WPJET2: Material erosion, migration and dust

Marek Rubel , Per Petersson and JET2 Team

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Thanks

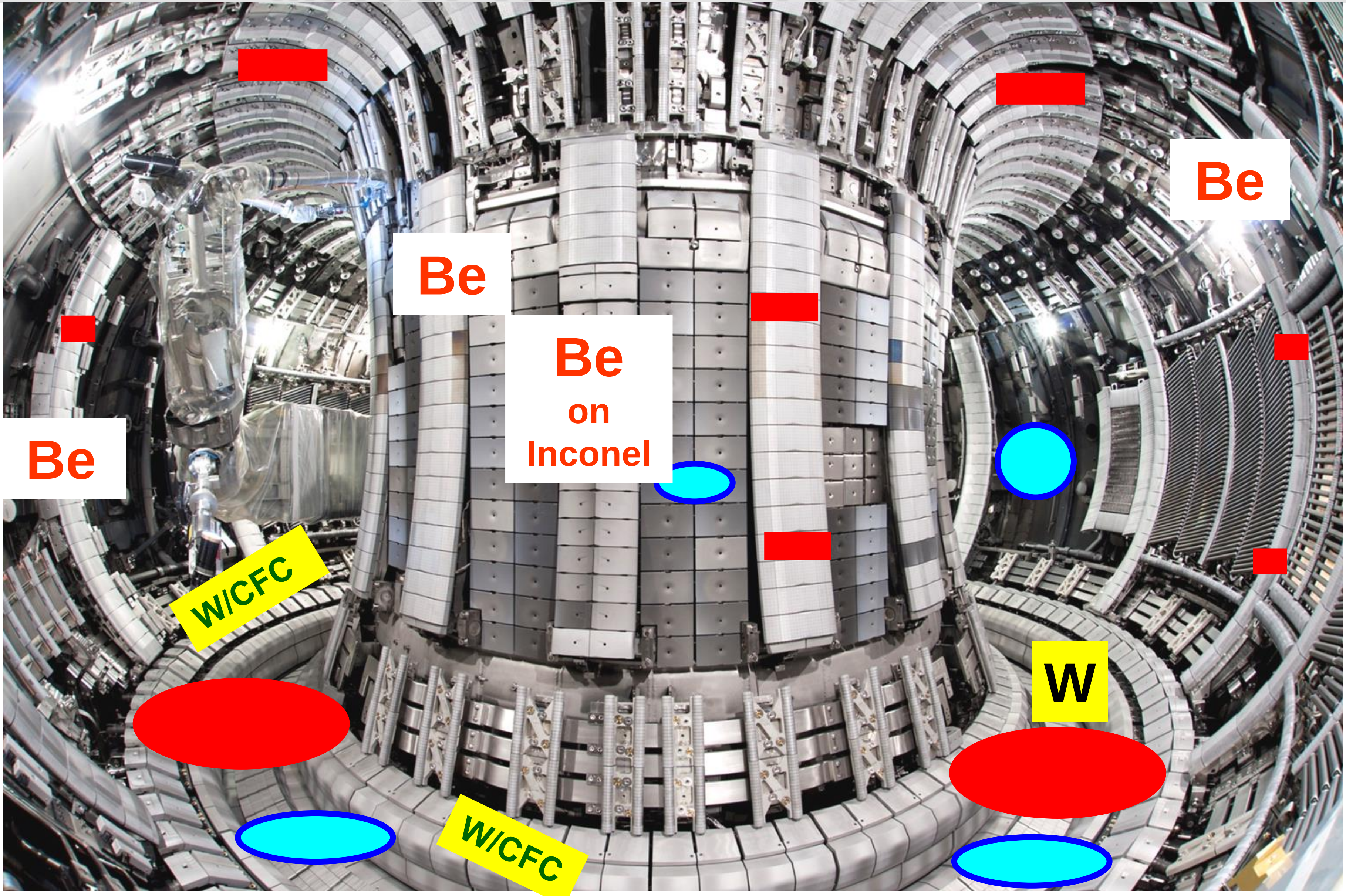
Many thanks to the Team

for excellent contributions.

In three JET2 overview talks we shall try to present highlights.

- We have received many slides for the overview talks.
- All contributions will be addressed.
- Sorry if not all slides will be shown *(time constraints).*

Tools: Erosion-Deposition Diagnostics in JET-ILW
Marker Tiles and Probes



The aim is to have a complete overview of material migration and material damage, not just a number *(even large)* of analysis points and isolated findings.

WPJET2: 7 years

We work with PFCs and tokamakium containing beryllium and tritium.

- *Laboratories: 12 in EU and cooperation with IFERC within Broader Approach*
- *Great human capital: experience and expertise*
- *Special equipment and many dedicated developments.*

- **Over 40 different material characterisation techniques from nano to macro:**
  - *Imaging*
  - *Composition from the first nm to depth (cross-sectioning)*
  - *Mechanical properties*
  - *Optical properties*

  - *9 techniques for deuterium and hydrogen studies.*
  - *9 (10) techniques/approaches in tritium assessment and analyses.*

Original scope of WPJET2 (2014) has been vastly broadened by new projects originating from:

- *new findings, own ideas, needs for clarification;*
- *ITER needs (requests).*

WPJET2: Materials analysed

- ***Limiter tiles***
- ***Divertor tiles***
- ***Wall Probes***
- ***Dust and metal splashes***

Comparison of campaigns

ILW-1: 19.3 h	***150 GJ***
ILW-2: 19.1 h	***201 GJ***
ILW -3: 23.6 h	***245 GJ***

- Exposure during single campaigns.
- Exposure during two or all three campaigns.

Are material migration effects additive (*retention, deposition****)?***

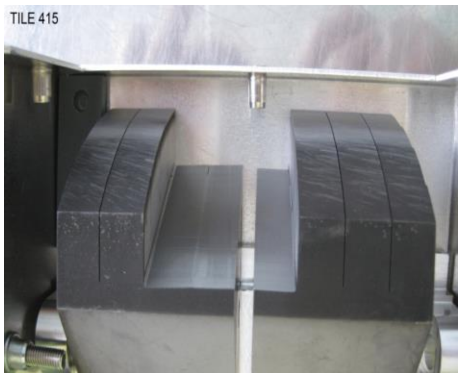
Beryllium Handling Facility (BeHF) at JET

Handling of beryllium and tritiated components

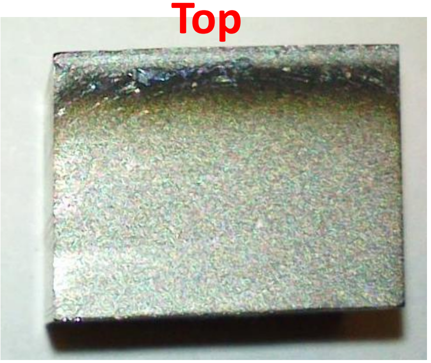
All materials retrieved from JET go through that place and get their "passports" before shipment to other labroratories for detailed analyses or sectioning to smaller specimens.

Sectioning of JET tiles:
pre-requisite for definition of tasks and detailed studies

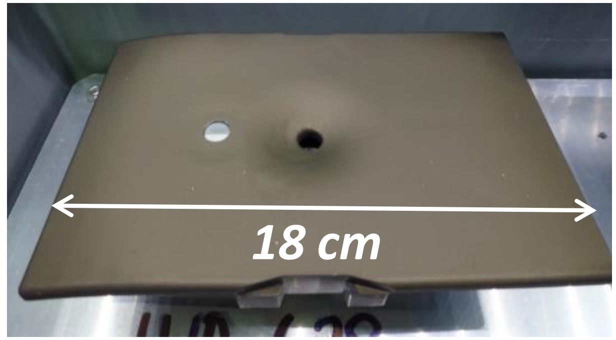
Segmented Be limiters



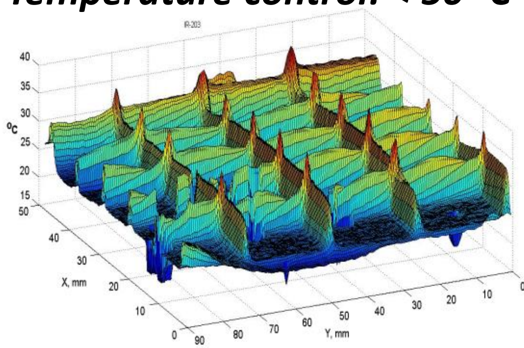
Top



Be-coated Inconel

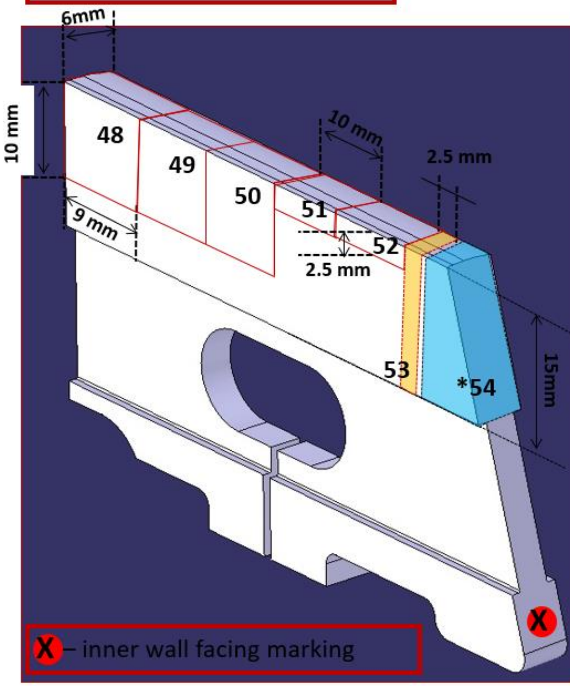


Temperature control: < 50 °C



Bulk W lamella, Tile 5

A23 – Standard lamella

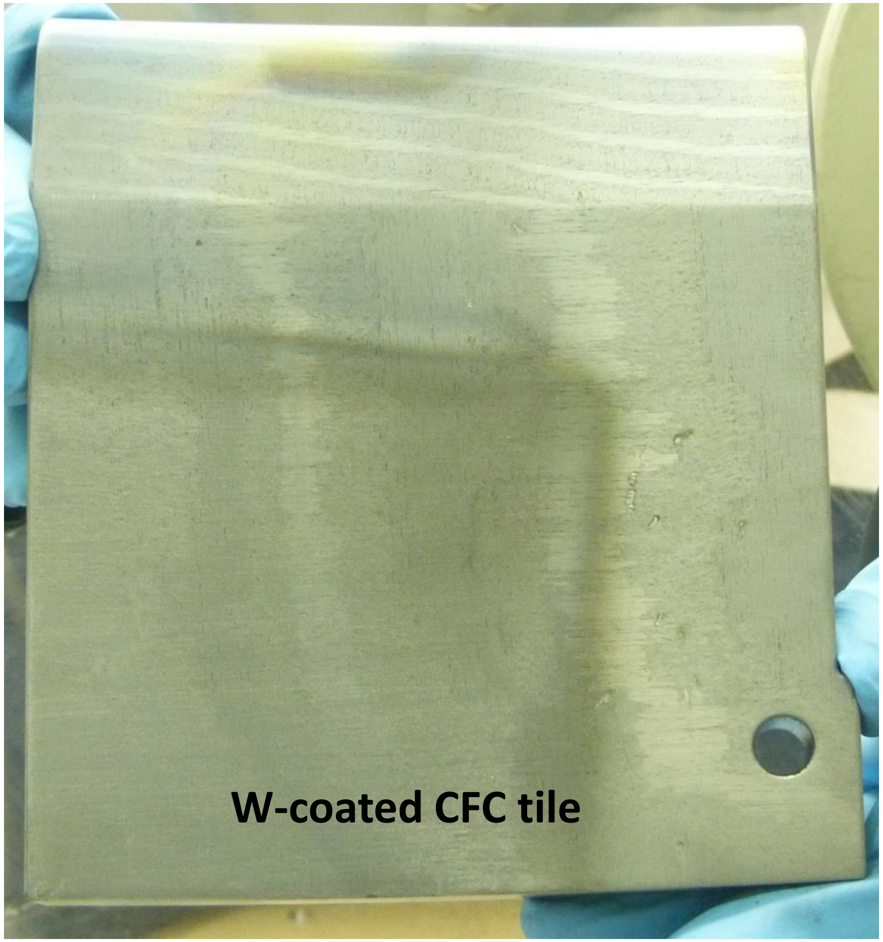


- *For microscopy*
- *Ion beam analyses*
- *Thermal desorption*
- *Tritium measurements*
- *Emissivity*
- *Metallography*

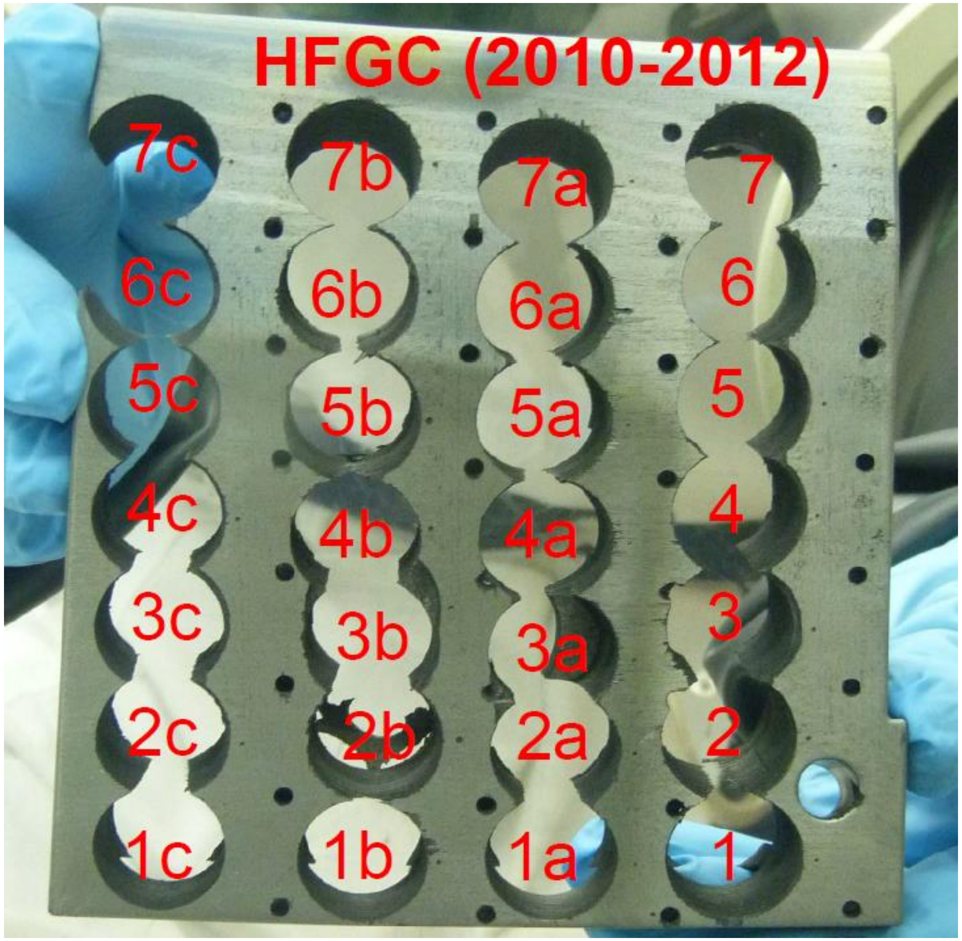
C. Lungu, C. Porosnicu, IAP

Sampling/cutting & traceability/labeling

Before



… and after coring



Sampling for:

SIMS, metallography, SEM, FIB/TEM, EDX, m-beam IBA, TDS, etc.

