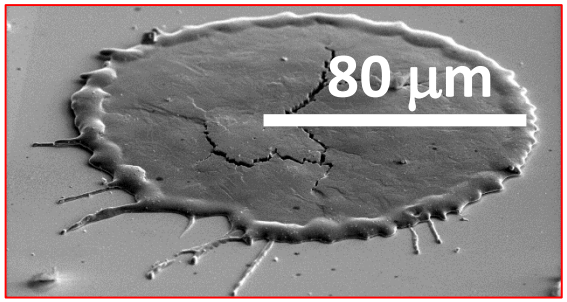


#84832 KL11-P1DB 51.559s (+-0.1s)

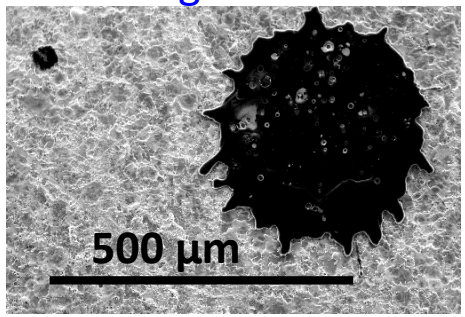




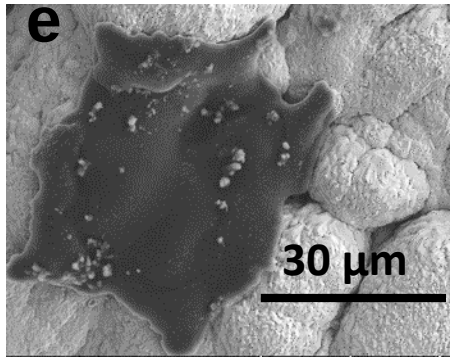
On dust monitors



On a diagnostic mirror



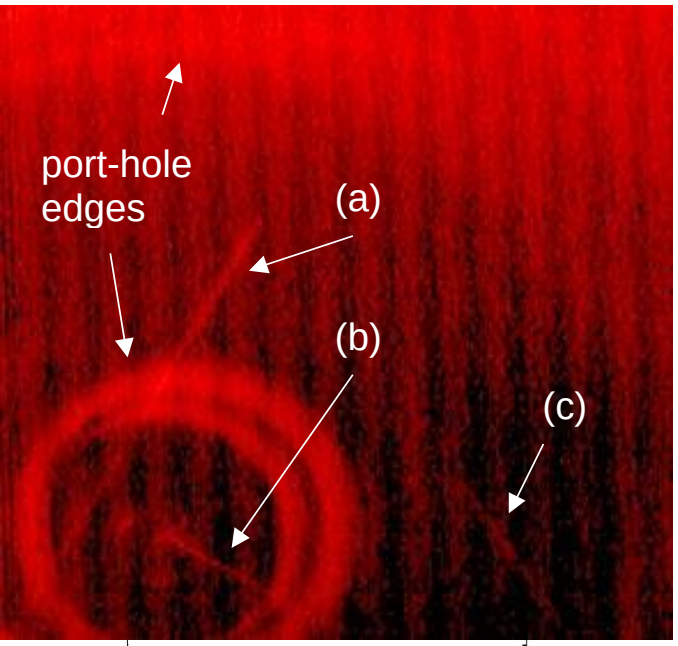
On the outer divertor tiles

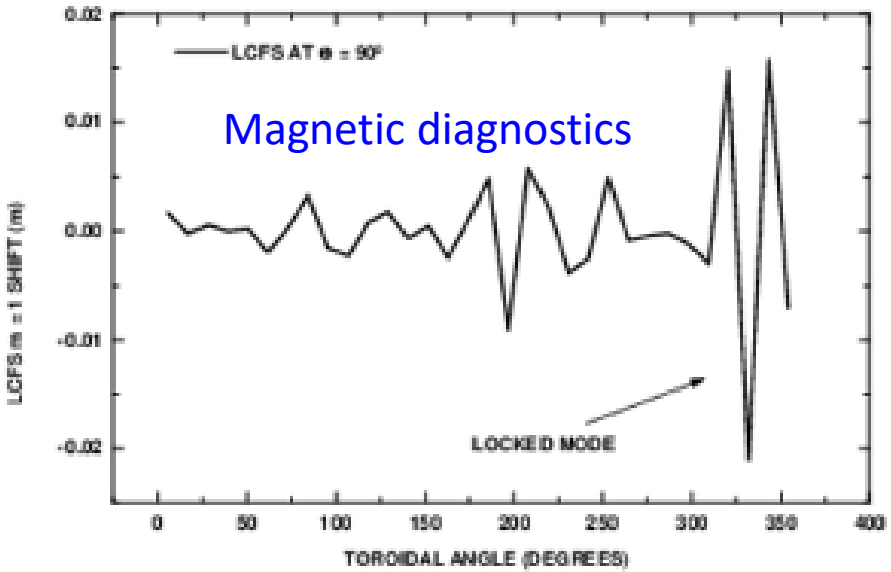


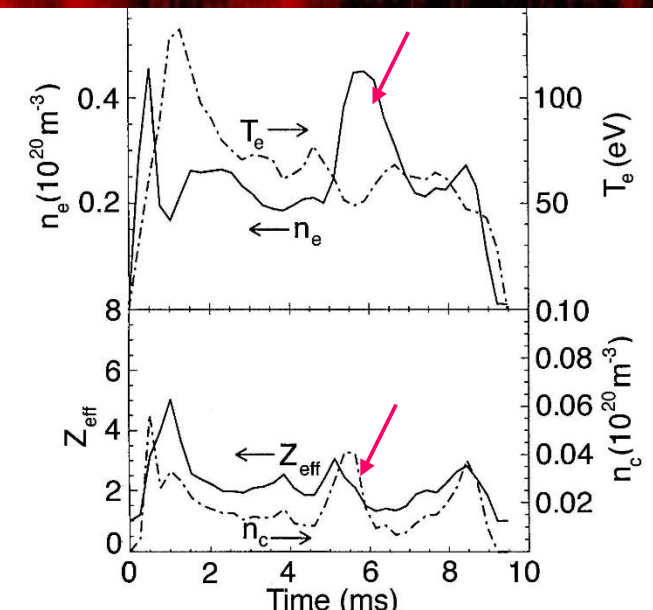
Messages:

- *Be droplets and splashes adhere fairly well to surfaces.*
- *Splashes are mostly round and only very thinly coated by deposits ➔ "rain" of fine droplets at right angle from dump plates in the run-away experiment, last in ILW-2.*

Brittle destruction of carbon by wall locking modes at the EXTRAP-T2 RFP device



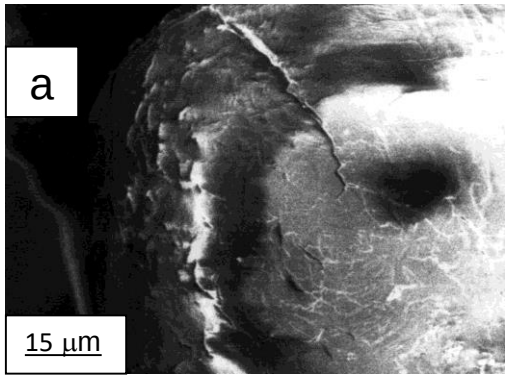


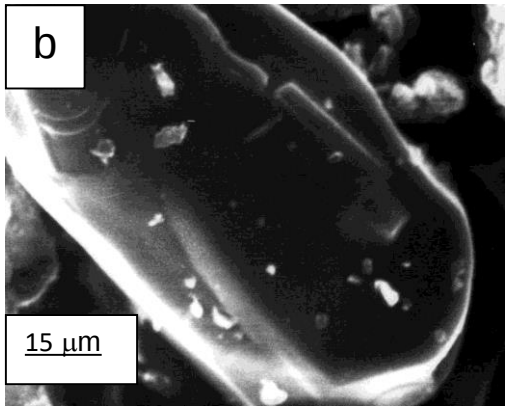


A burst of particles is caused by wall locking mode → extreme local energy deposition.

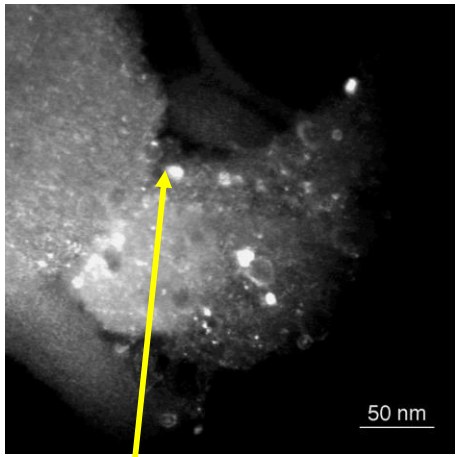
Particles' release from the wall is accompanied by a drastic increase of all spectroscopy signals: n_e T_e Z_{eff} n_{carbon}

Extrap-T2 RFP: crystalline debris and co-deposits

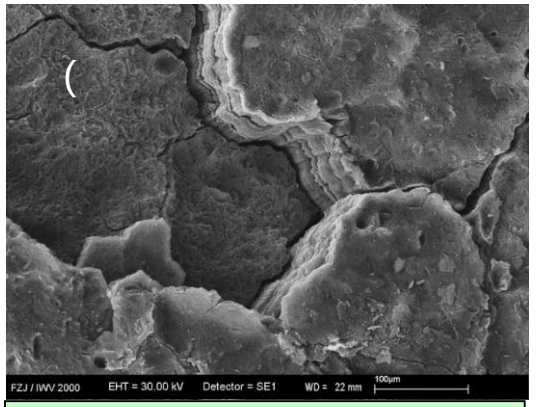




Debris after passing through the plasma.

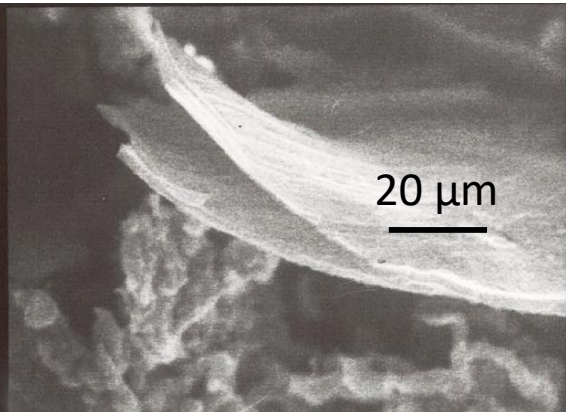


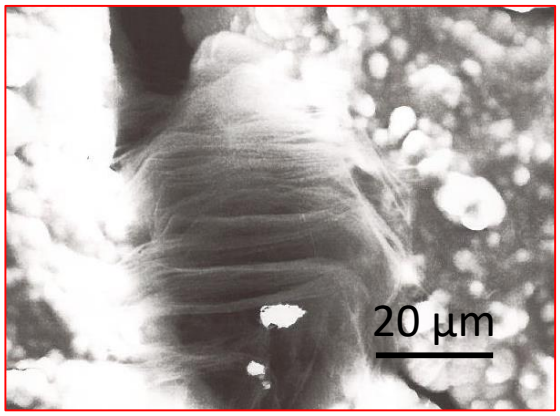
Dark field image of a co-deposit with embedded crystallites (bright spots) and a diffraction pattern.

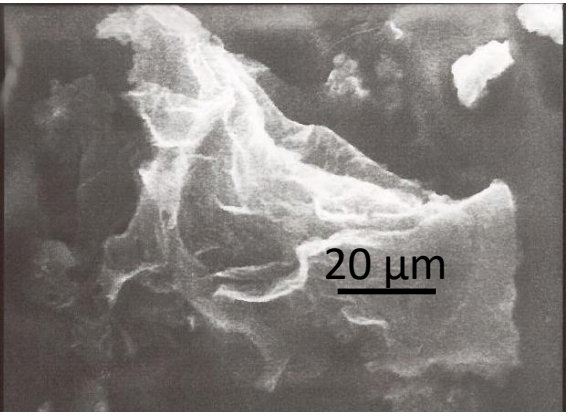


Large graphite debris (2 mm) with a co-deposit.