Jari Linonen, VTT, Finland

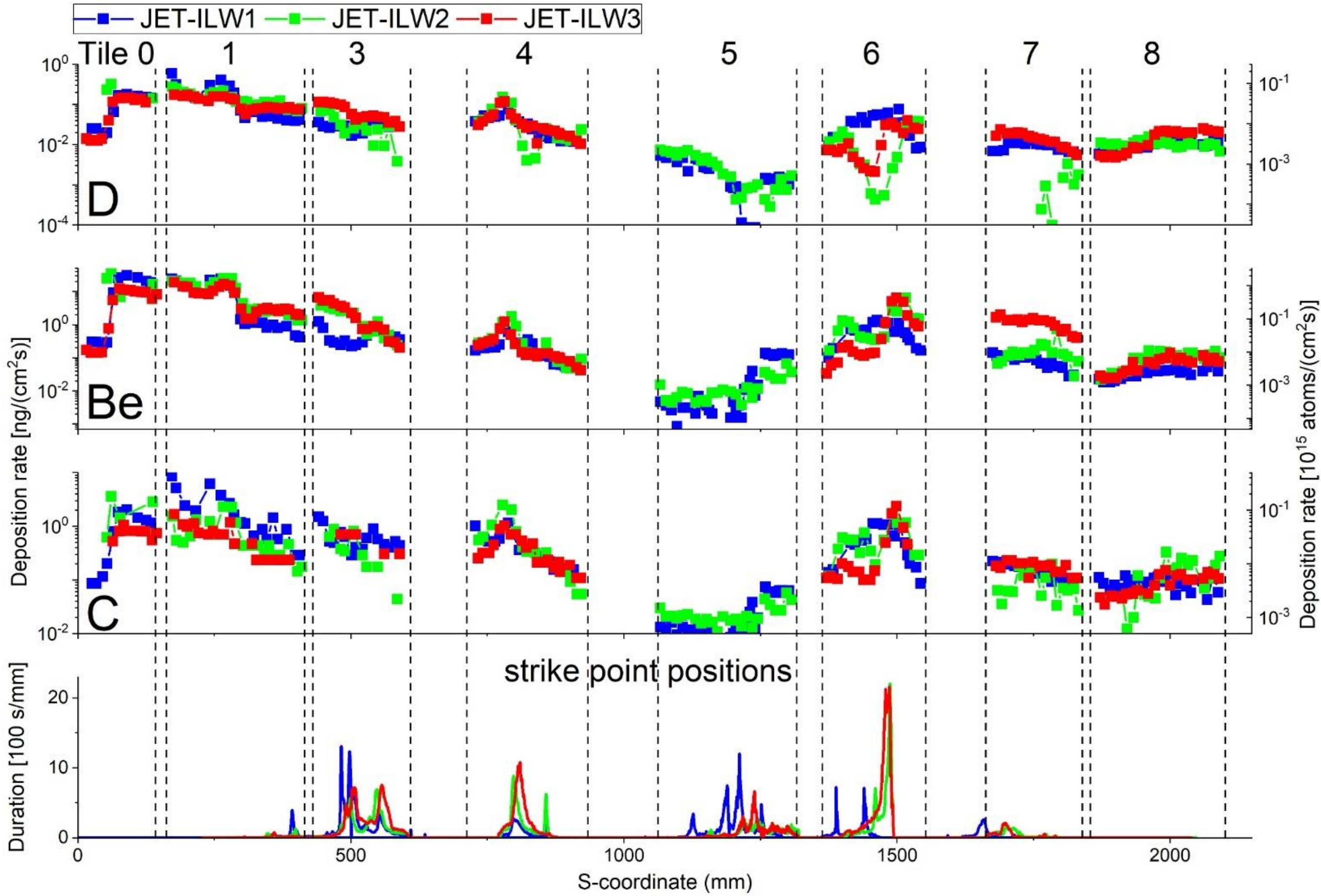
Erosion - Deposition pattern in three campaigns

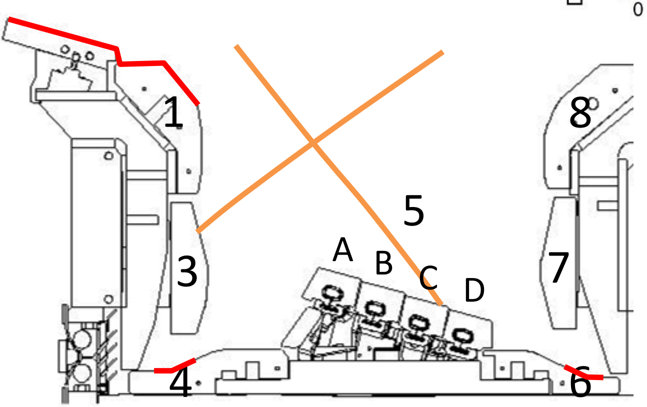
Divertor

Divertor: deposition from ILW-1 to ILW-3

Messages:

- *Qualitatively similar distributions in all campaigns.*
- *Maximum deposition on Tiles 0, 1*
- *Higher deposition on Tiles 4, 6 in ILW-2 and ILW-3*





S. Krat, Phys. Scr. T171 (2020) 014059

Divertor: deposition from ILW-1 to ILW-3

Deposited mass (g)

	ILW-1	ILW-2	ILW-3
D	0.9	0.7	0.9
Be	53	60	46
C	13	7	6

Deposited mass rate (µg/s)

	ILW-1	ILW-2	ILW-3
D	13	10	11
Be	771	877	544
C	189	102	71

Concentration (at.%)

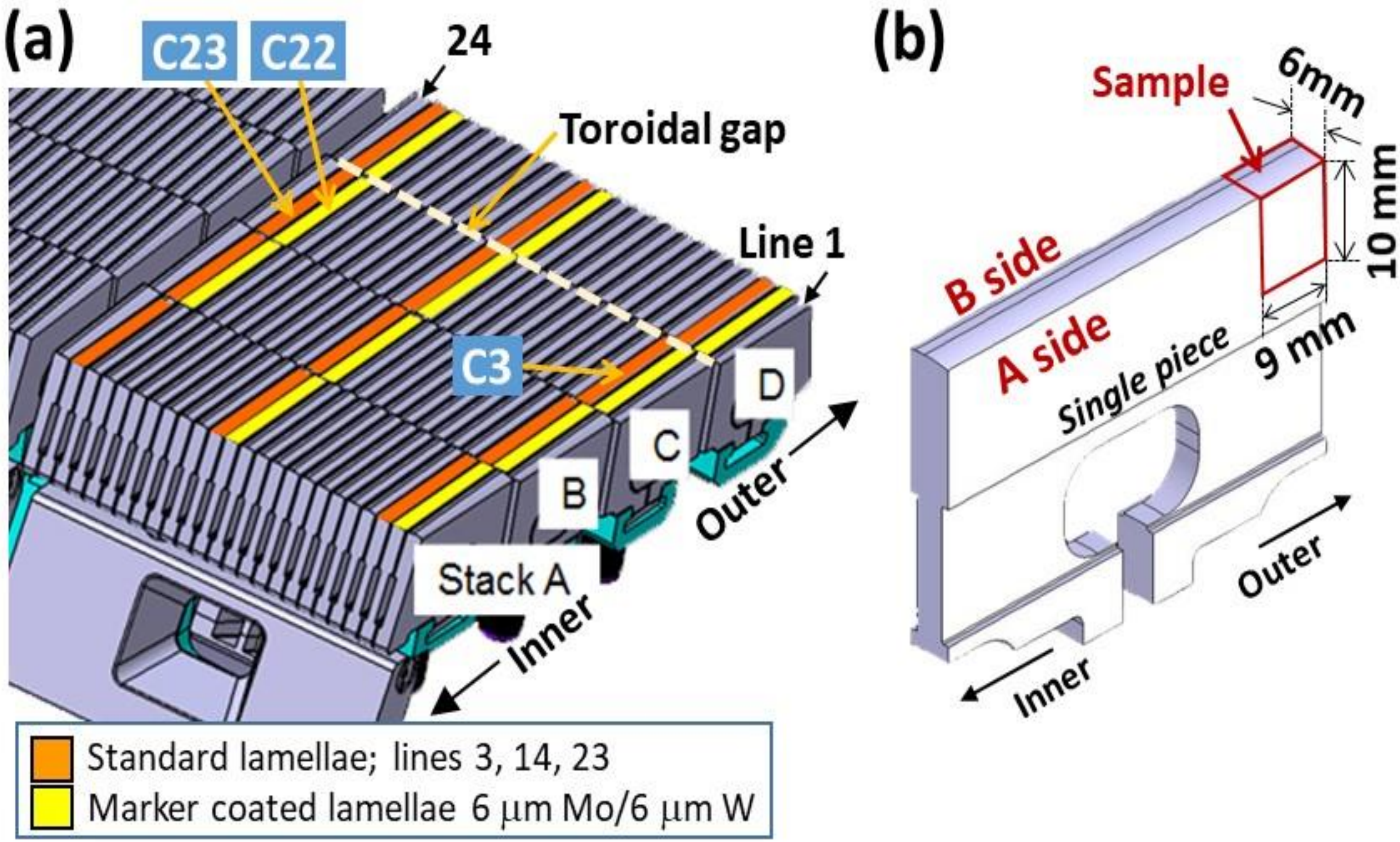
D	6.0	4.6	7.4
C	14.6	7.7	8.3

Messages:

- *More or less constant deposition rate of D.*
- *Slowly varying deposition rate of Be.*
- *Decreasing deposition rate of C from ILW-1 to ILW-3.*

S. Krat, Phys. Scr. T171 (2020) 014059

Divertor: Tile 5, Bulk W lamellae

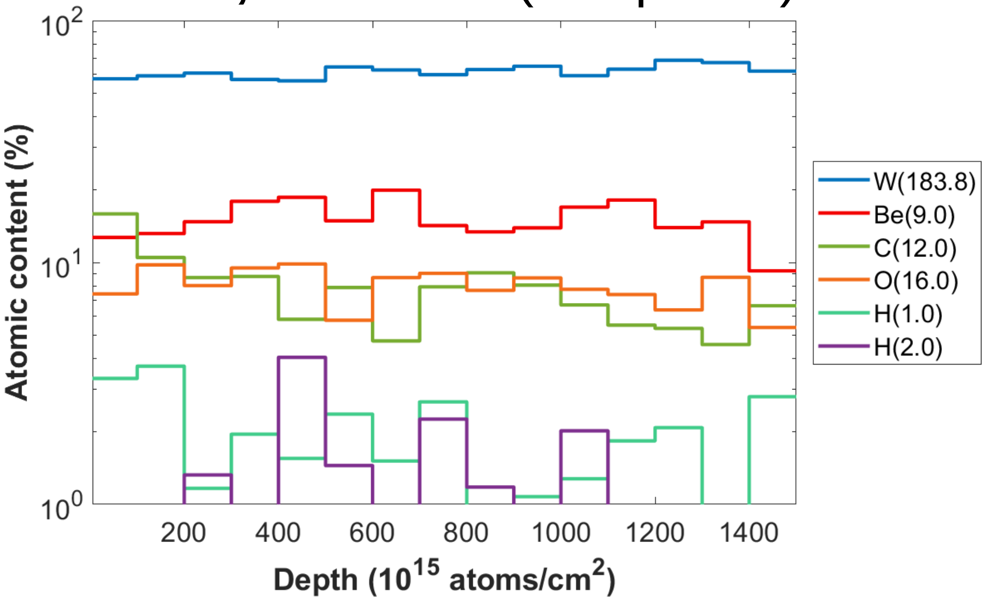


Plasma operation mainly on Stack C and D.

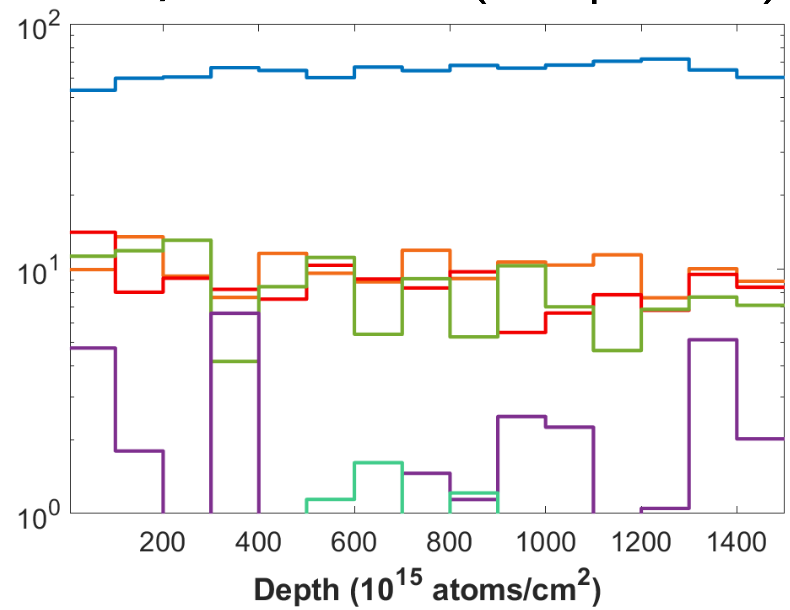
Lamellae 1-3:	*in the shadow of the adjacent tile*
Lamellae 12-14:	*central part of the assembly*
Lamellae 20-24:	*most exposed*

Divertor, W bulk lamellae: Depth profiling with ERDA

ILW-2, lamella C3(sample 55)



ILW 1+3, Lamella C2 (sample 104)



Deuterium content: $1.7 \times 10^{16} \frac{at.}{cm^2}$

Hydrogen content: $3.2 \times 10^{16} \frac{at.}{cm^2}$

More Hydrogen than Deuterium

(End of ILW-2 campaign in hydrogen.)