Carbon-based polymer-like films. Precursors of co-deposits?

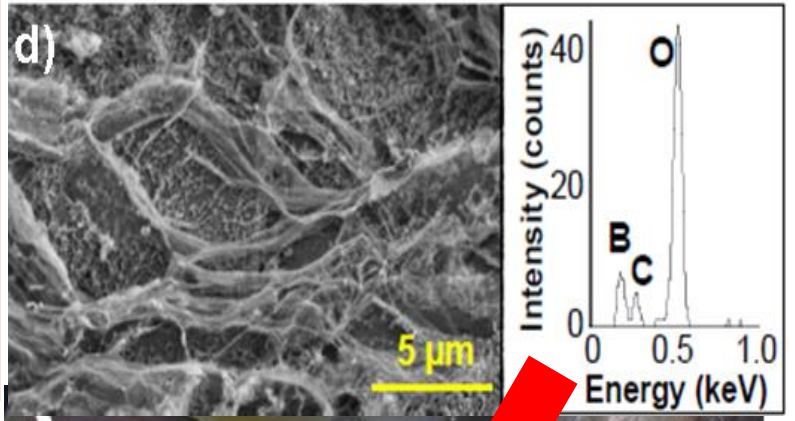


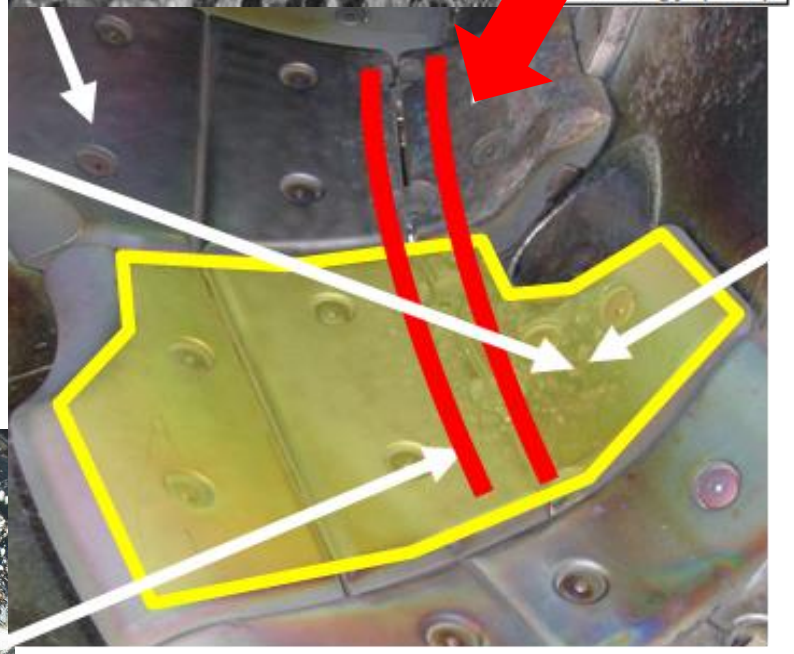




TEXTOR

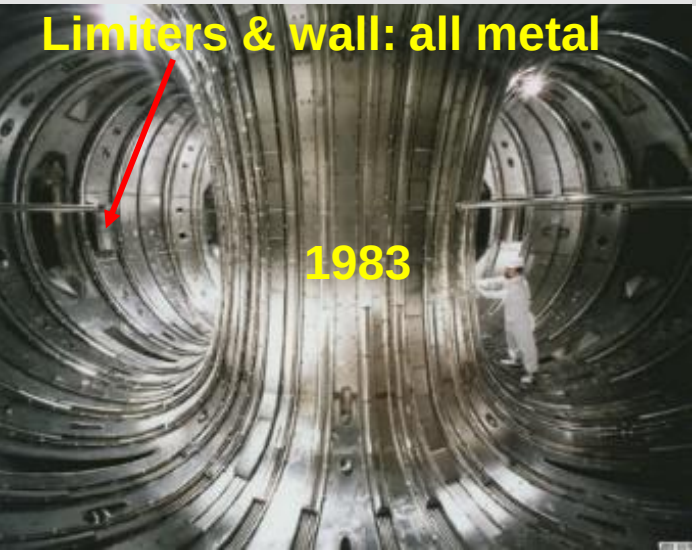
EXTRAP-T2

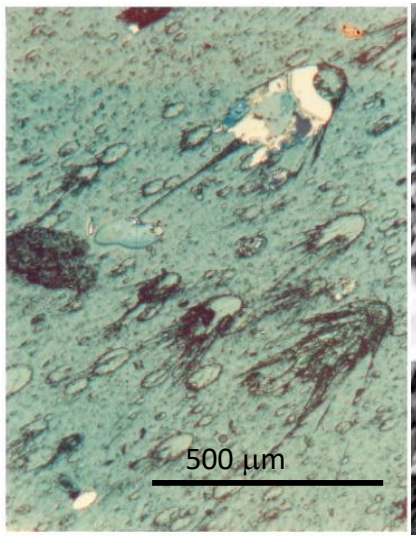


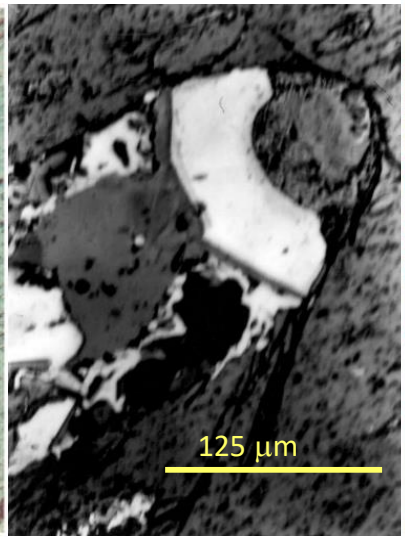


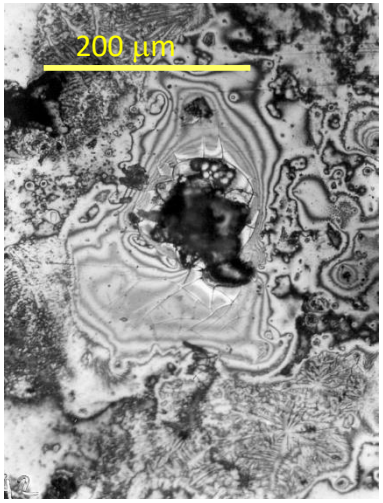
COMPASS

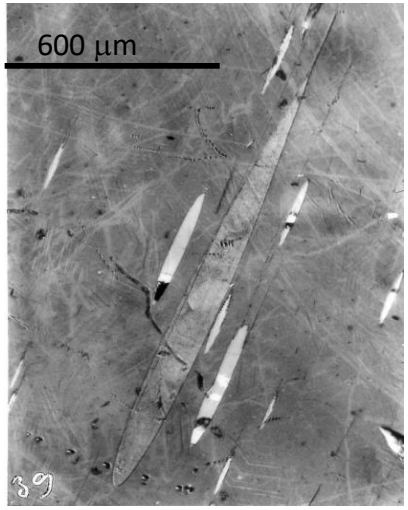
Metal splashes: JET with full metal wall (1984)

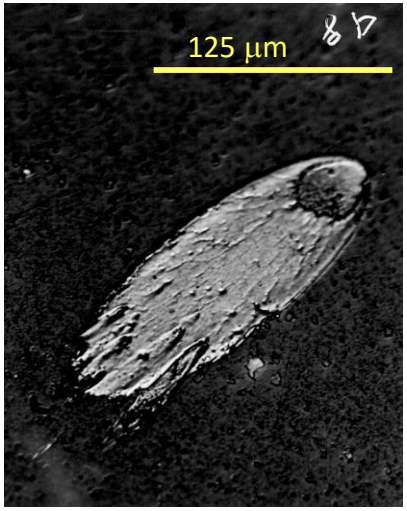






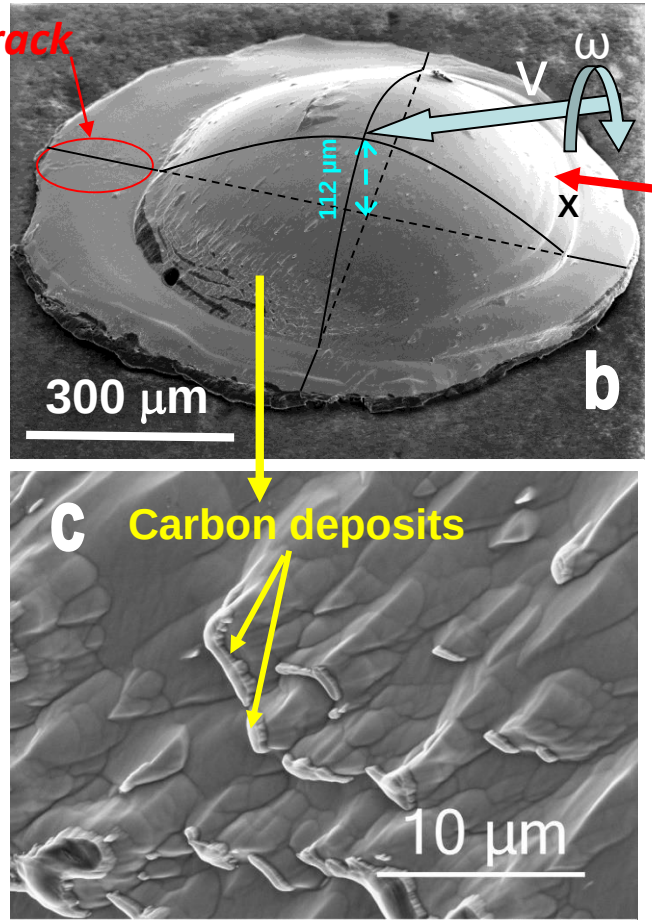






Metal splashes: TEXTOR

- Inconel splash on the graphite limiter.
- Origin: the liner or the ICRH antenna grill.



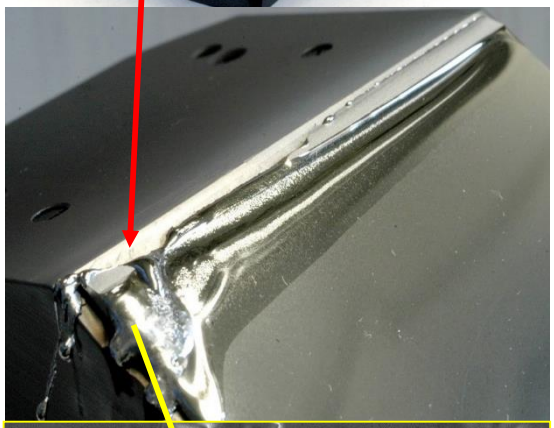
Rotation of molten material after splashing.

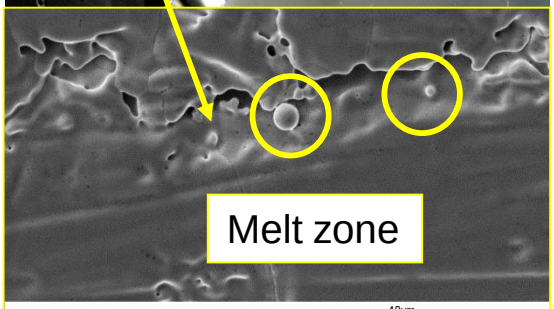
Metal melting & splashes: What about tungsten?