Deuterium: $3.1 \times 10^{16} \frac{at.}{cm^2}$

Hydrogen: $1.1 \times 10^{16} \frac{at.}{cm^2}$

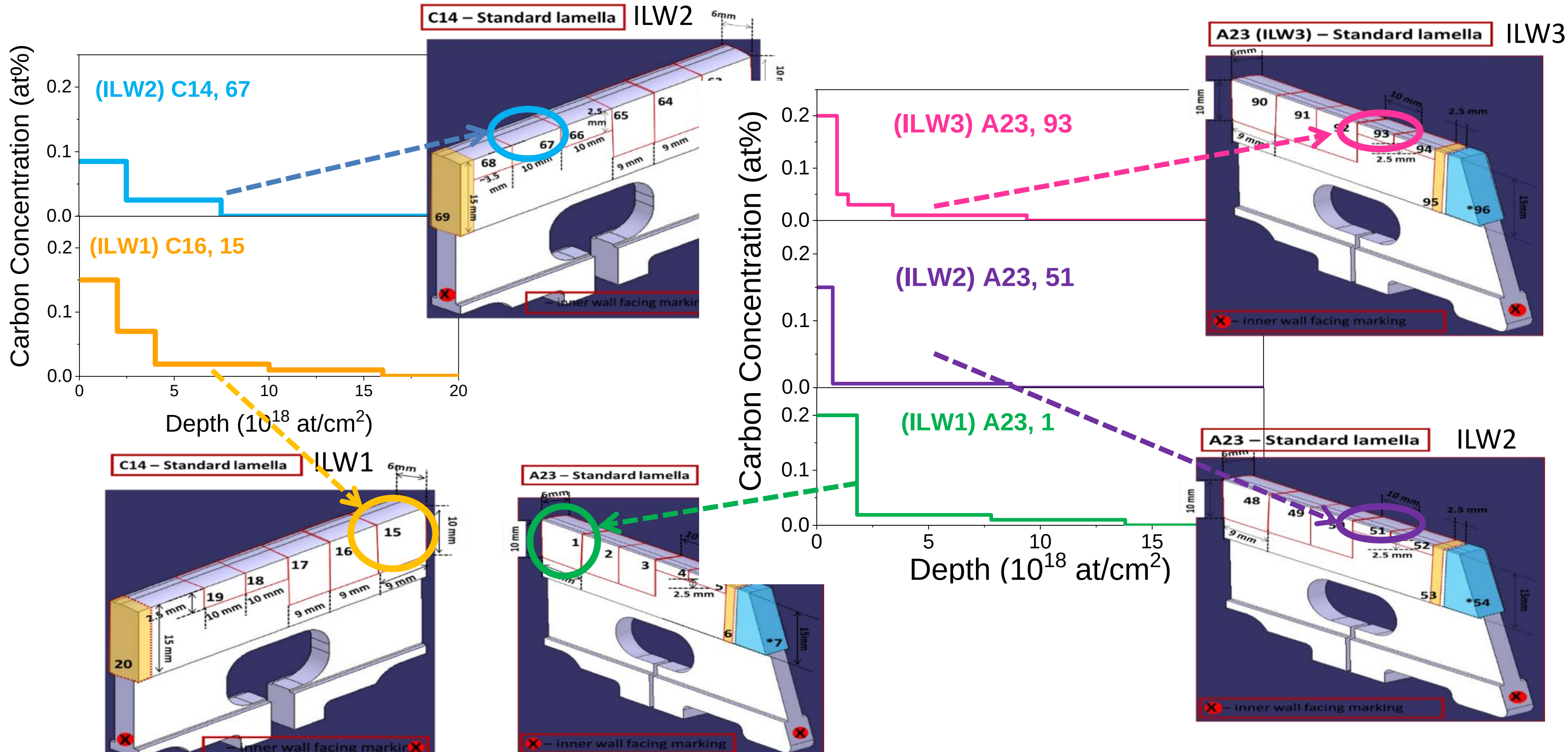
More Deuterium than Hydrogen

Other species, contents in 10^{16} cm^{-2}:

	ILW 2	ILW 1+3
Be	24	14
C	14	13
N	6.5	3.4
O	13	17
Ni	--	4

L. Dittrich, P. Petersson, VR

Carbon on W lamellae: Deuterium NRA on top surfaces



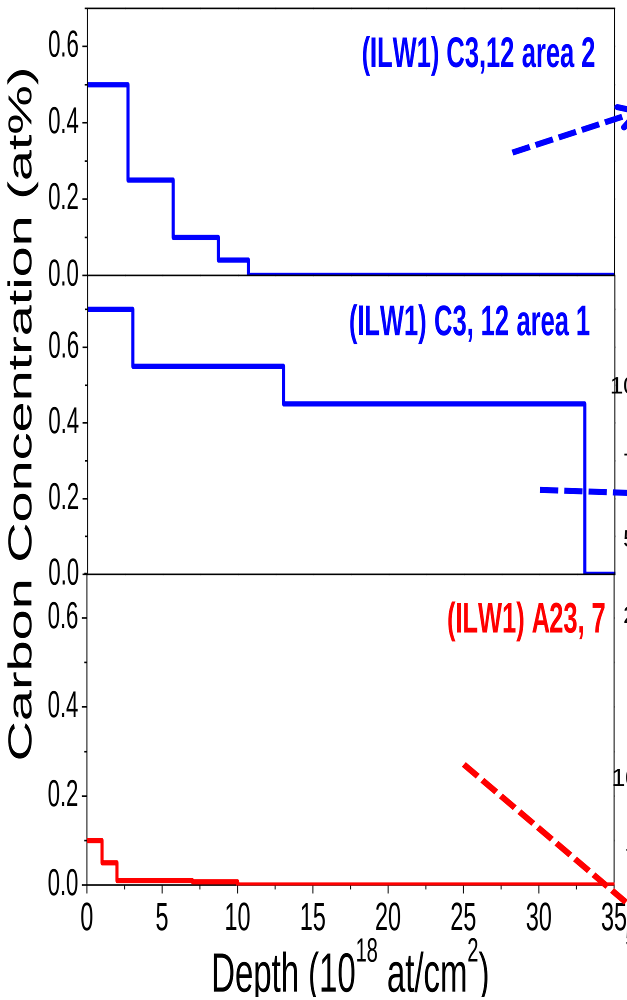
Lamella	Experiment Period	Sample No	Carbon (10^{17} at/cm^2)	Deposition thickness (10^{18} at/cm^2)
A23	ILW 3	93	3.25	9.4
A23	ILW 2	51	1.53	8.7
A23	ILW 1	1	5.34	13.8
C14	ILW 2	67	3.38	7.5
C14	ILW1	15	6.14	16

Messages

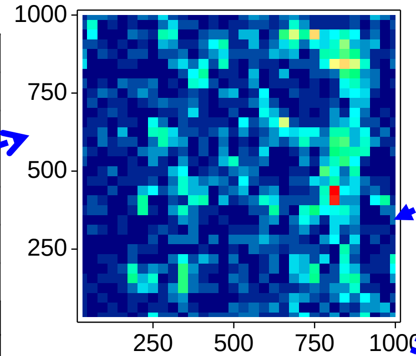
- *The highest **carbon** deposition with the largest thickness is observed in ILW-1 samples.*
- *Central lamella in ILW1 presents the highest **carbon** amount and larger thickness overall*

T. Lagoyannis, P. Tsavalas, D. Mergia, NCSRD, Greece

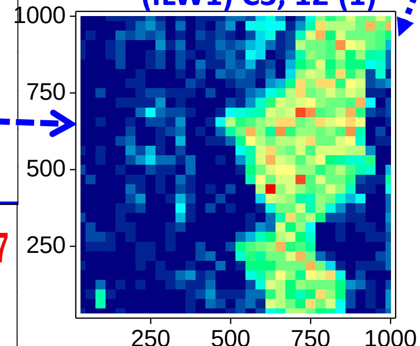
Carbon on W lamellae: D micro-beam NRA on top surfaces



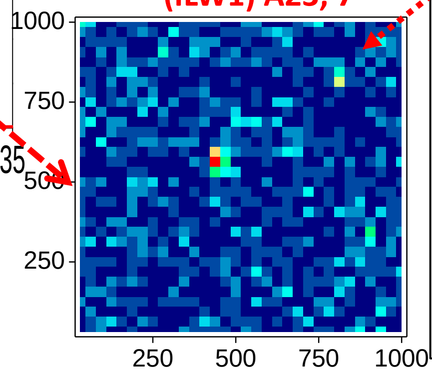
(ILW1) C3,12 (2)

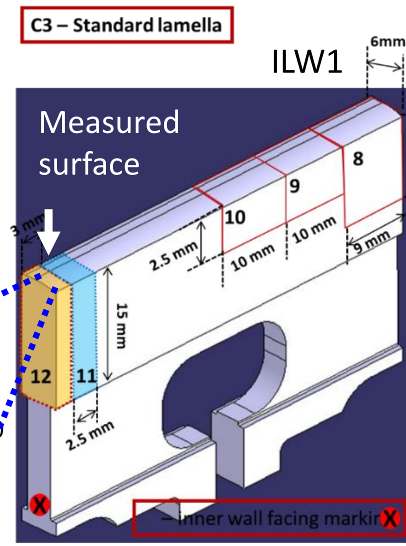


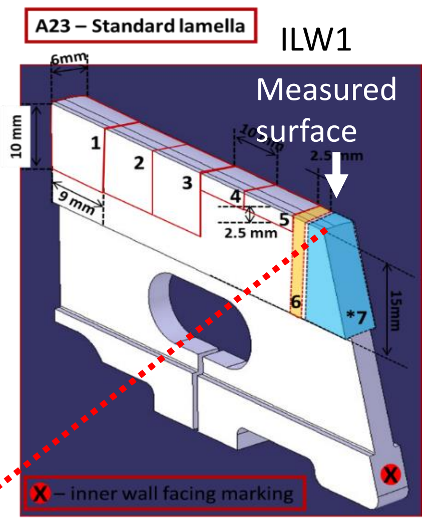
(ILW1) C3, 12 (1)



(ILW1) A23, 7







Lamella	Exp. Period	Sample	C Amount (10^{17} at/cm^2)	Deposition Thickness (10^{18} at/cm^2)
C3	ILW-1	12 (2)	24.8	10.7
C3	ILW-1	12 (1)	166	33
A23	ILW-1	7	2.21	10

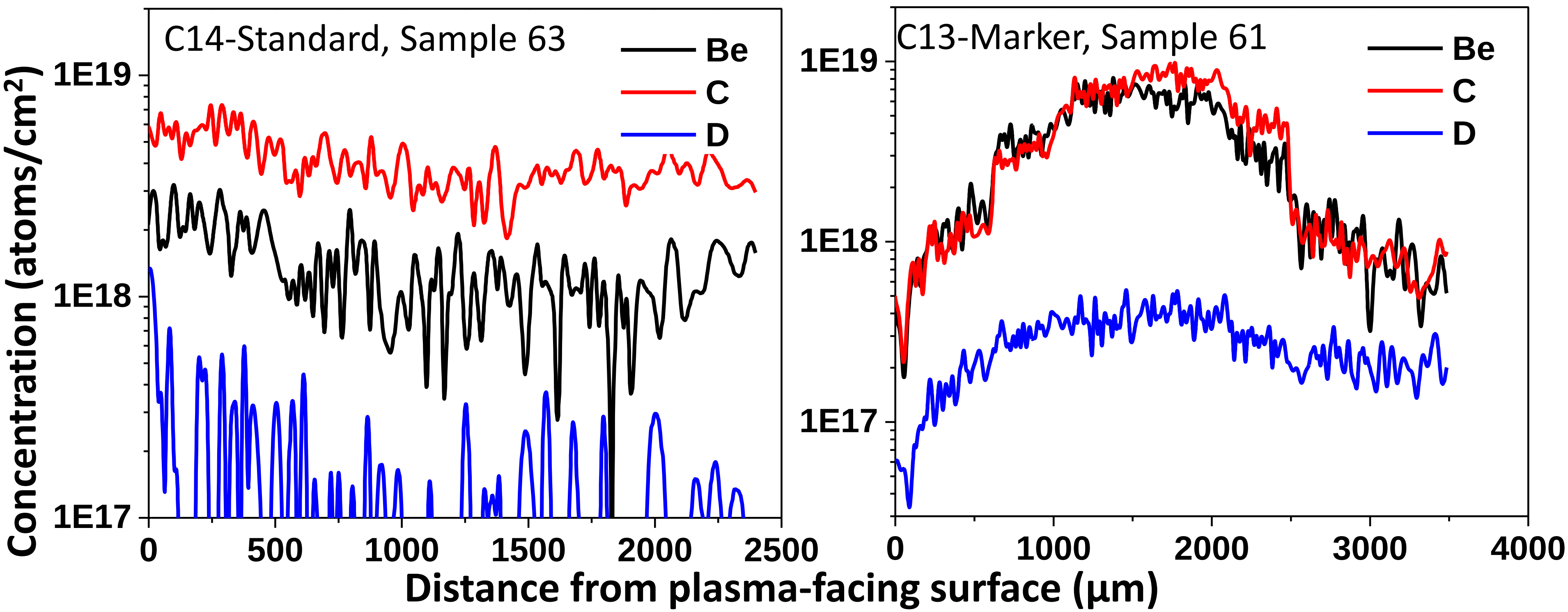
Messages

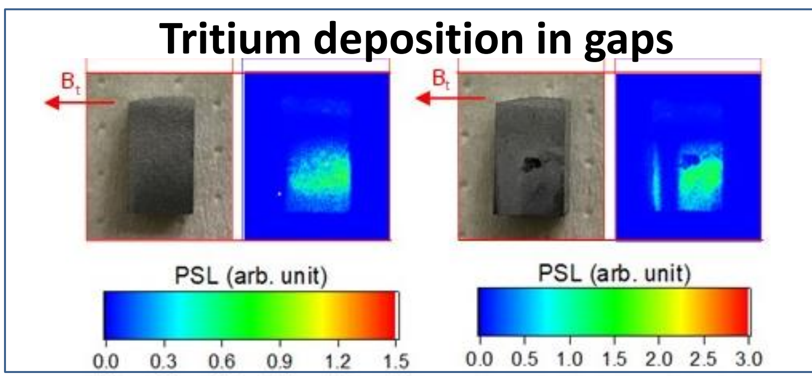
- *C3,12 during ILW1 presents stripe-like C deposition having a width varying between ~100 μm (area 2) and ~250 μm (area 1) and 2 to 3 orders higher C amount than other W lamella.*
- *Carbon agglomerates with diameter of ~50 μm in A23,7*

T. Lagoyannis, P. Tsavalas, D. Mergia, NCSRD, Greece

W lamellae ILW-2: Deposition in gaps, μ-NRA

0.4 mm wide gap to another lamella | **1.5 mm wide gap to Stack D**





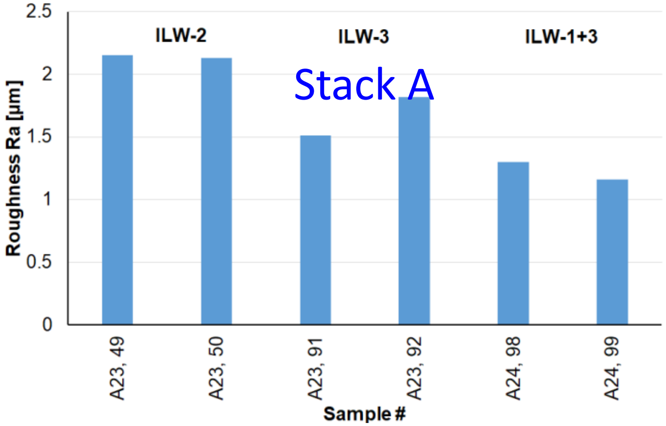
Messages:

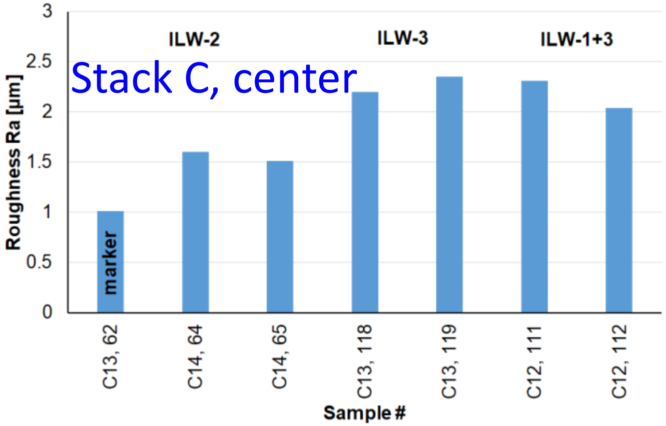
- *Deposition increases with the gap width.*
- *Relatively high C content, C/Be > 1.*
- *Coherence with T deposition pattern in gaps betwéen stacks.*

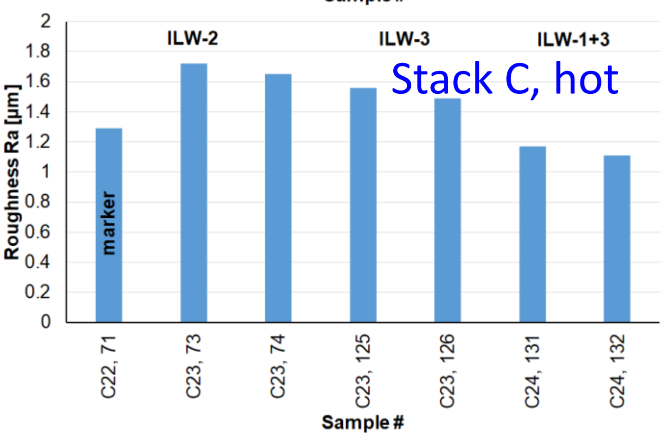
P. Petersson, SW Moon, D. Dittrich, VR-KTH

Y. Hatano, S. Lee, Toyama Univ., Japan

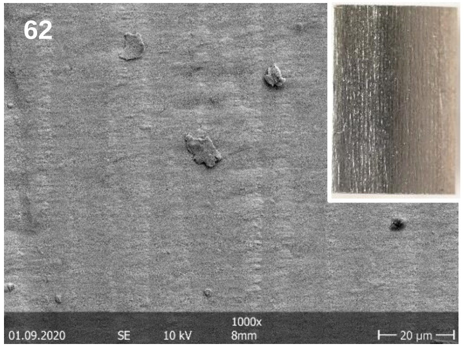
Tungsten lamellae: ILW-2, ILW-3, ILW-1+3

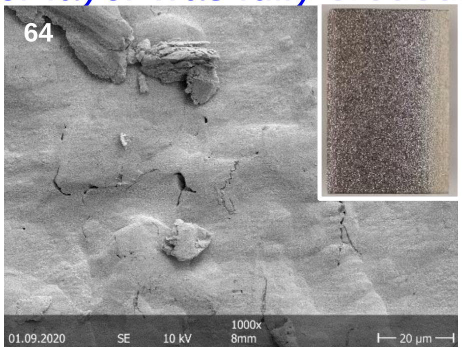




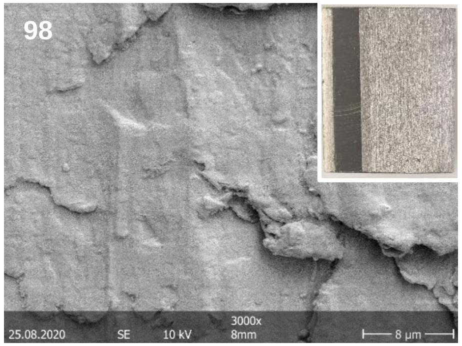


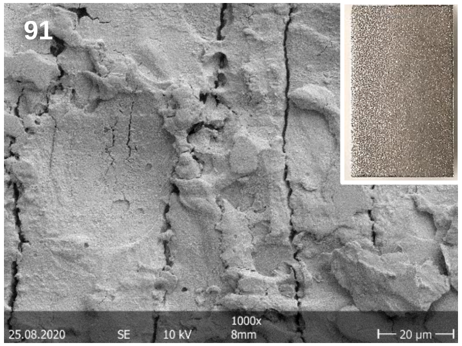
- *Reduced surface roughness for marker lamellae.*
- *In-some lodations marker layer was fully eroded.*

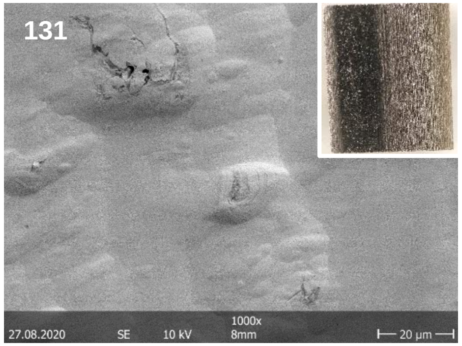


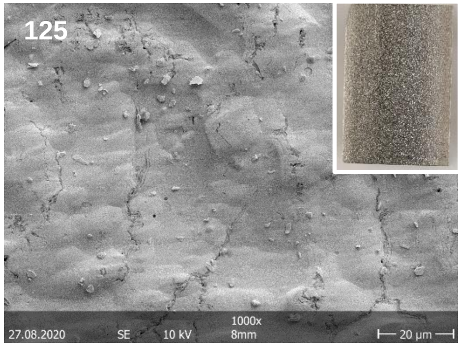


- *Reduced surface roughness for ILW-1+3*



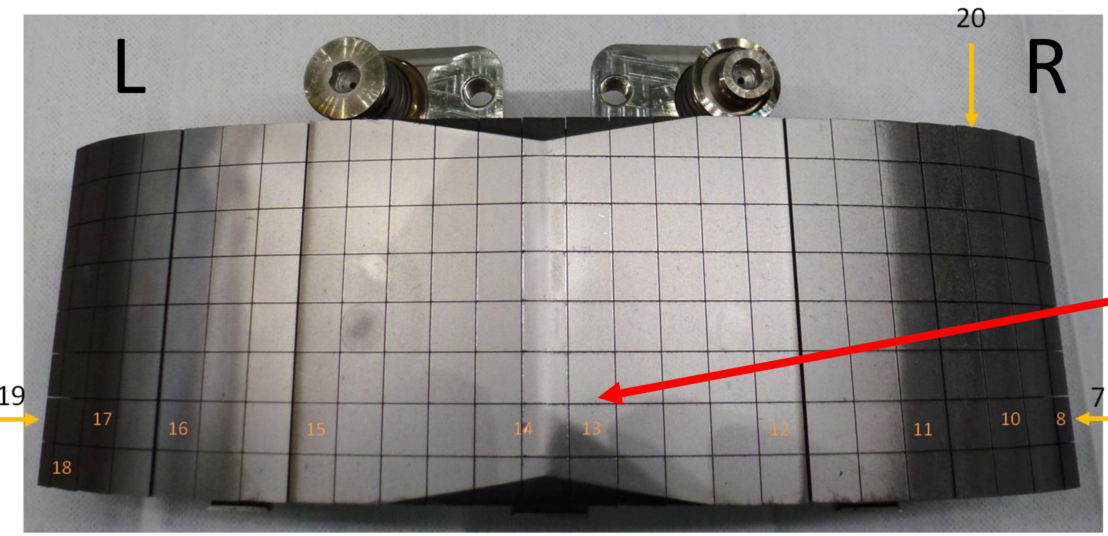




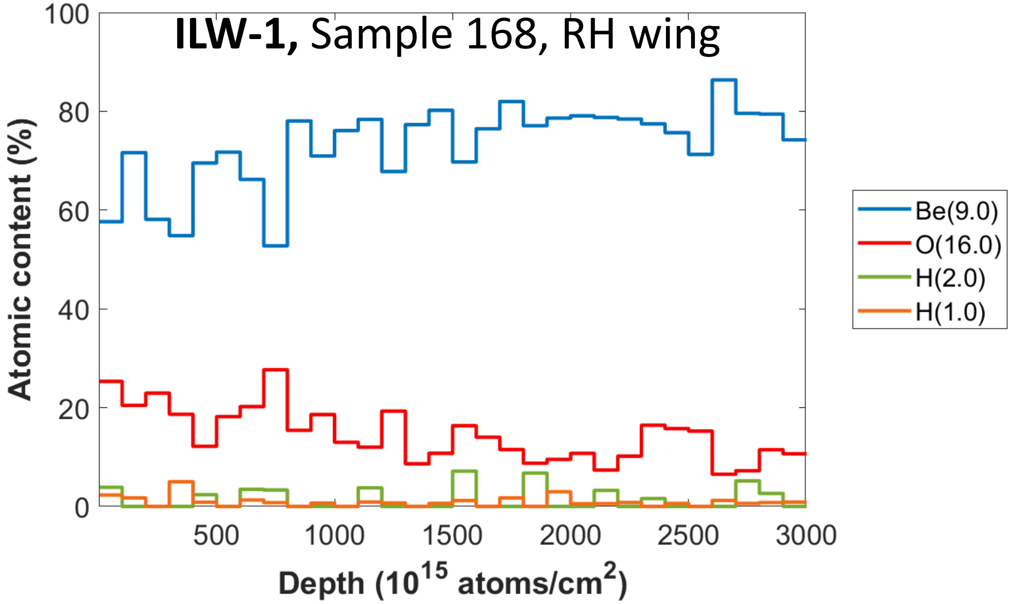


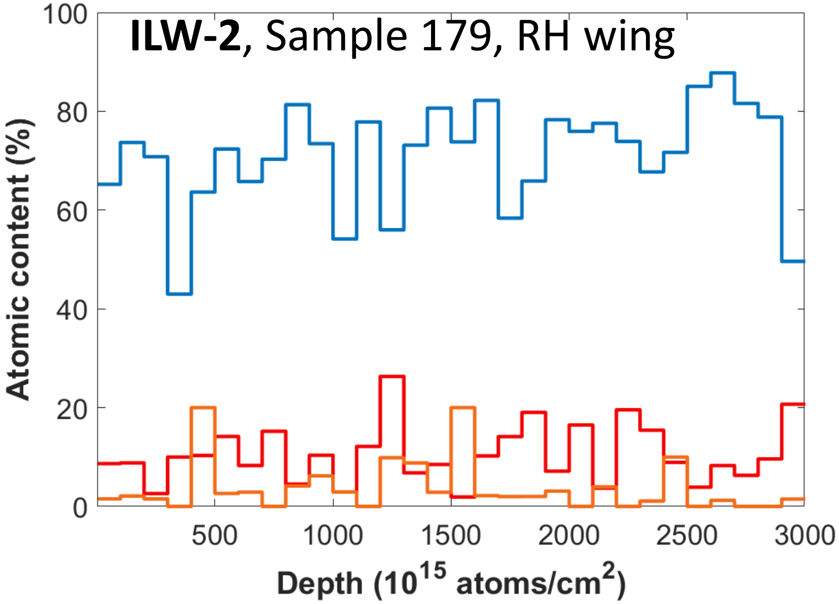
G. Pintsuk, FZJ

Beryllium limiters



Beryllium Inner Wall Guard Limiters:ILW-1 and ILW-2





Deuterium content: $4.8 \times 10^{16}\,\frac{at.}{cm^2}$

Hydrogen content: $2.7 \times 10^{16}\,\frac{at.}{cm^2}$

Hydrogen content: $1.2 \times 10^{17}\,\frac{at.}{cm^2}$

No Deuterium on ILW-2

(The result of ILW-2 campaign finish in H)

Other species, contents in 10^{16} cm^{-2}:

	ILW-1	ILW-2
Be	226	220
C	14	14
N	5	11
O	45	32
Ni	10	3
W	traces at the detection limit.	