Dedidated experiments on W melting

TEXTOR: Test limiter with W plate)

G. Sergienko et al.,
Phys. Scr. T128 (2007) 81



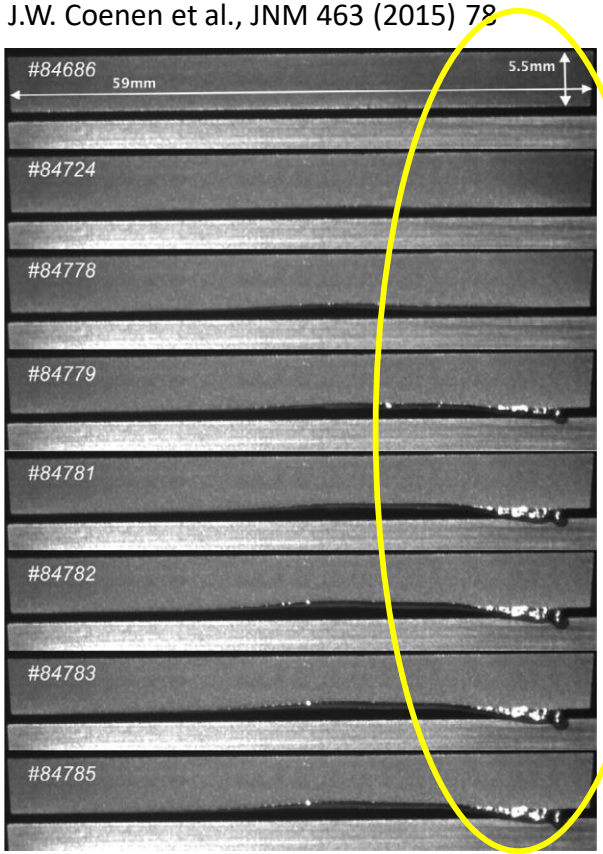


W droplets in the melt zone.

No W droplets found in the collected debris.

JET-ILW: special lamella in bulk W divertor

J.W. Coenen et al., JNM 463 (2015) 78

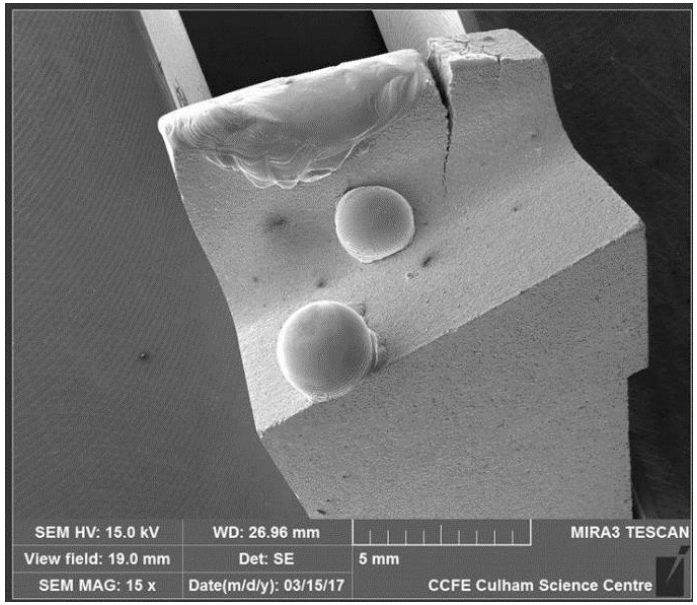


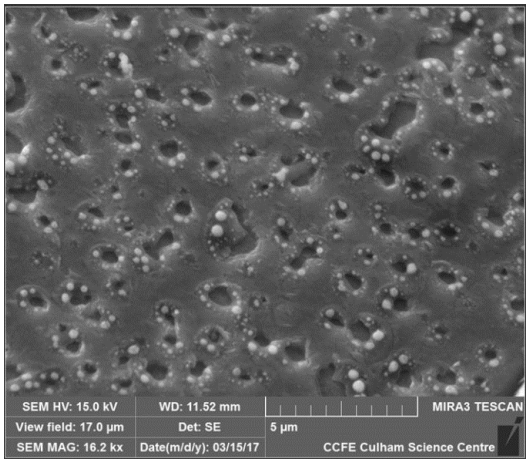
Evolution of melt damage.

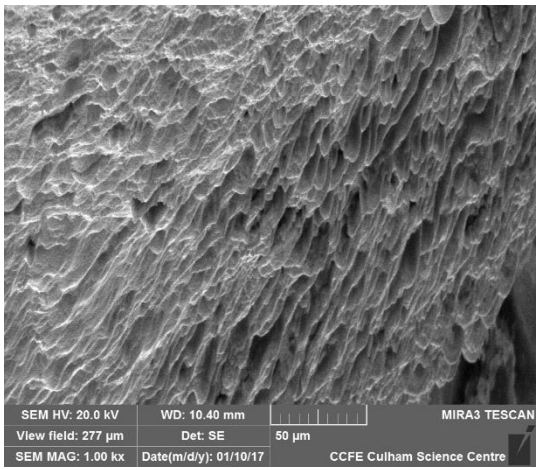
No single loose W droplet has been found on that damaged piece and on the adjacent lamellae.
Nothing in other regions of JET-ILW.

Metal melting & splashes: What about tungsten?

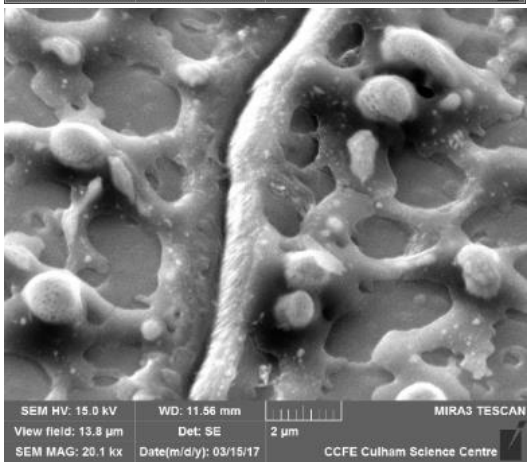
JET-ILW: Langmuir probes

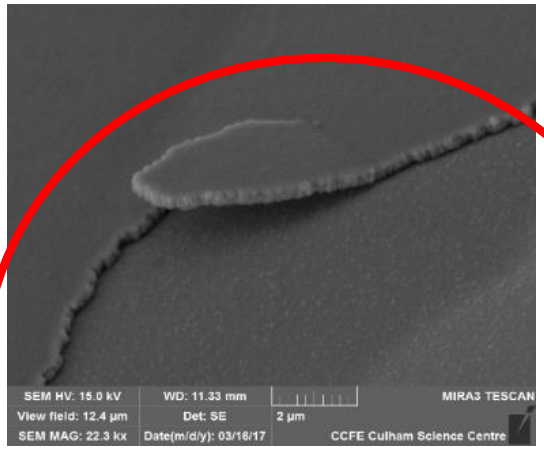


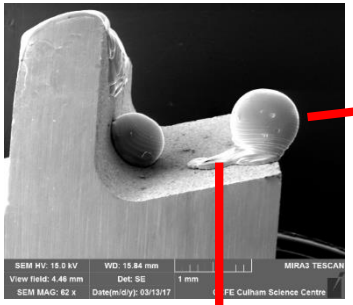


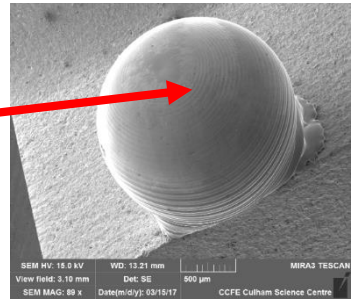


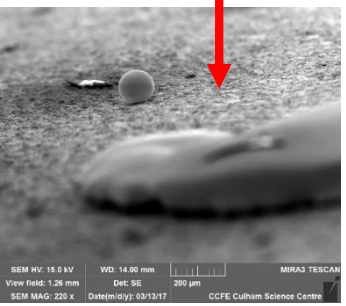
Deficit of W: blown out?

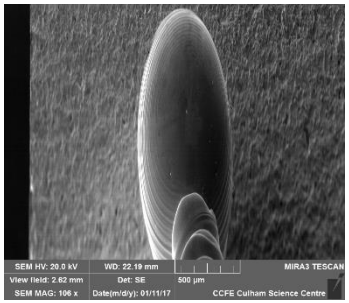












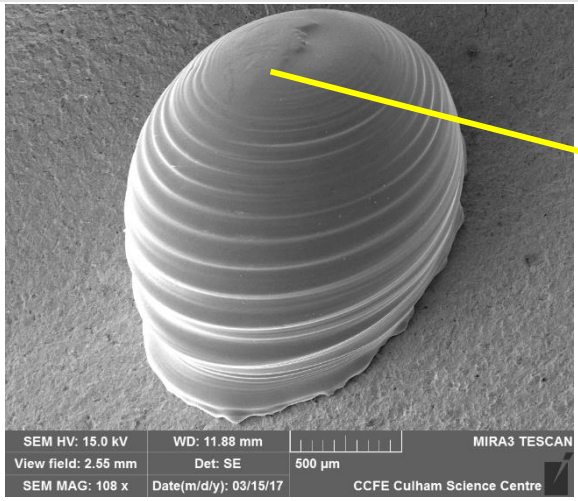
Boiling W

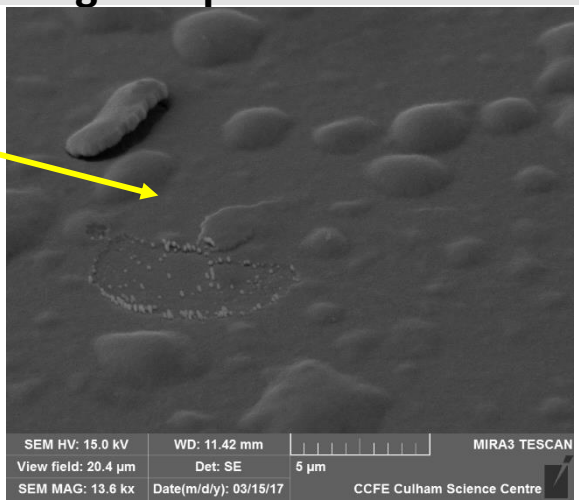
No single loose W droplet found in the matter retrieved from JET-ILW.

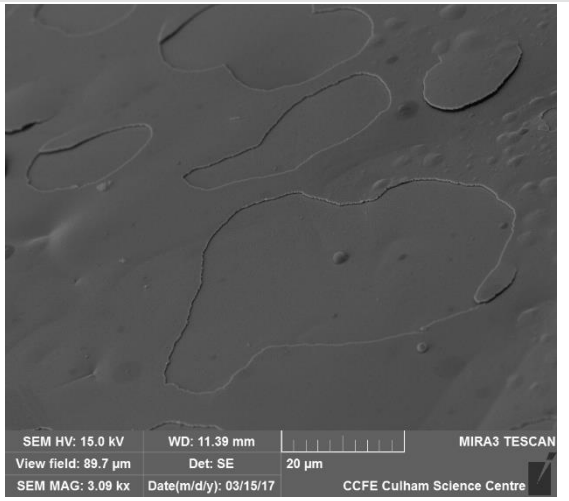
Exfoliation of the overheated surface?

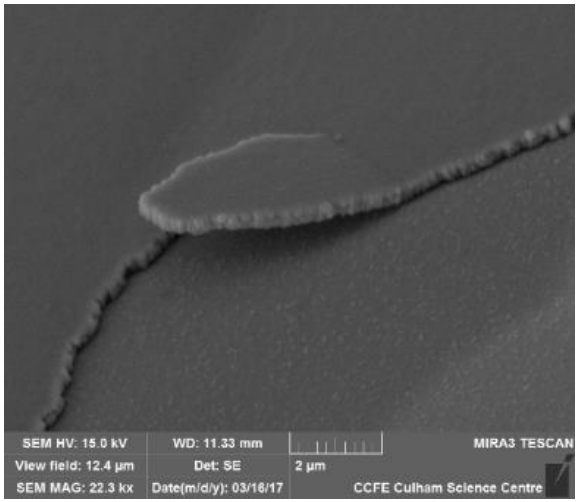
Metal melting & splashes: What about tungsten?

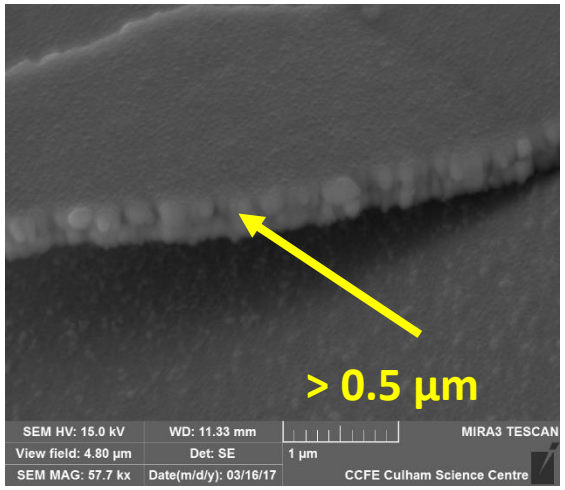
JET-ILW: Langmuir probes

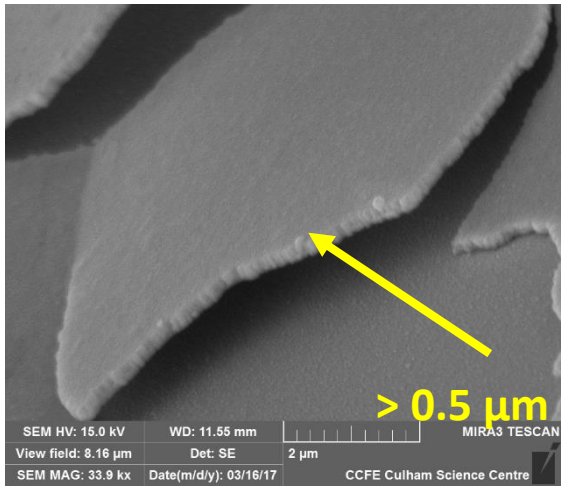












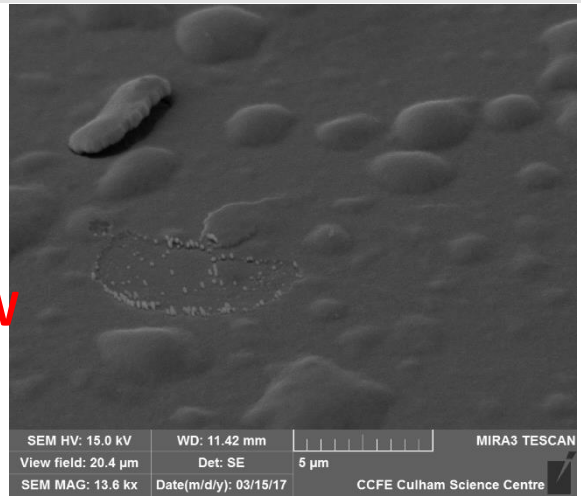
- **Metal exfoliation in the overheated region. This may be a real contributor in the W erosion.**
- **Are these pure W flakes or …?**

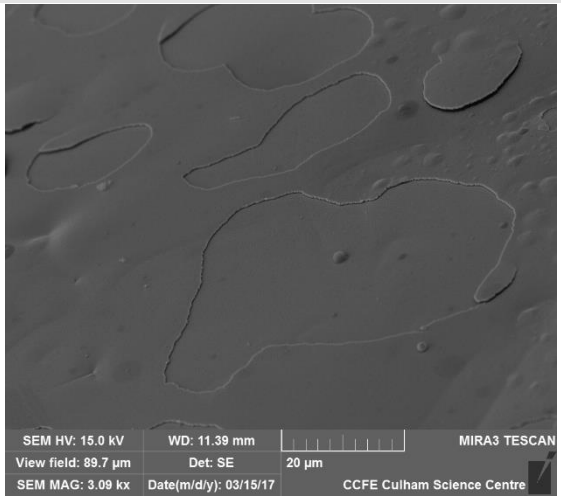
LP26, Tile 6, 16BW

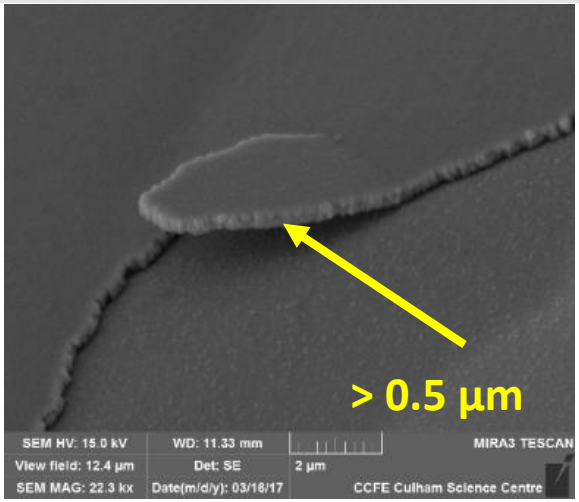
Comparison of W and C flaking. Identical?

W

JET-ILW



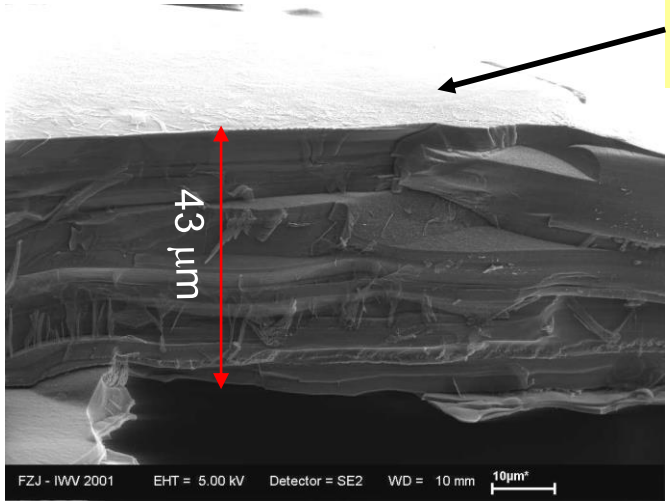




C

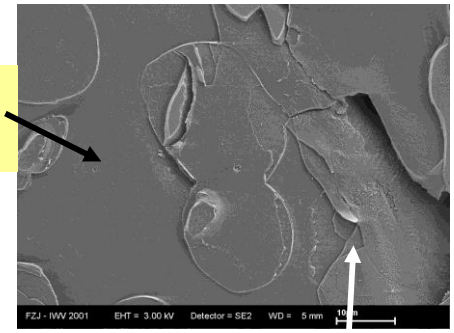
TEXTOR

~ 15 000 s of plasma operation

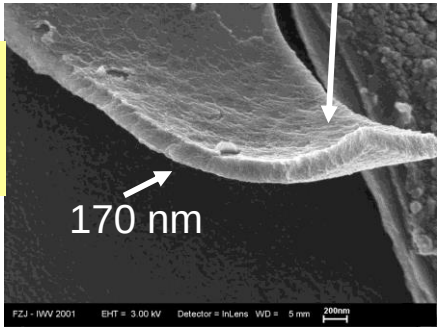


Cross - section

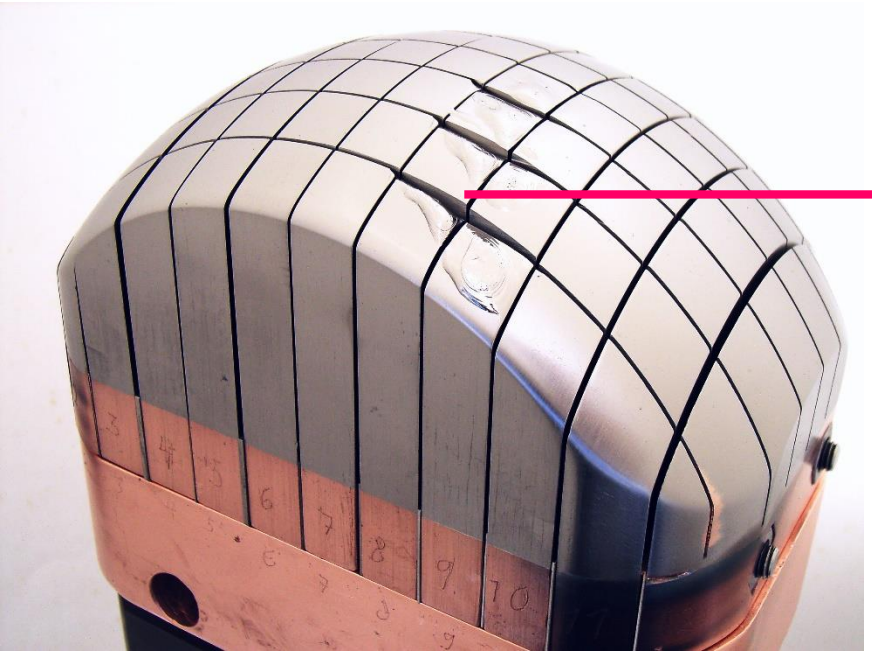
Top surface

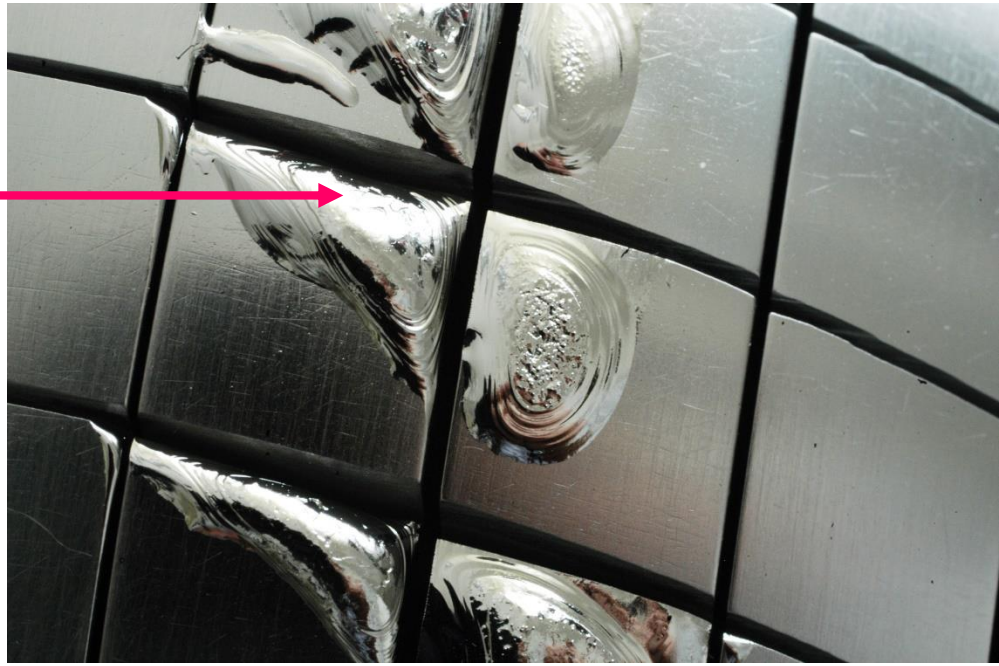


Single flaking layer



W melting: Castellated W test limiter in TEXTOR

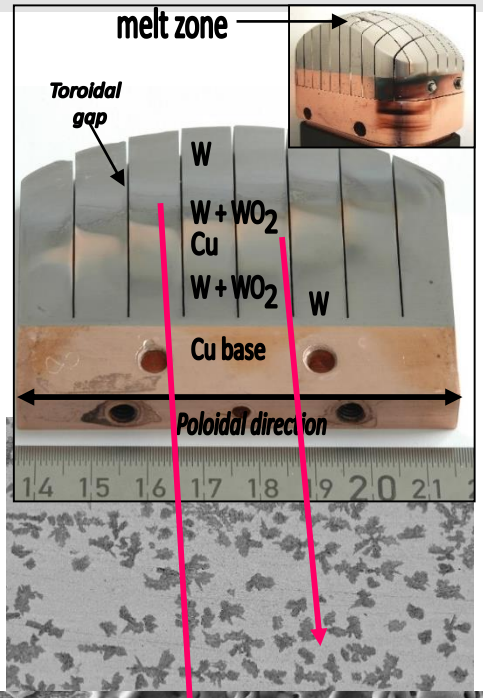


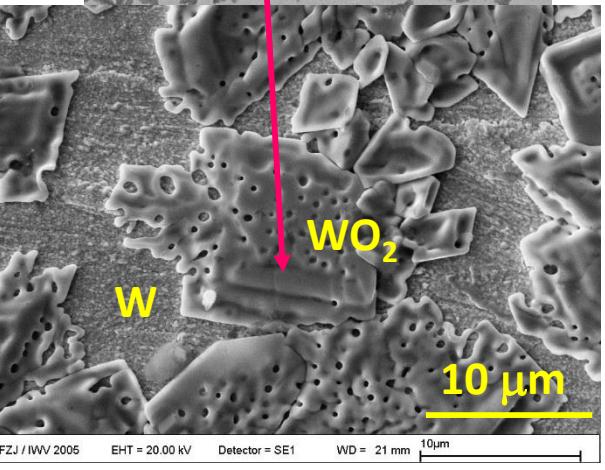


Deliberate melting.