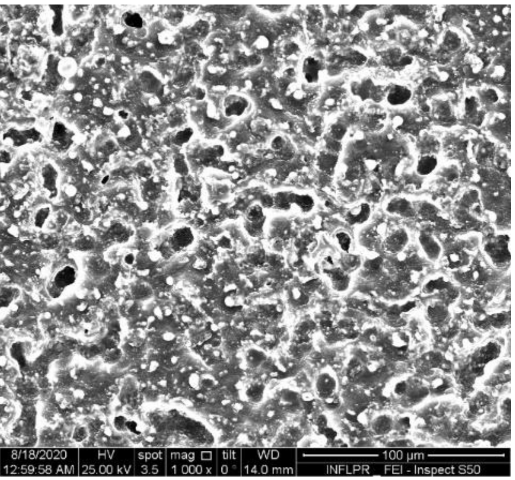
L. Dittrich, P. Petersson, VR

Beryllium limiters: *SEM/EDX*

IWGL 2XR11 – sample 674

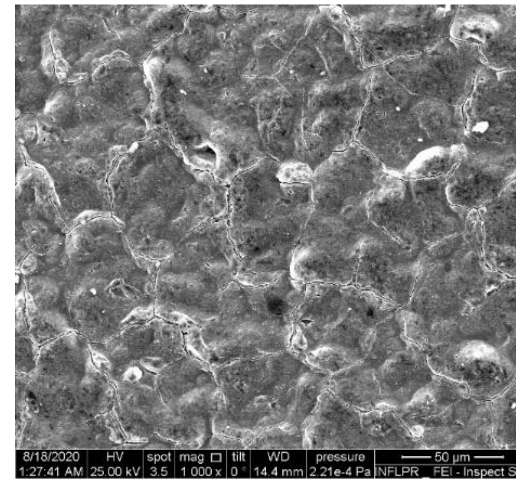
WOPL 4D15 – sample 754

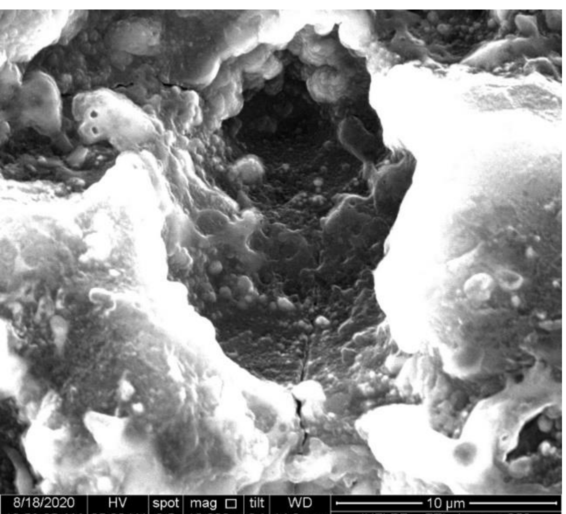
Impurities from *EDX* measurements:

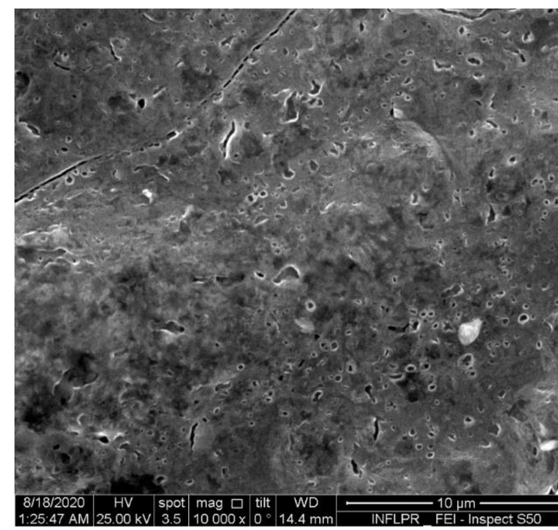


Element	At. %
O	*55.34*
Cr	*3.17*
Fe	*4.84*
Ni	*12.73*
Cu	*5.71*
W	*3.18*

Element	At. %
O	*68.39*
Cr	*2.81*
Fe	*4.57*
Ni	*11.16*
Cu	*5.16*
W	*3.72*



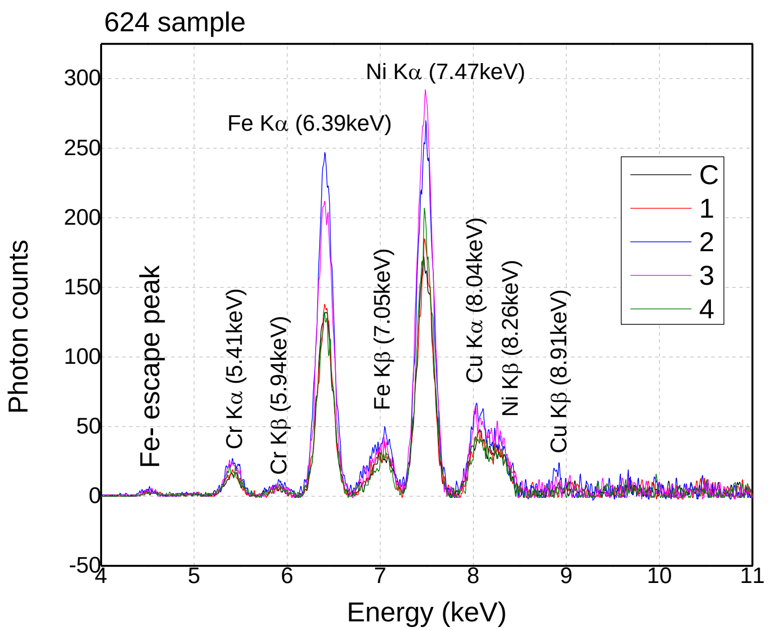


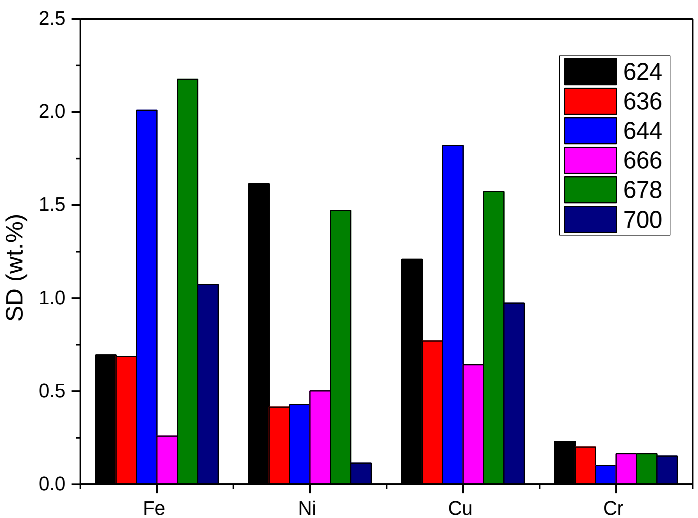


C. Lungu. C. Porosnicu, IAP, Romania

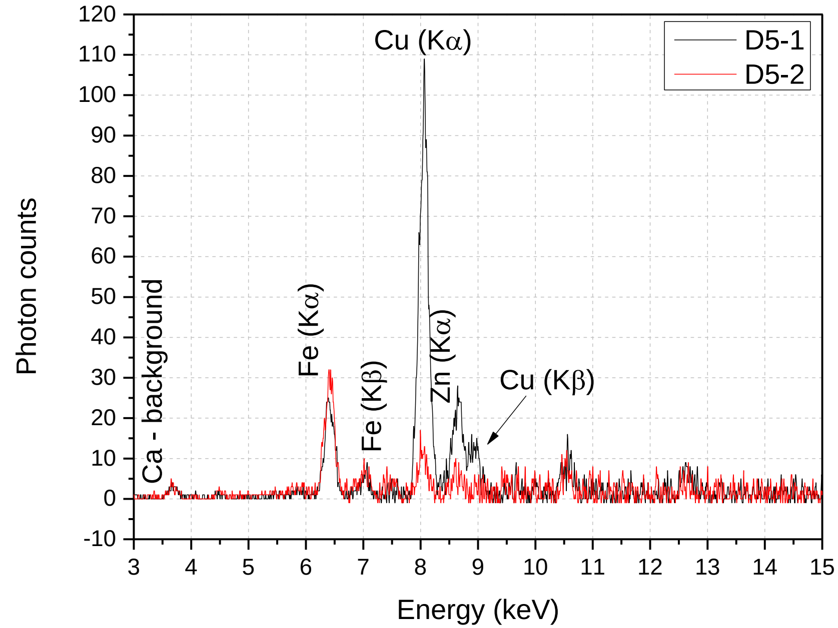
µXRF in Be limiter castellations and on dust

µXRF on Be limiters





µXRF/XCT on dust



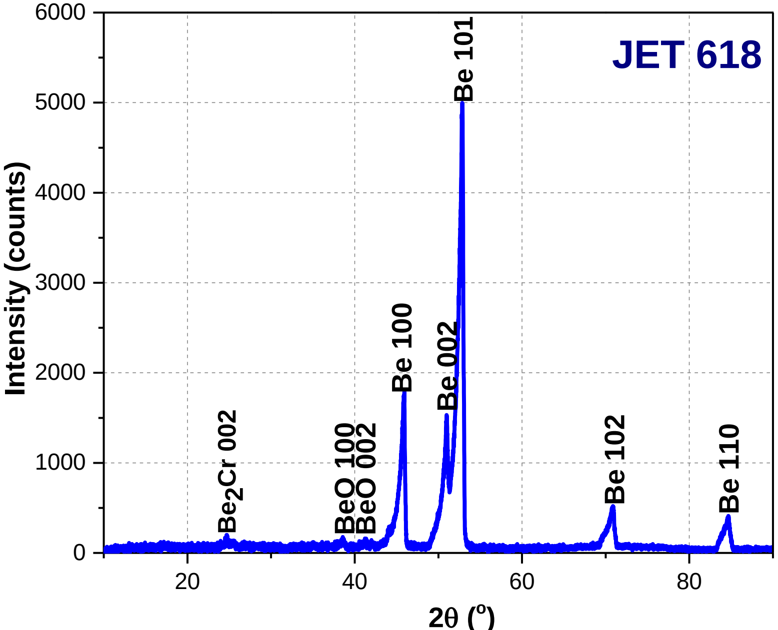
Composition of inclusions in dust particles (D5)

Element	D5-1 (Wt.%)	D5-2 (Wt.%)
Fe	13.8+1.2	15.5+1.3
Cu	70.4+3.1	69.4+3.1
Zn	15.7+1.6	15.1+1.6

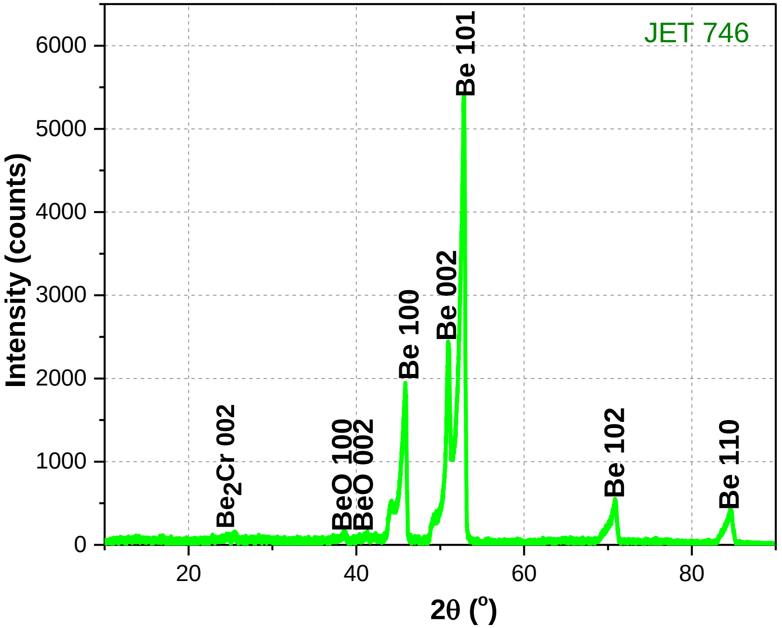
I. Tisuanu, IAP, Romania

Be limiters after ILW-3: X-ray diffraction

Inner Wall Guard: 2XR11



Outer Poloidal: 4D15



Crystalline Phases:

- **Be; BeO (bromellite)**

Grain size measured on Be 101 peak:

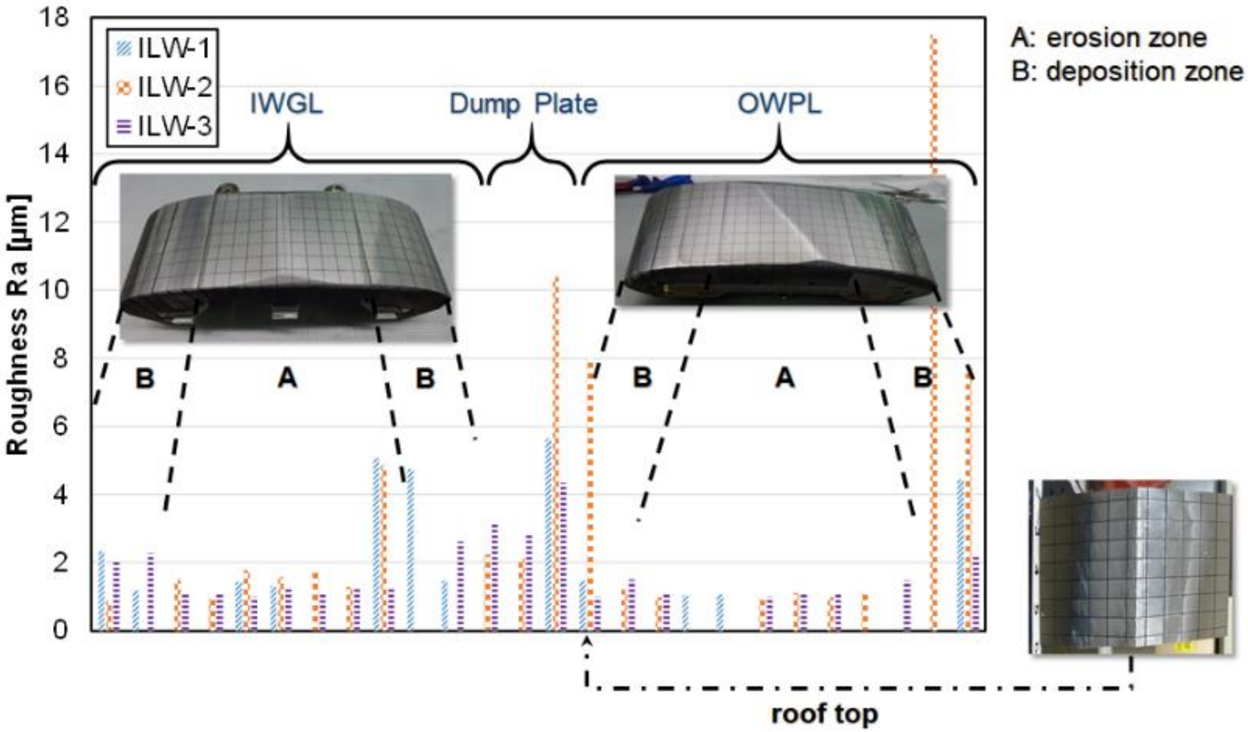
- **13.48 nm (618)**
- **11,83 nm (746)**

Messages:

- *No significant changes in crystalline phases observed on all the samples.*
- *No other peaks corresponding to other elements (impurities) observed.*

C. Lungu. C. Porosnicu, IAP, Romania

Be limiters ILW-1 to ILW-3: Surface Roughness



Roughness:

- *Enhanced either by melting (dump plate) or in the deposition zones.*
- *Hardly any effect for the erosion zones.*
- *For ILW-1 and ILW-3 almost identical results.*
- *Significantly increased roughness on OWPL, ILW-2.*

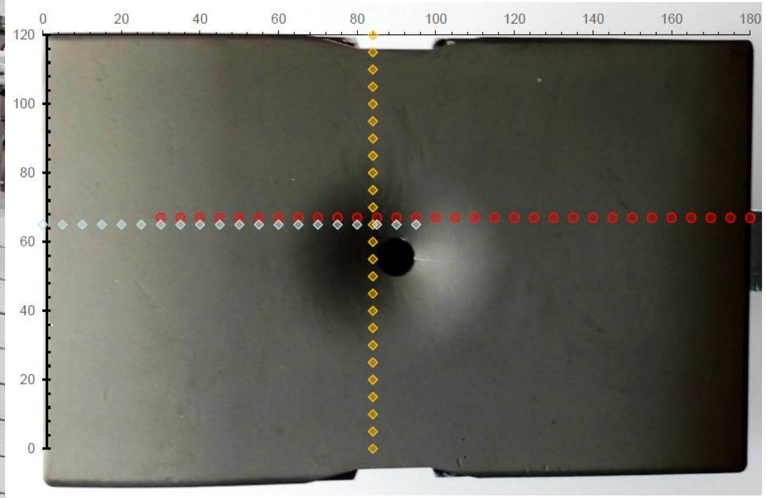
Messages

- *In ILW-3 areas with full or partial erosion of the Be top layer.*
- *ILW-3: In contrast to ILW-1 and ILW-2 no areas with melting.*
- *For the dump plate no relevant erosion nor melting of the roof top was found (specimen 462, 2B2C); 2B4C (not part of this investigation) shows heavy melting.*
- *Metallographic results showed more or less full erosion of the marker layer in all the locations, at least in the cross sectional micrographs no Ni-remains were found as it was the case for ILW-1 and ILW-2.*

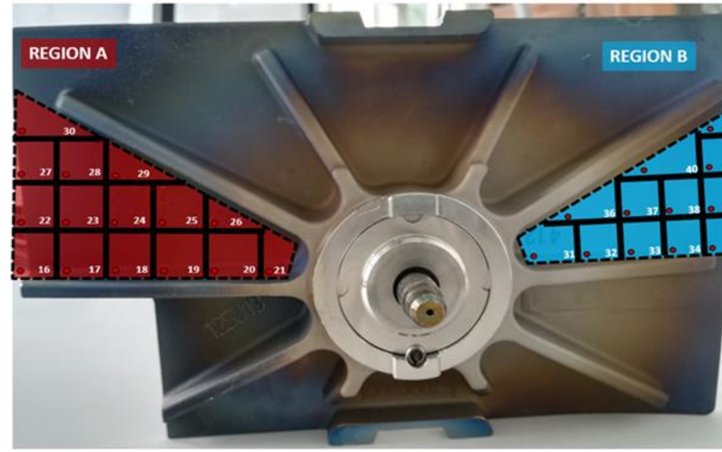
G. Pintsuk, FZJ

Inner Wall Cladding

Inner Wall Cladding



IWC – 412(2011-16) cutting plan



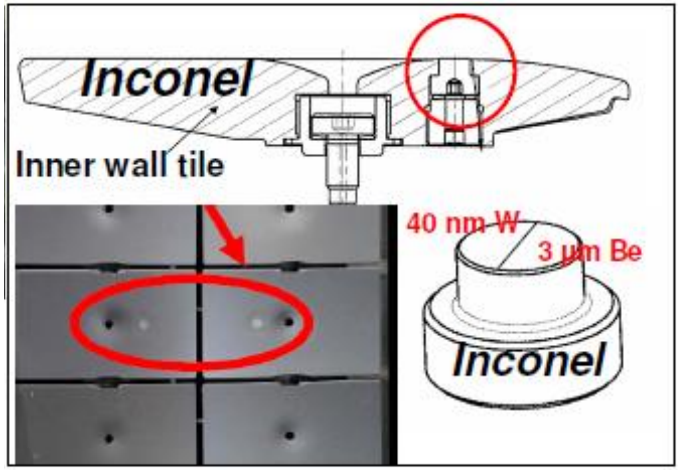
Total IWC surface area: ~9 m^2

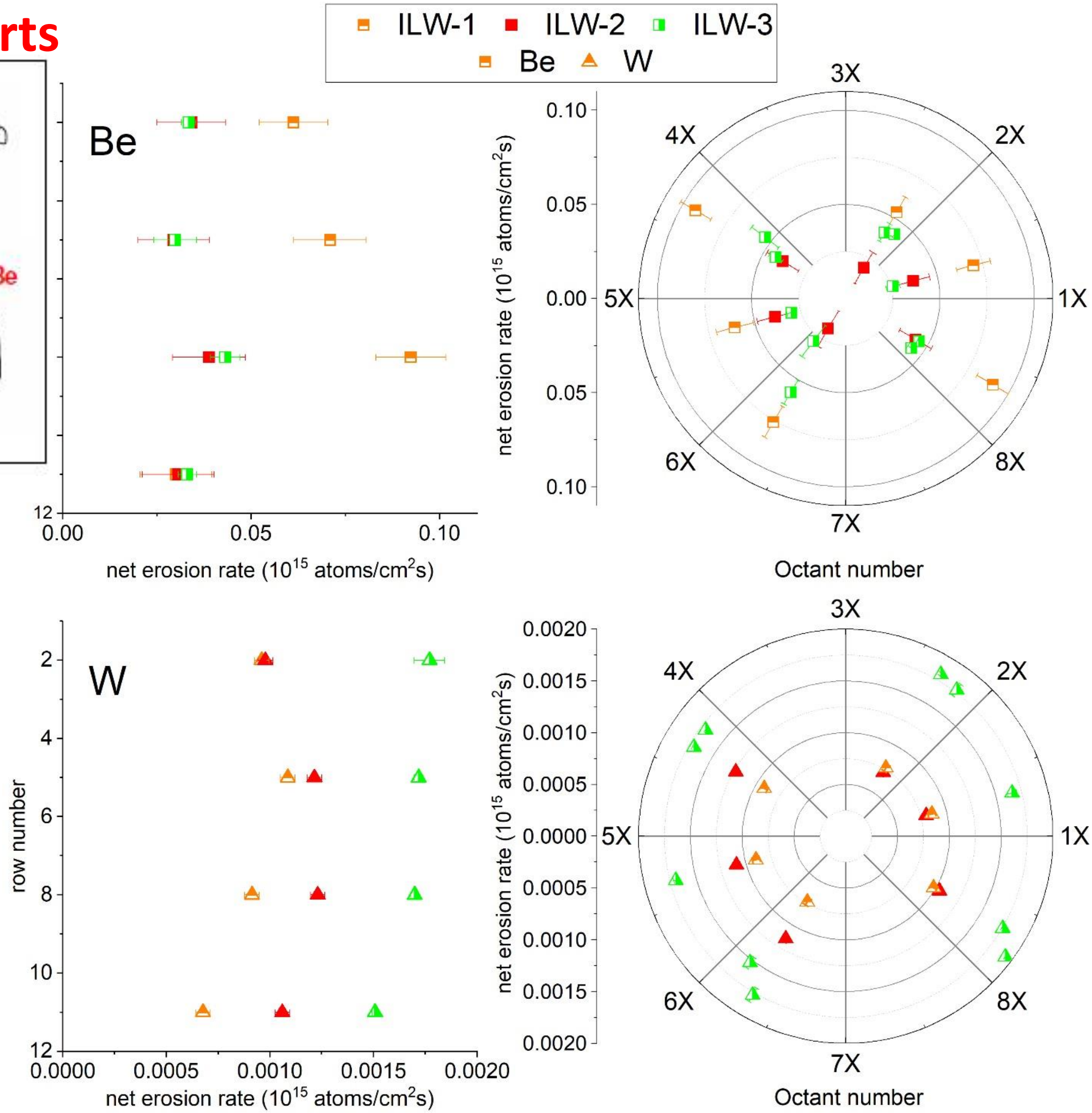
Main questions:

- ***Erosion rate***
- ***Fuel content***
- ***Impurity content***

Inner wall erosion: from ILW-1 to ILW-3

Data for Be/W Wall Inserts



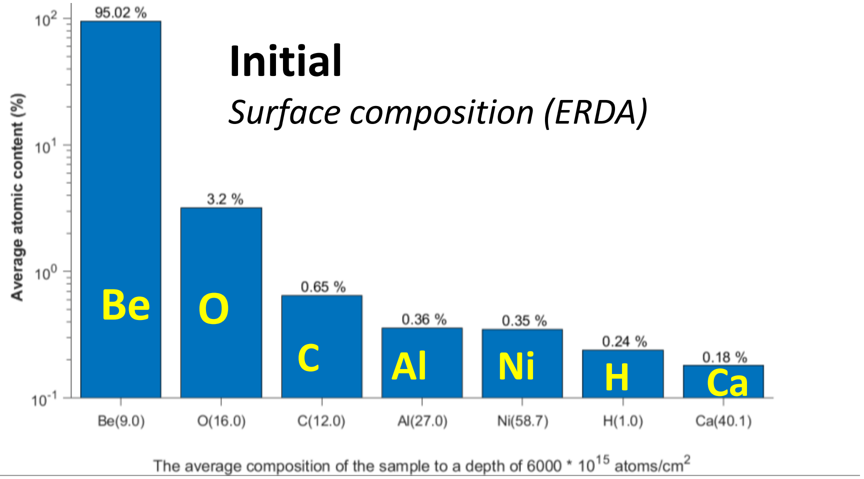


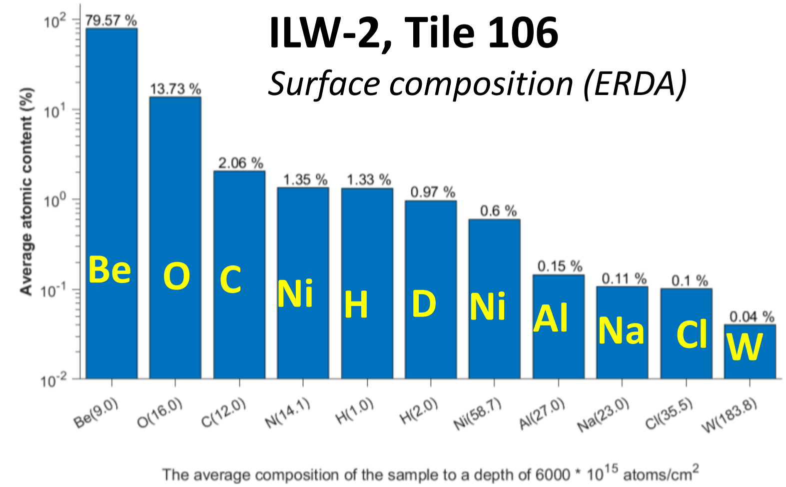
Messages:

- *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*

M. Mayer, IPP

Inner Wall Cladding: ERDA and ^{3}He-NRA





NRA – whole layer analysis

Sample	Thickness 10^{18} cm^{-2} (µm)	Impurity %	D $_{surface}$ 10^{17} cm^{-2}	D $_{content}$ %
Initial	112 (9.4 µm)	4 – 5	0	0
ILW-2 (106)	82-110 (6.7 – 9.3)	7 - 9	0.9 - 1.7	0.13 – 0.20
ILW 1-3 (412)	125 -149 (10.1 – 12.0)	8 - 15	3 - 6	0.20 – 0.44

Messages:

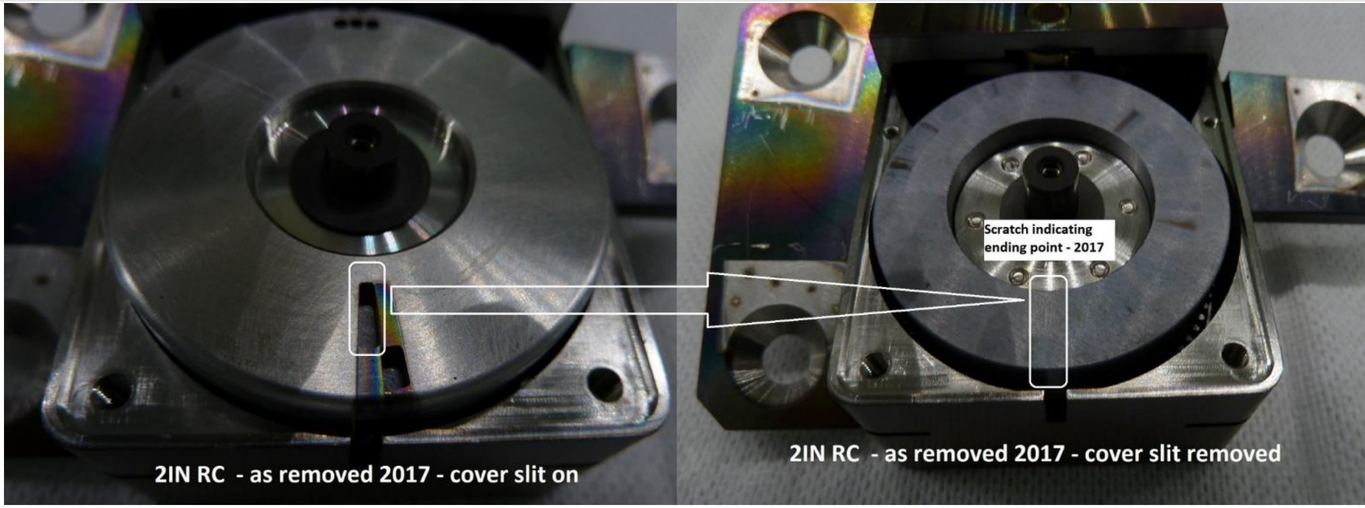
- *Low or no layer erosion.*
- *Probably Be deposition from eroded limiters*
- *Low fuel retention, both at the surface and in the bulk.*
- ***Total D inventory: 0.8 - 5.4 x10^{21} (3 – 21 mg)***
- *Microscopy is needed to check topography.*