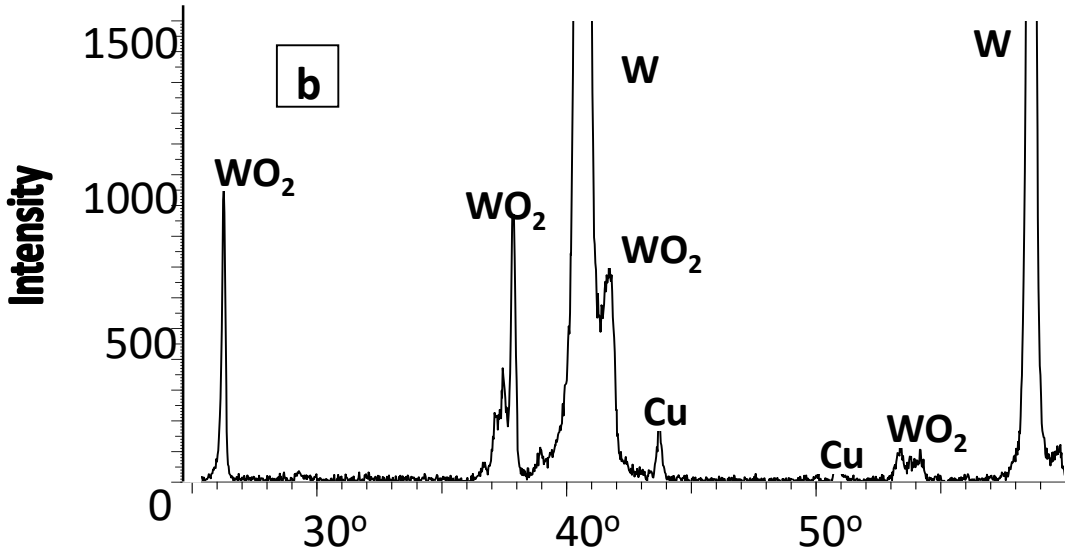
W melting: Castellated W test limiter in TEXTOR

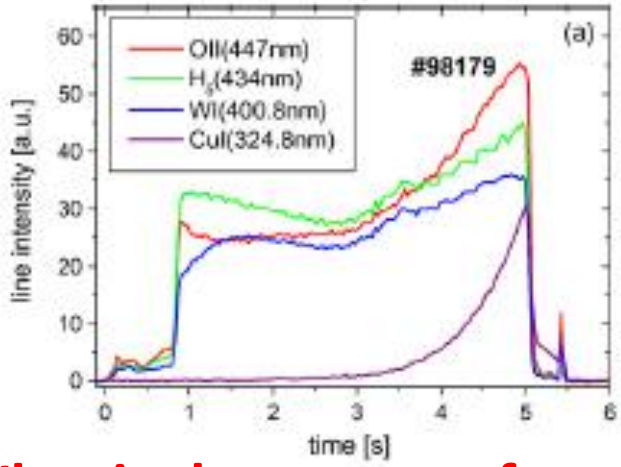
The role of chemistry in W transport.





WO_2 "leaves"





Evolution of signals when melting occured at 2.34 s.

What is the source of oxygen?

O_2 or H_2O desorption from bulk Cu or W?

Categories of dust in JET-ILW

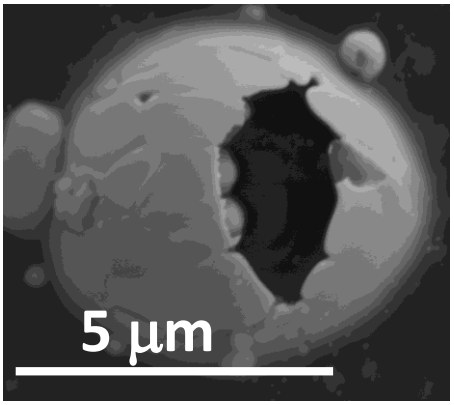
ITER not relevant

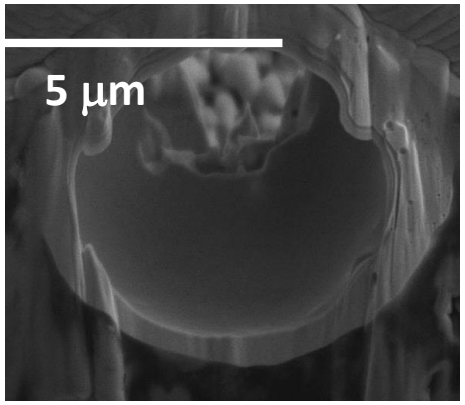
Be flakes of coatings from inner wall cladding tiles

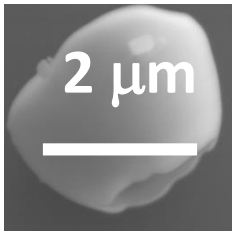
Debris of CFC or BN (probes heads)

W-Mo coatings from CFC

- ***Small debris, flakes not molten.***
- ***Partly molten (glassy structure)***
- ***Spheroids by aggregation of W flakes***







Formation phase

ITER relevant

Be-rich flakes of co-deposited layers

Be droplets and splashes

W droplets and splashes

Steel (and Inconel) droplets and splashes e.g. from antennae grills

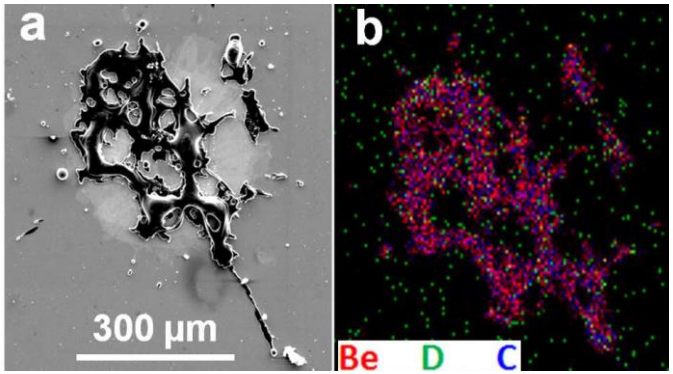
Swarf from in-vessel work

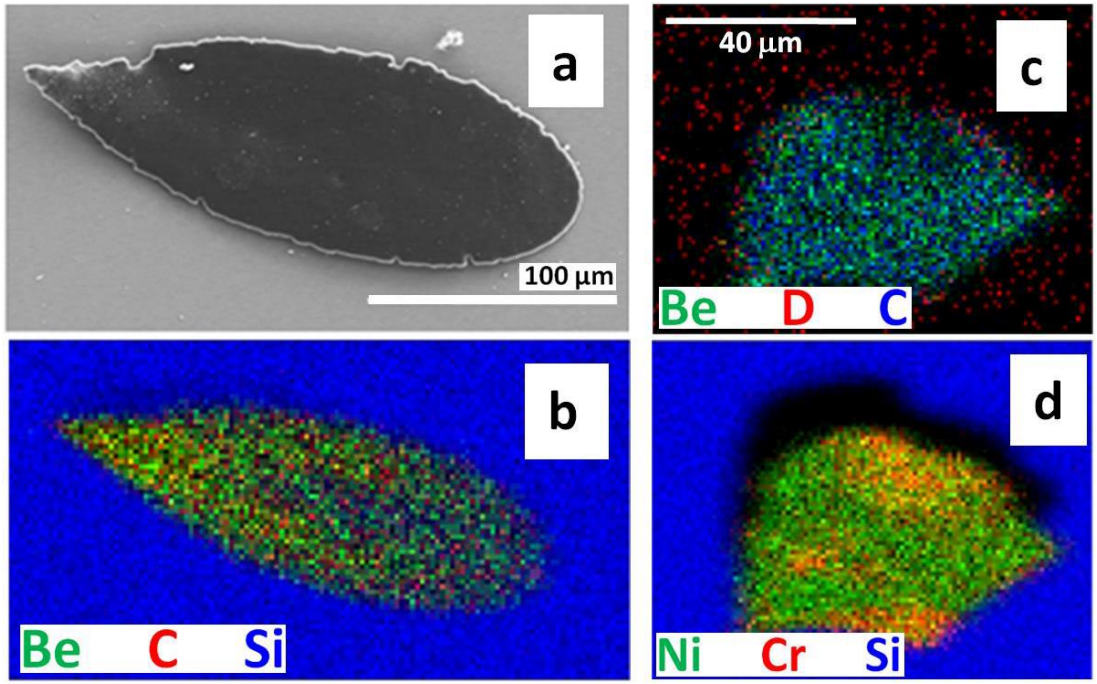
Cu chunks from NBI systems, etc

Fuel tracing in individual dust particles

JET-ILW: Deuterium in particles on dust monitors

- Combination of several methods: μ-NRA, μ-PIXE with SEM and EDX (different laboratories).
- Main difficulty: identification of the same study object in the two labs.