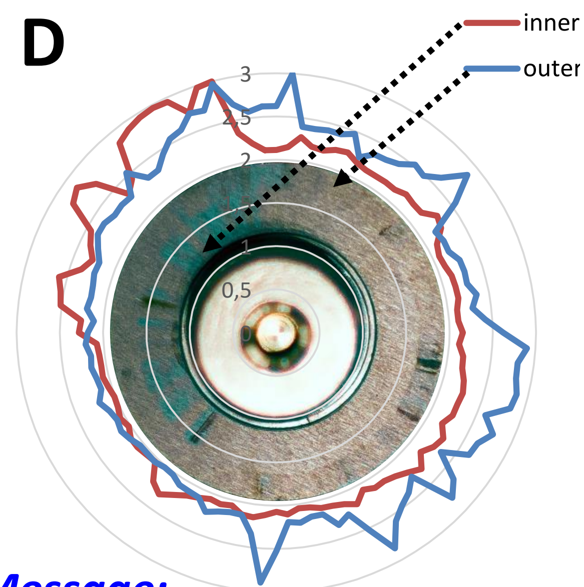
P. Petersson, L. Dittrich, VR

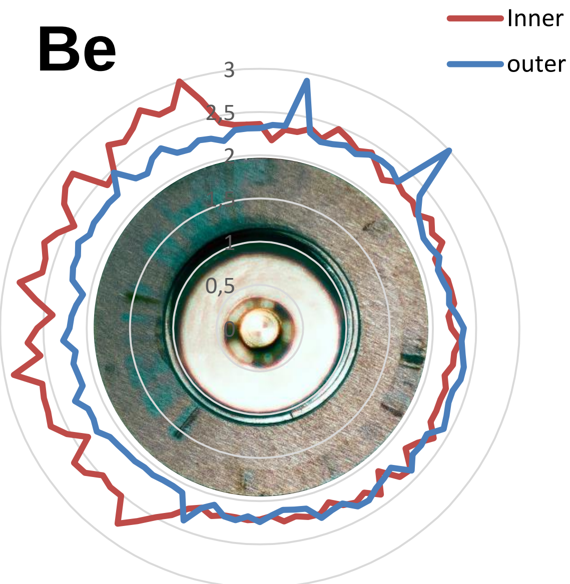
Wall Probes

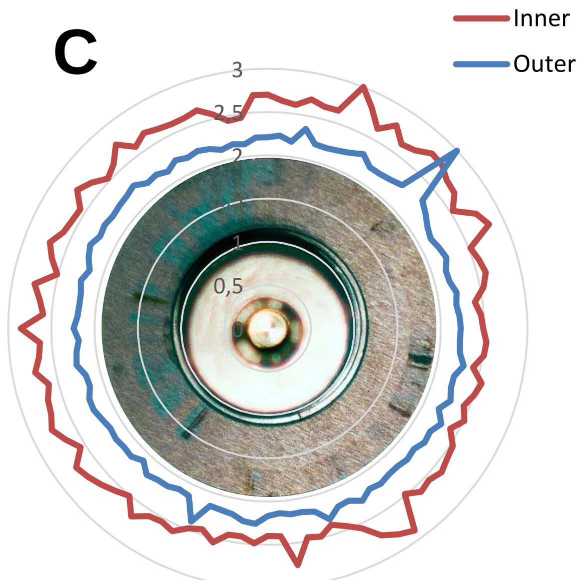
Rotating Collectors

- *2 cycles of exposure.*
- *Each up to 3000 shots.*







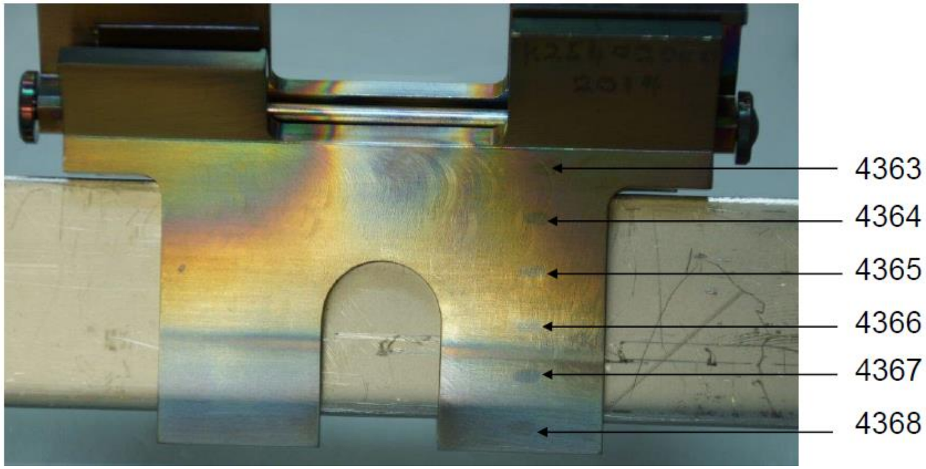


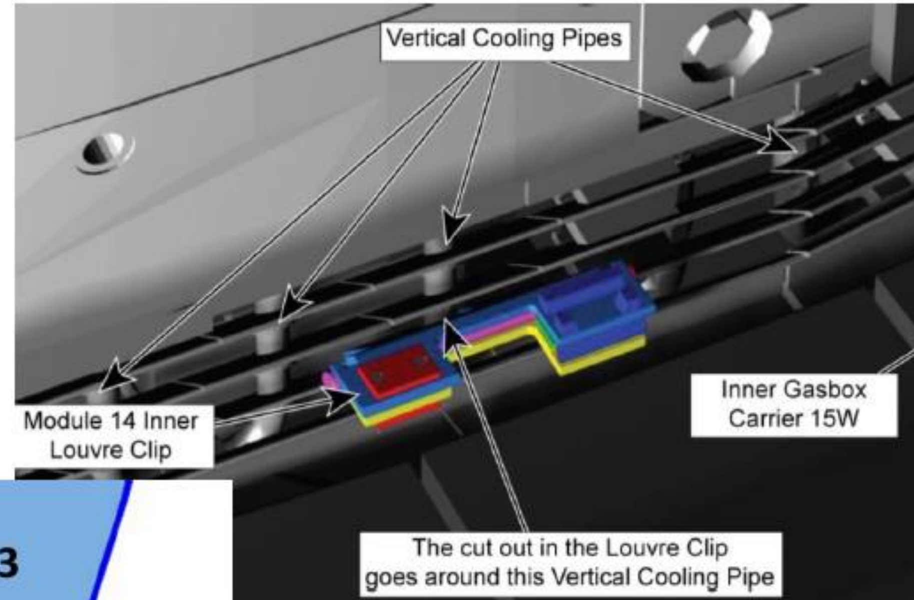
Message:

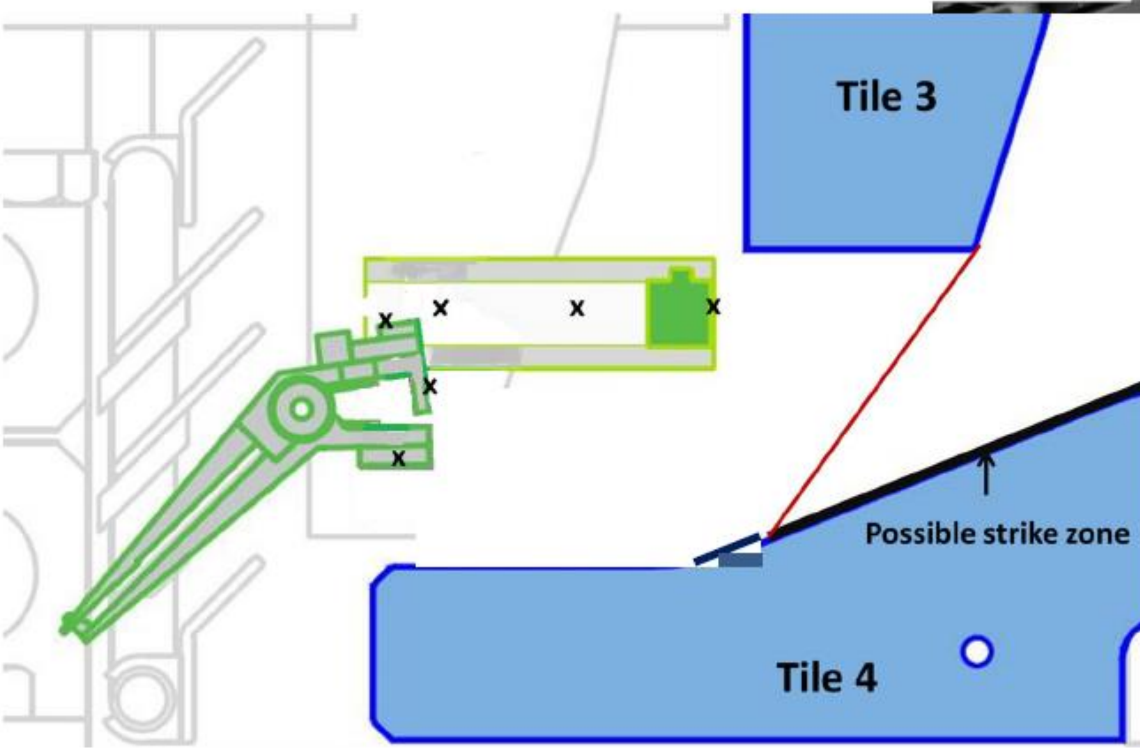
- *Analyses completed, data ready for modelling/correlation with operation modes.*
- *Contents of metals are very on the $10^{15}/cm^2$ level.*

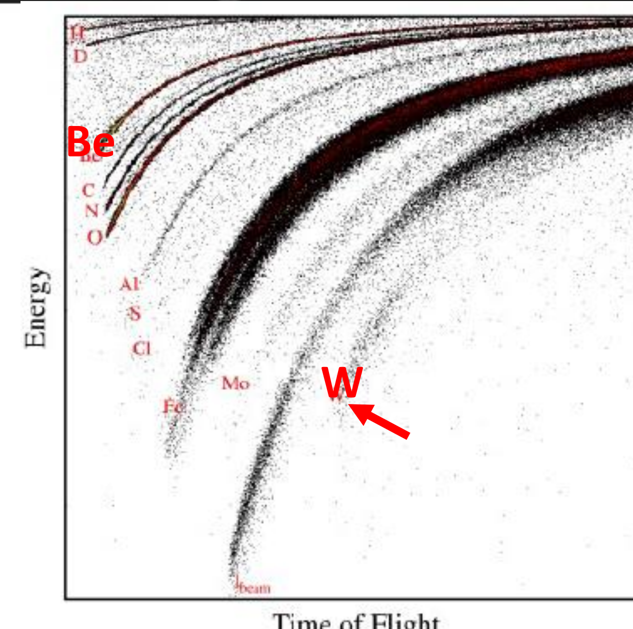
E. Alves, N. Catarino, IST, Portugal

Louvre clips ILW-1 to ILW-3



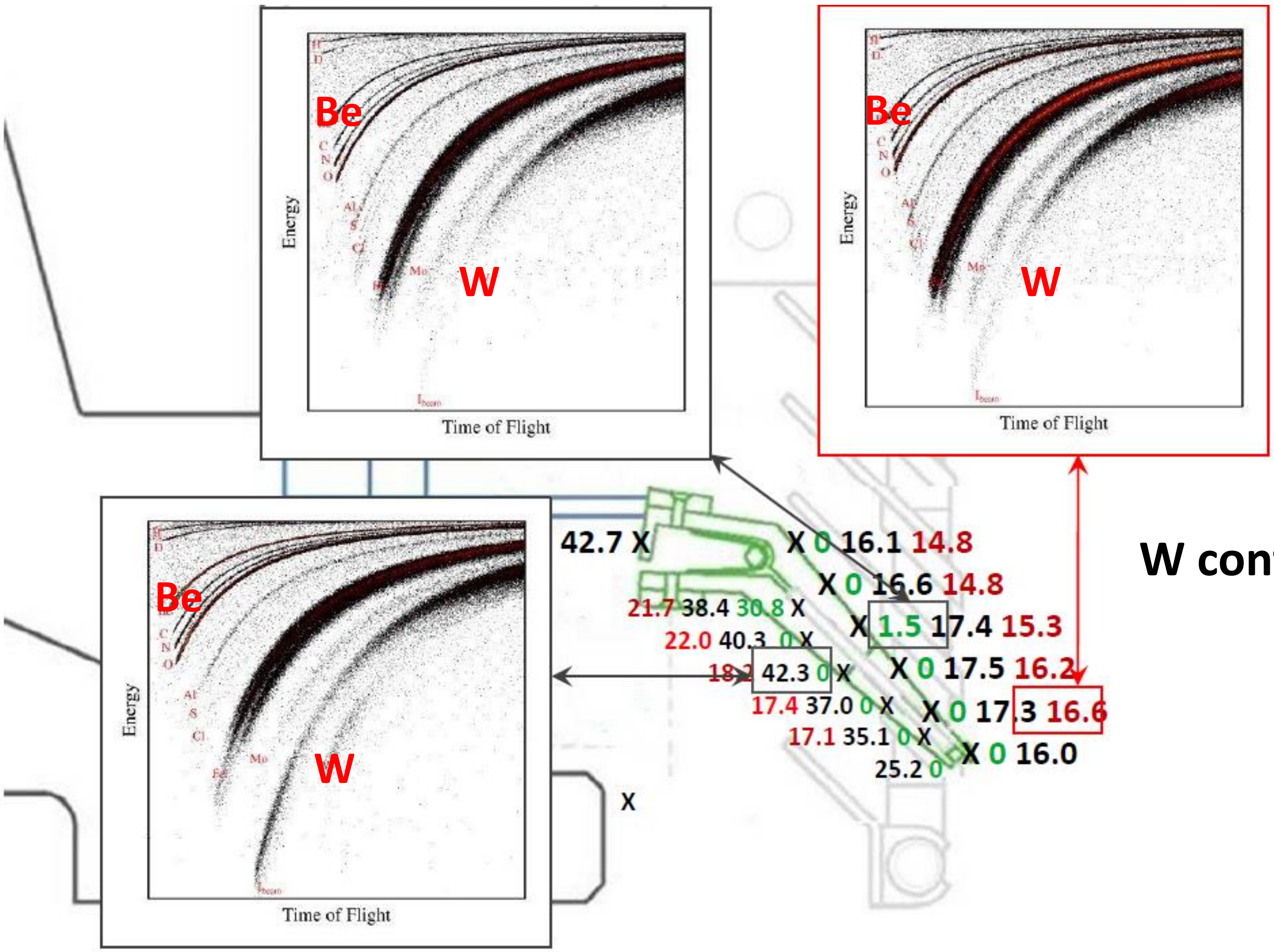






K. Mizohata, VTT, Finland

Louvre clips ILW-1 to ILW-3:
Transport of Be and W to remote areas



W content (10^{15} cm^{-2})