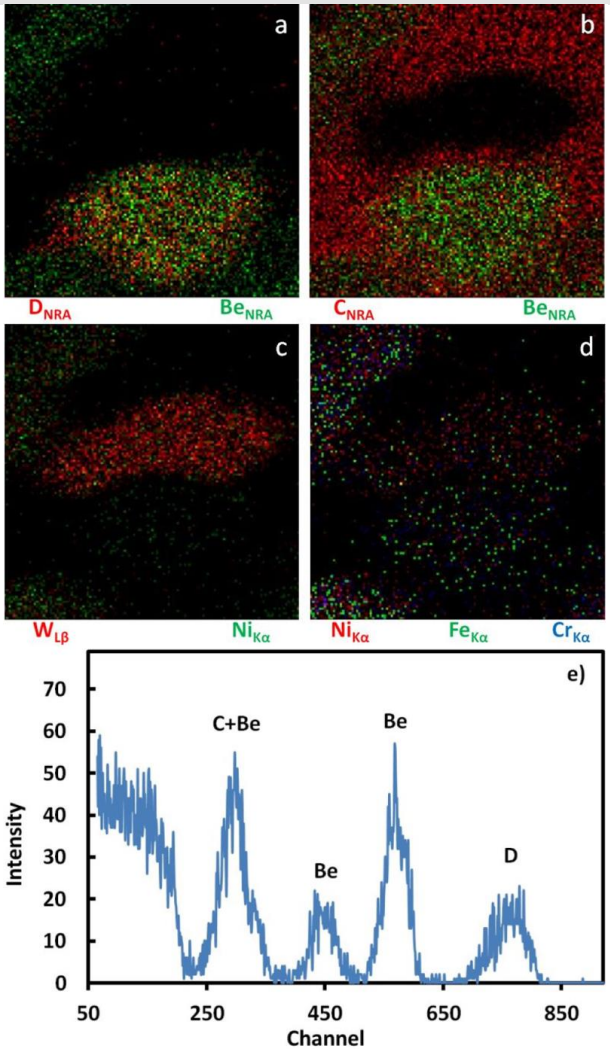


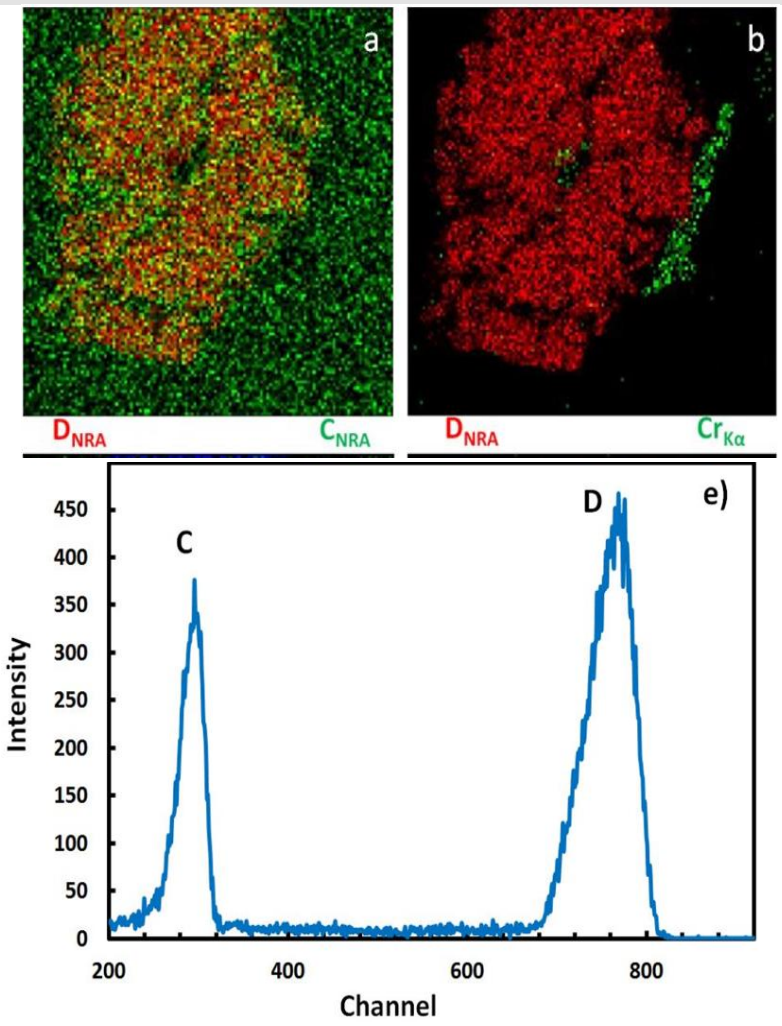
Message:

Only traces of deuterium detected in/on metallic dust particles

S. Fazinić et al., Anal. Chem. 90 (2018) 5744; Nucl. Fusion 60 (2020) 126061; MDPI Materials 15 (2022) 08353.

JET-ILW: Deuterium in particles on dust monitors





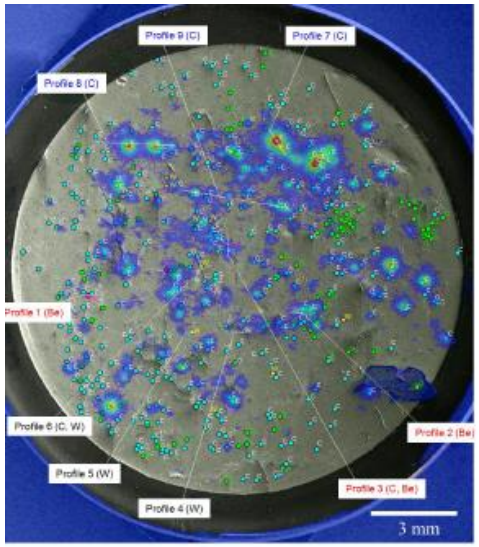
Messages: ***Deuterium presence is amainly associated with carbon.***

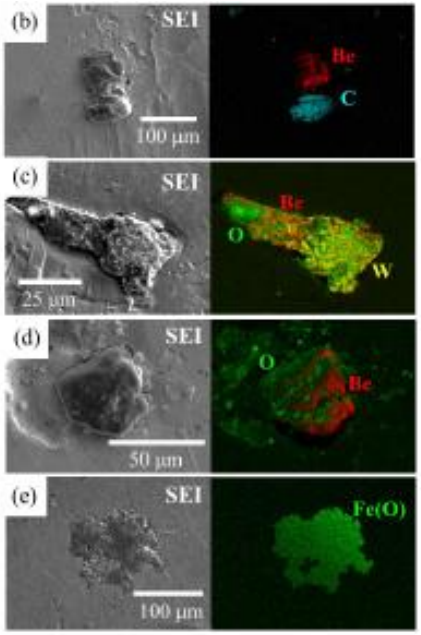
In quantitative terms, the D content even in C dust is small, 0.01-0.05 *(also experience from TEXTOR)*

S. Fazinić et al., Anal. Chem. 90 (2018) 5744; Nucl. Fusion 60 (2020) 126061; MDPI Materials 15 (2022) 08353.

JET-ILW: Tritium in individual particles

Radiography of T in different particles (ILW-1)



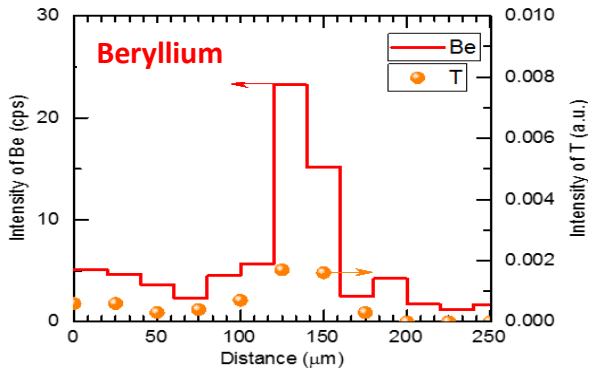


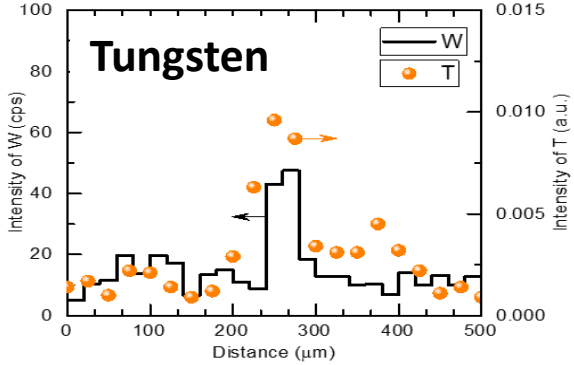
- ***Dust particles are placed on In disk.***
- ***Composition of individual particles is identified with EPMA (WDS).***

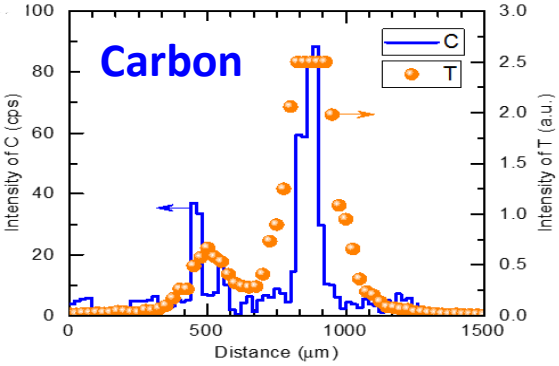
- ***β^- (T) recorded by radiography.***
- ***Superposition of profiles.***

Message:
T presence is associated with C
(legacy from JET-C)

T. Otsuka, Osaka-Kindai U. / IFERC

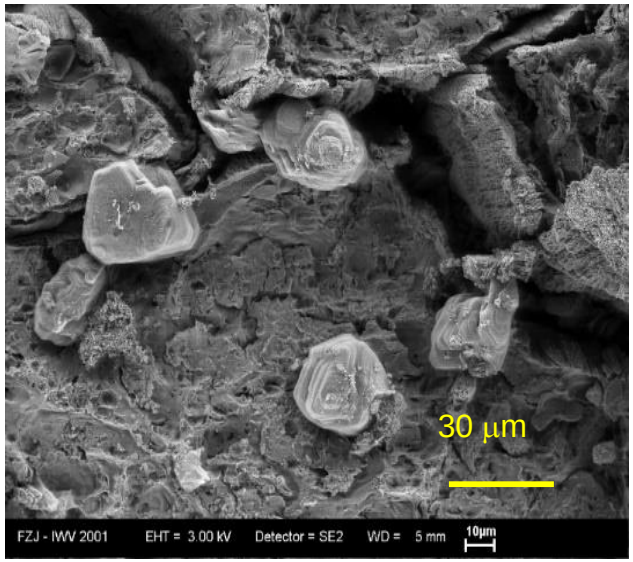


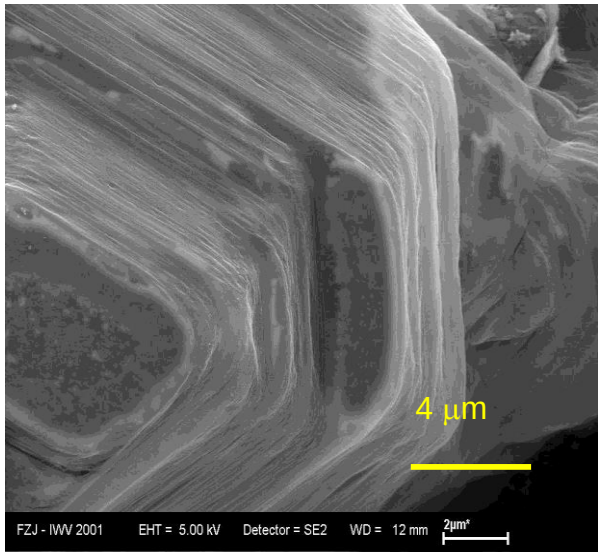




Note the scale. 100x more in C than in metals

Boron dust crystals



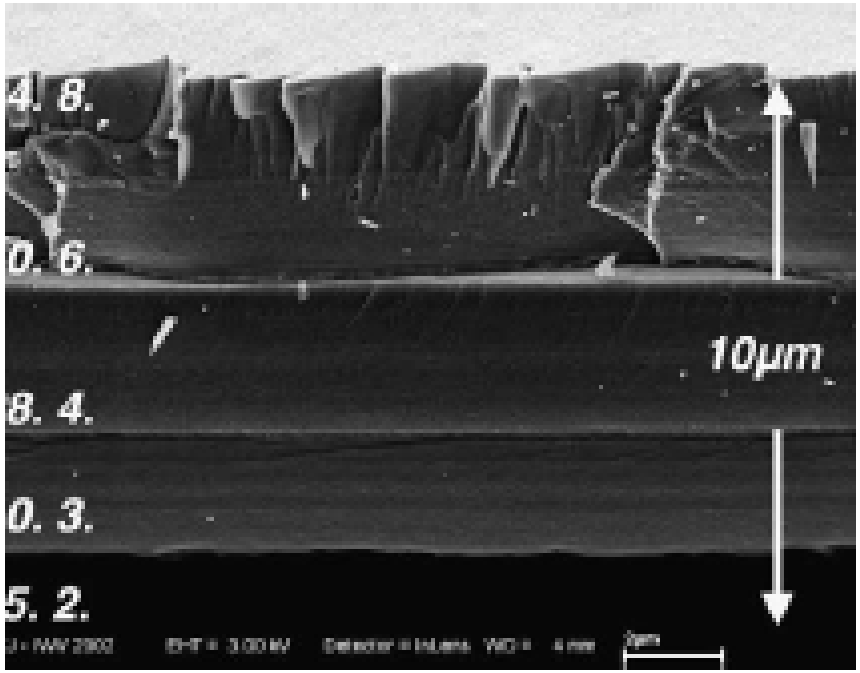


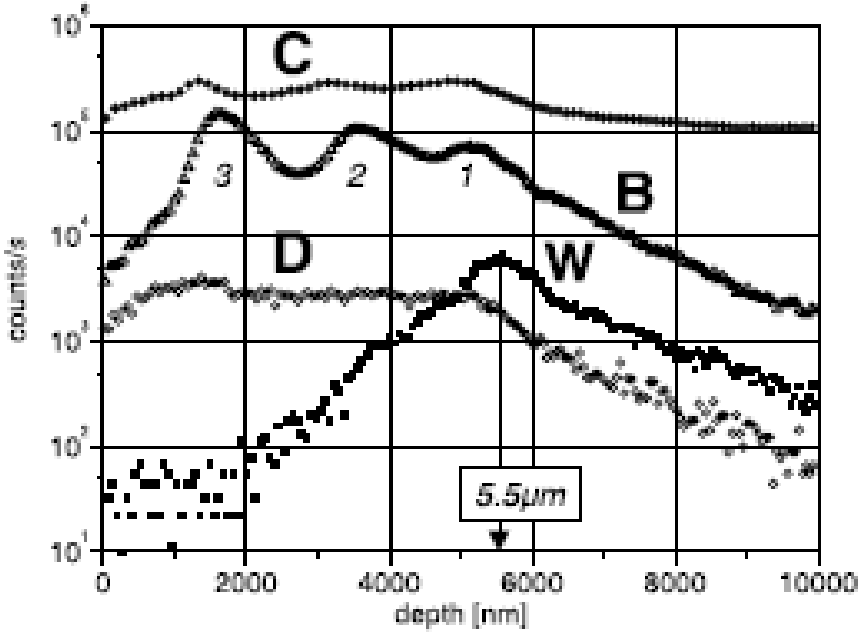
Precipitation of boron from co-deposit?

T_{plates} ~600 – 700 ºC (*thermocouples*)

$T_{deposit}$ >2000 ºC (*still below T_m of B and/or B_4C*)

Boron/Boronisation as a marker





A flake of a stratified co-deposit with three boronisation layers: SEM and SIMS.

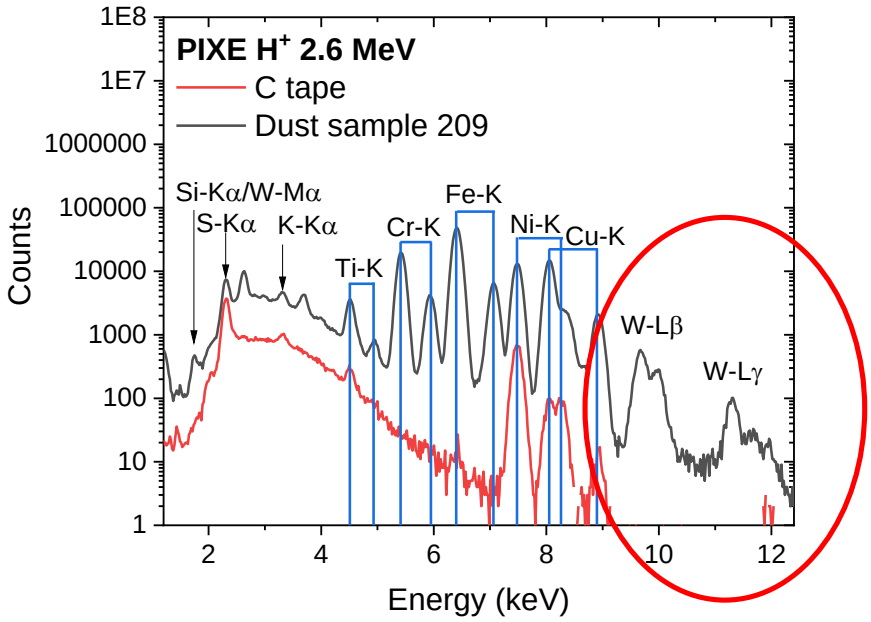
P. Wienhold et al., JNM 313-316 (2003) 311.

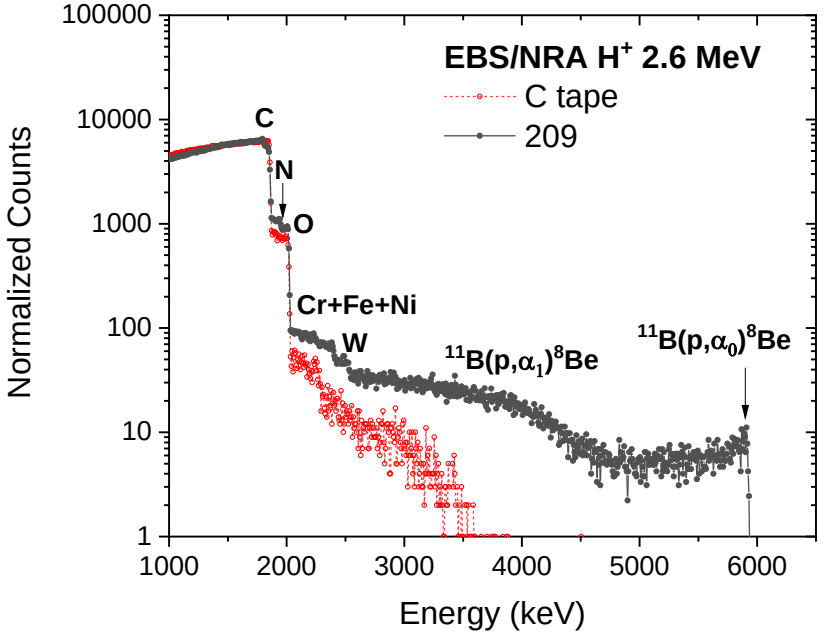
Ion beam analyses of dust from W7-X (VR)

Example of data for from sample 209:

- Sample from Module M1, Divertor (DU18).
- Identified the presence of B, Fe, Cr, and W in sample. Ti, Ni, and Cu also present in tape.

E. Pitthan et al., VR





W originates from a marker tile.
Dust with W is a material transport tracer.

Boronisation with B-10 diborane would contribute to transport studies.

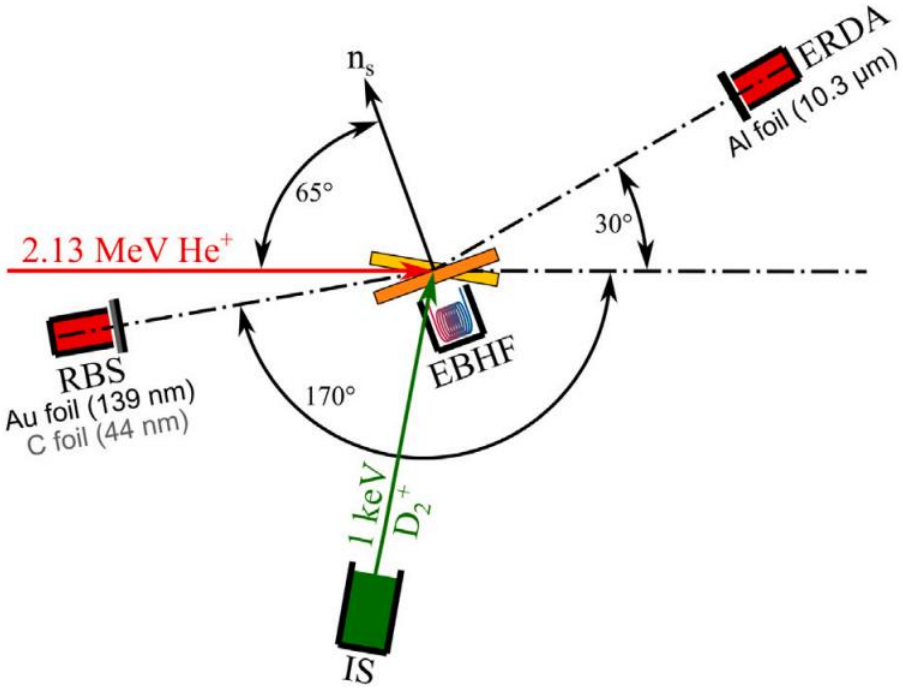
Outlook: Proposal for studies of W7-X dust

W7-X dust is deuterium free → good chance for:

- ***stepwise desorption – re-saturation exercise;***
- ***H-D isotope exchange***
- ***…***

SIGMA apparatus for in-situ experiments and measurements.

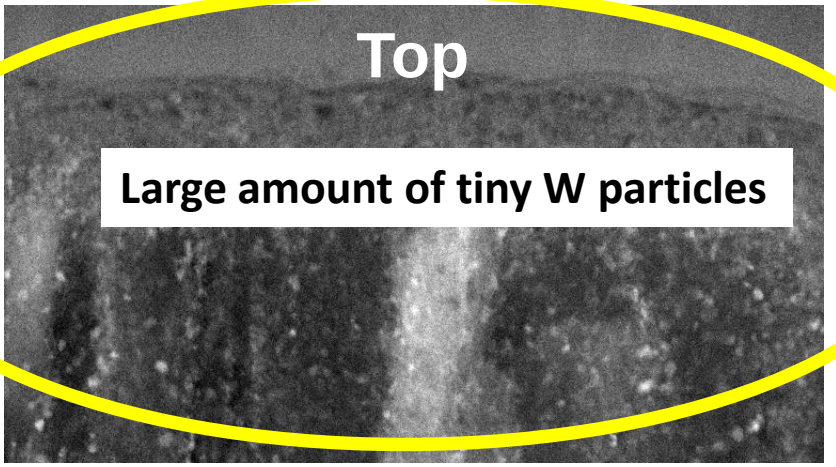
- ***IBA***
- ***Heating to 1000 °C***
- ***QMS***
- ***Gas inlets (gas mixing)***
- ***Ion source***

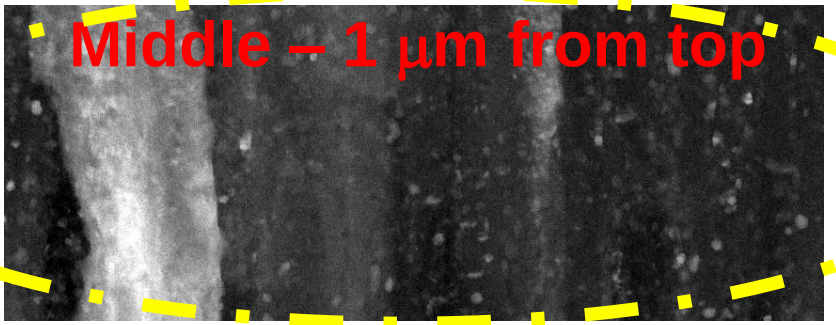


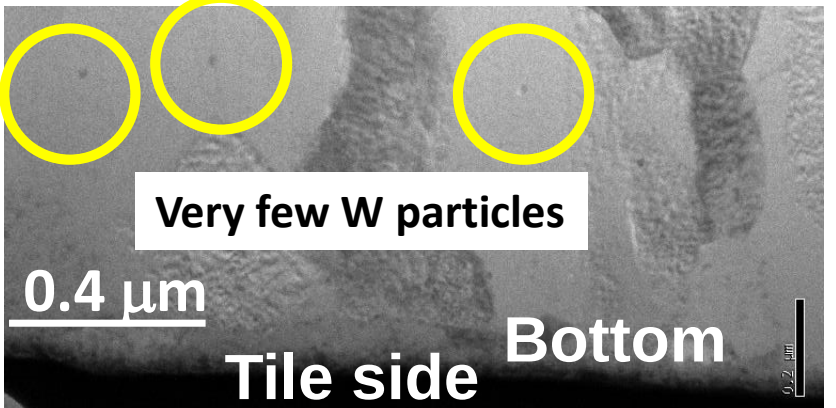
Extra slides

ILW 2011-2012 Dust studies: Beryllium flakes

Dust removed by vacuum cleaning. Studies performed at IFERC- Rokkasho







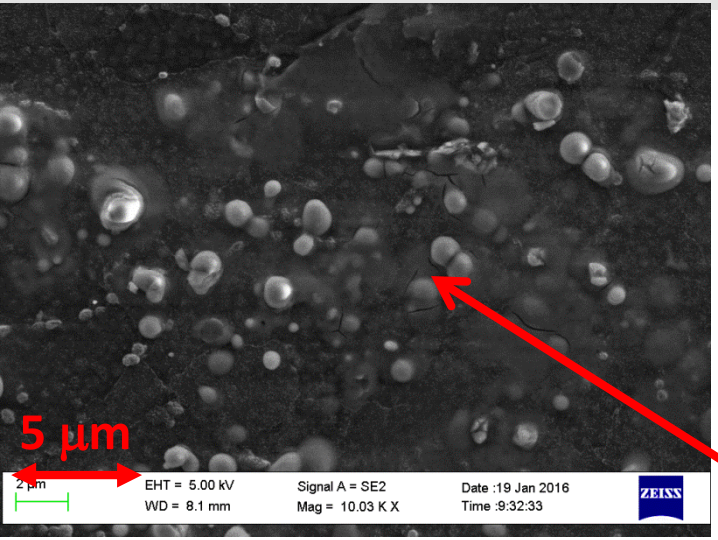
8.9 μm

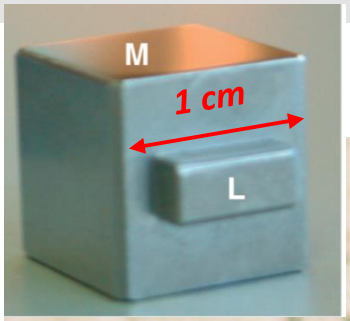
Messages:

- **TEM Dark Field images reveal heavy particles (white) of nm size in deposits.**
- **Particles of nm size identified by EDS as Tungsten.**
- **The amount of particles increases towards the top, i.e. rises with the power of the JET-ILW operation.**

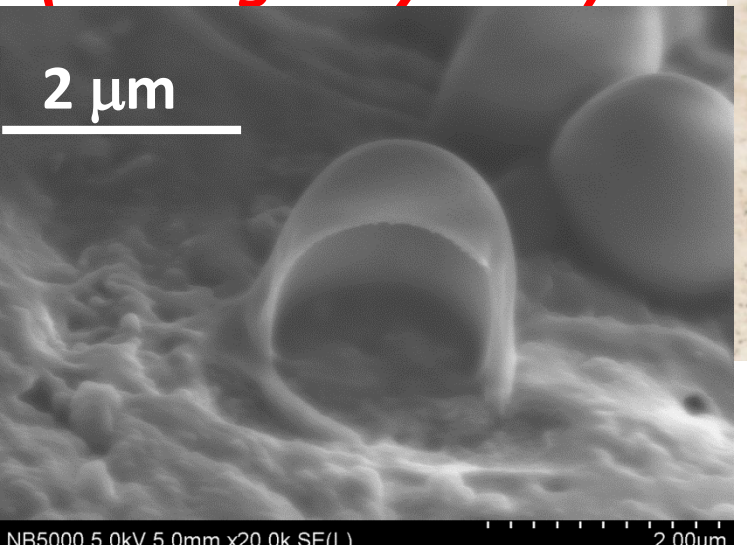
M. Rubel et al., Fusion Eng. Design 2018.

ILW 2013-2014: Be splashes on test mirrors





Droplets or bubbles? (boiling beryllium)



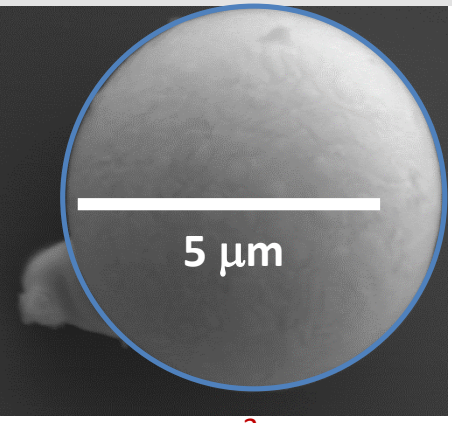
Mirror 127, Mo bulk, Main chamber wall

A. Garcia-Carrasco at al. Nucl. Mater. Ener. 2017
X. Litaudon, IAEA-27, Nucl. Fusion 57 (2017)

Tungsten:

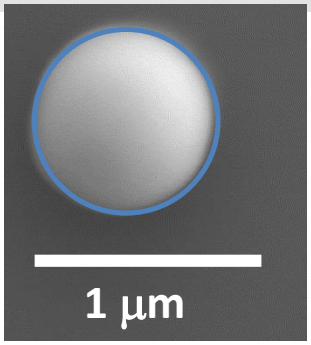
Droplets (?)

W on dust collector (outer divertor)



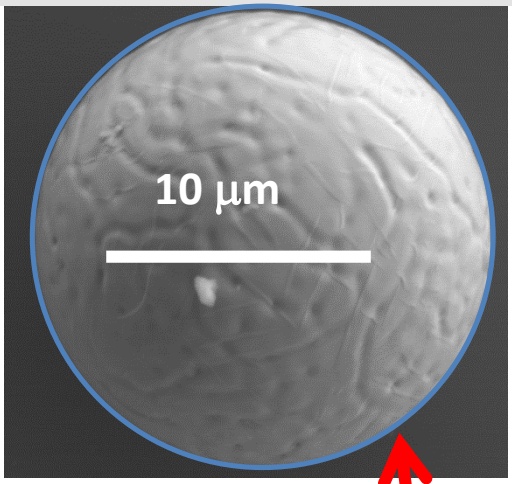
V: **131** µm^3

r: **3.15** µm



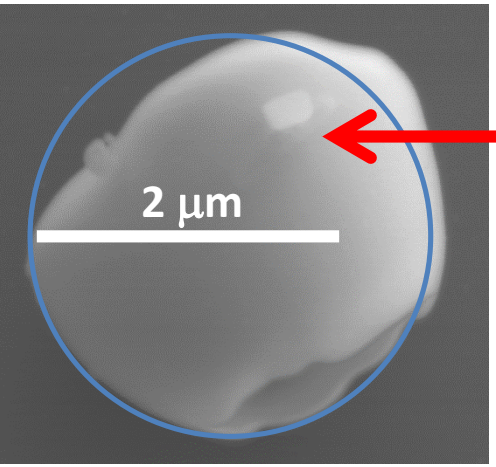
V: 0.21 µm^3

r: 0.37 µm



V: 1767 µm^3

r: 7.5 µm



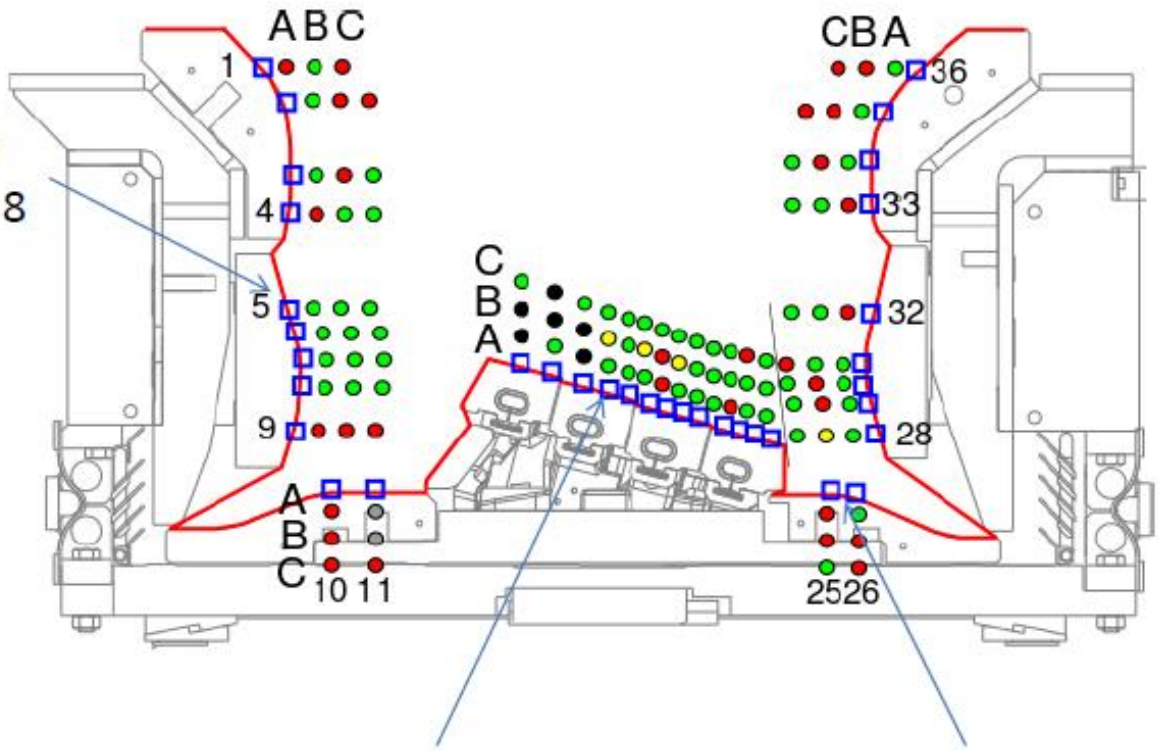
Most probably "spheroids" *(shell with empty interior)* **in the phase of formation by agglomeration of W flakes detached from the coatings.**

<u>Message:</u> There is no evidence of W droplets which would indicate tungsten melting (either W coatings or Tile 5).

E. Fortuna, M. Rubel, Phys. Scr. 2017

LPs in JET

16IN and 17IN
Probes 5, 6, 7, 8



15W and 16W
Probes 15, 16, 19, 23

15BW and 16BW
Probes 25, 26

Categories of dust in JET-ILW

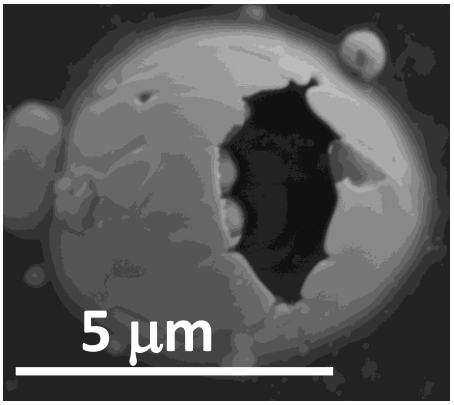
ITER not relevant

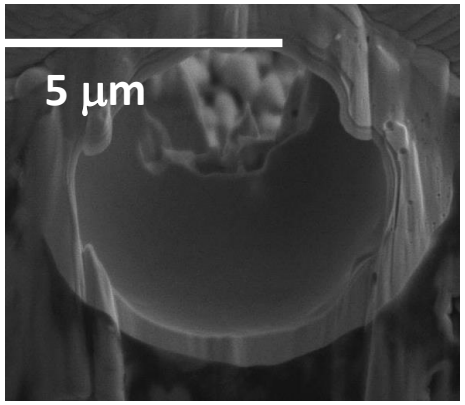
Be flakes of coatings from inner wall cladding tiles

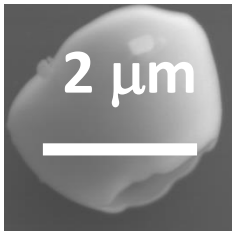
Debris of CFC or BN (probes heads)

W-Mo coatings from CFC

- ***Small debris, flakes not molten.***
- ***Partly molten (glassy structure)***
- ***Spheroids by aggregation of W flakes***







Formation phase

ITER relevant

Be-rich flakes of co-deposited layers

Be droplets and splashes

W droplets and splashes

Steel (and Inconel) droplets and splashes e.g. from antennae grills

Swarf from in-vessel work

Cu chunks from NBI systems, etc