ILW-1

ILW-2

ILW-3

Message and main question (for modellers)

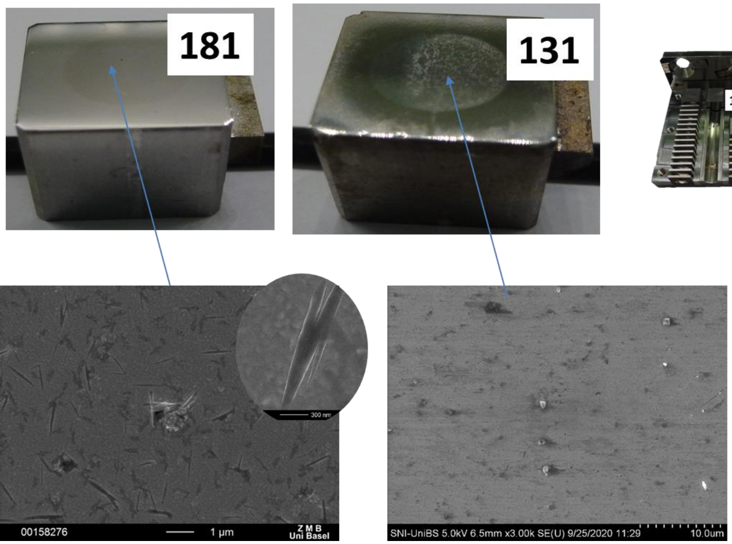
How do metals (Be, W) travel to such remote areas, to all surfaces of the clips?

K. Mizohata, VTT, Finland

Mirrors

Plasma-assisted cleaning

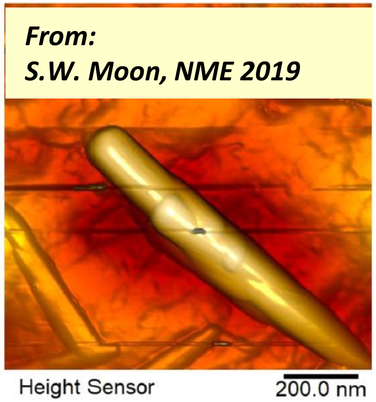
Plasma-assisted mirror cleaning

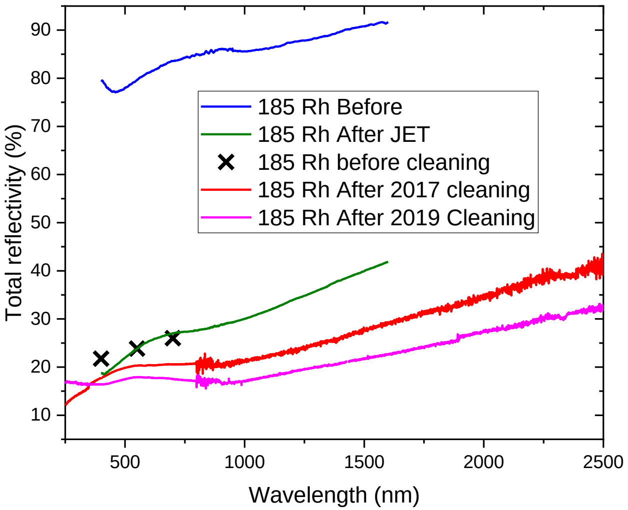


SEM before cleaning revealed needle-like structures on JET-ILW mirror exposed in cassette with fins. No needle without fins.

Aim:

To demonstrate cleaning on mirror with needles.





220 eV He ions are reducing the amount of Be (393 nm to 37 nm) but not removing the final layer.

XPS shows an enrichment of W oxide that stopped the cleaning.

Adding 3 h in 2019 (in comparison to 23 h for 2017) is not reducing the Be amount as measured by HÍERDA.

Reflectivity not recovered for these steps, Ar gas is required.

- ***Further cleaning experiments are delayed due to the COVID situation.***
- ***Next experiments will be performed at the beginning of 2021.***

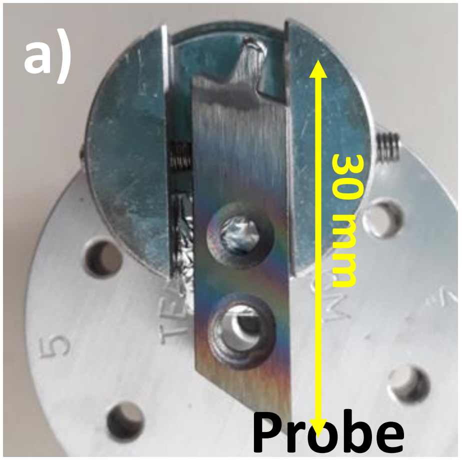
L. Marot et al.

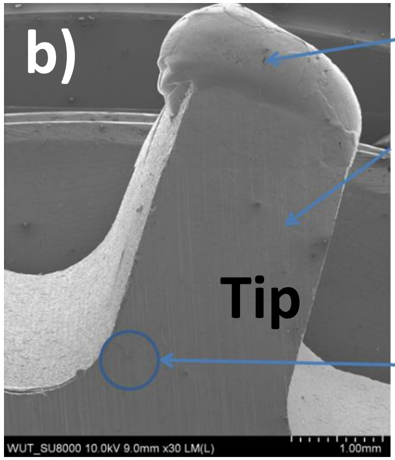
University of Basel

INFLPR

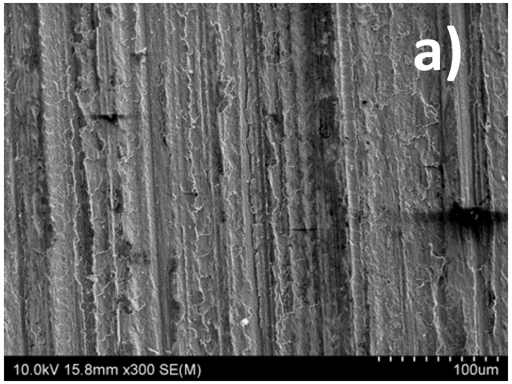
Mechanical properties of bulk W
Nanoindentation

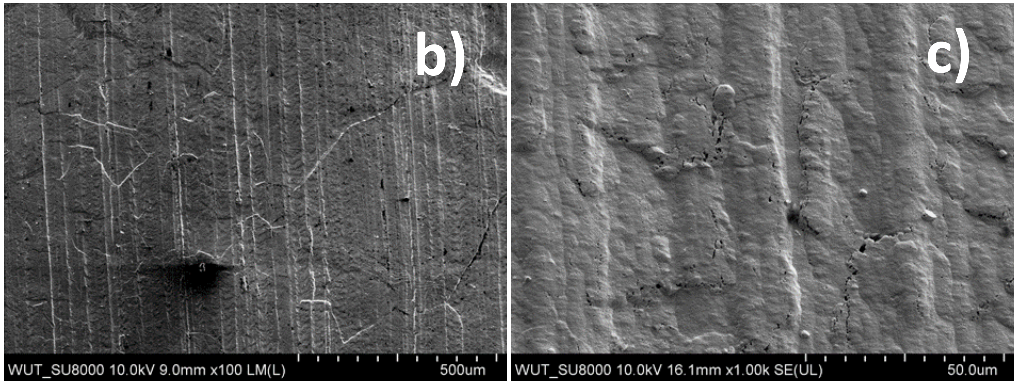
Langmuir Probe (No. 5, module 16IN,Tile 3, ILW-2)





Areas of measurements





(a) Zone III

(b-c) Tip

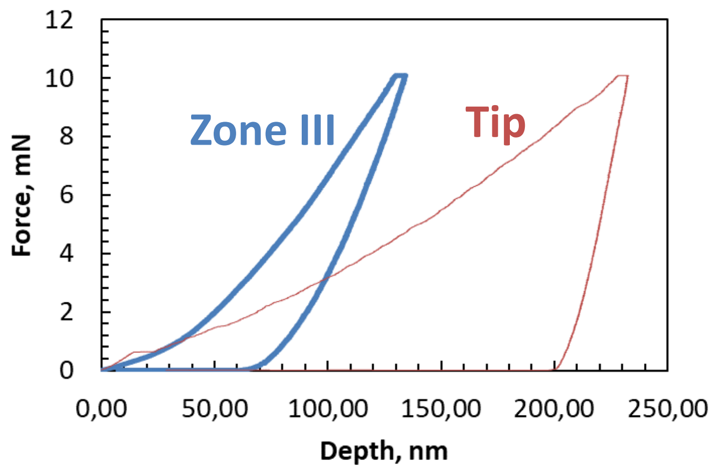
E. Fortuna, M. Spychalski, IPPLM-WUT, Poland

Langmuir Probe: Nano-indentation

	Young modulus, E, GPa			Hardness, H, GPa		
	Average(E)	SD*(E)	Error (E)	Average(H)	SD(H)	Error (H)
ZONE III	257	42	12	15.37	2.68	0.74
TIP	261	25	6	5.18	0.72	0.19

SD – standard deviation

Comparison of force-depth curves for both areas.



- ***Hysistron Ti-800 triboindenter.***
- ***Force 10 mN.***
- ***15 measurements in each area.***

- *Due to the large development of the surface, the surface was imaged in the SPM (scanning probe microscope) mode before each measurement.*
- *Large differences in the hardness between the tip and Zone III.*

E. Fortuna, M. Spychalski, IPPLM-WUT, Poland

Dust

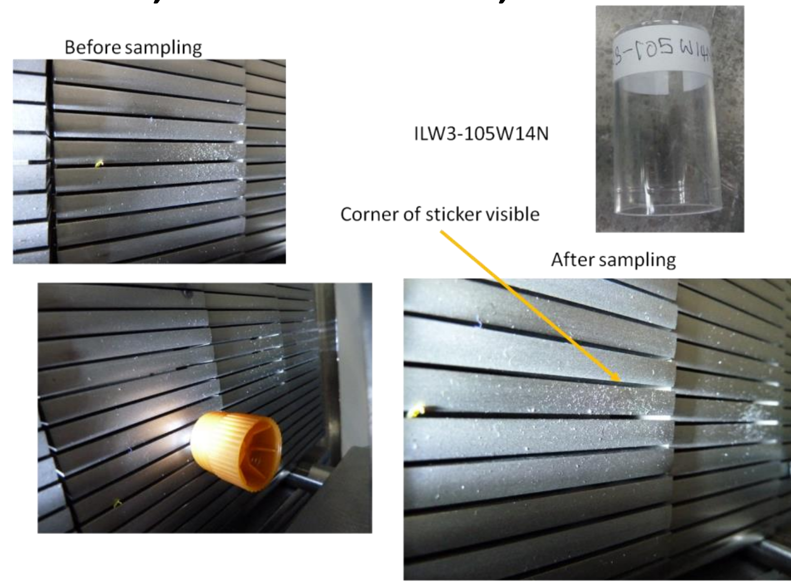
Dust

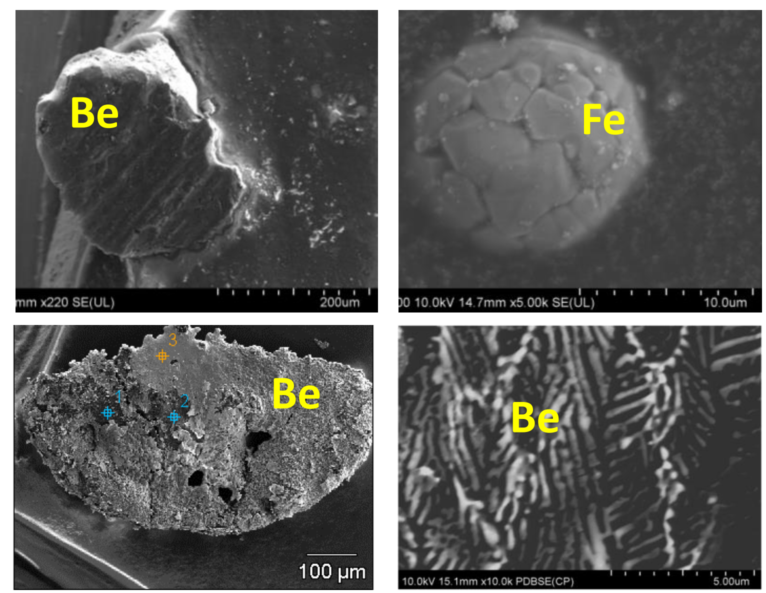
Types/Locations	Methods
Vacuum cleaning ILW - all	Optical microscopy
Sticky pads: Tiles 0, 1	SEM
Sticky pads: Tile 5	FIB
Sticky pads: Tile 8	TEM, STEM
Sticky pads: Tiles B, C	EDX, WDX, EPMA
Sticky pads: Be IWGL	µXRF/XCT
Dust monitors: ILW-2 and 3	µ-NRA
Mirrors (FMT)	µ-PIXE
KY-6 Mirror ILW-1 and ILW-2	µ-RBS
Spatial blocks	HIERDA (dust monitors)
QMB crystals	ICP-OES
	TDS: H, D, T
	Full combustion: T
	Radiography: T
	Cameras (in discharges)

Messages:

- *Very small quantity of loose matter in the divertor: 1 g/campaign.*
- *Very strong adhesion of dust to the substrate.*
- *No tungsten droplets.*

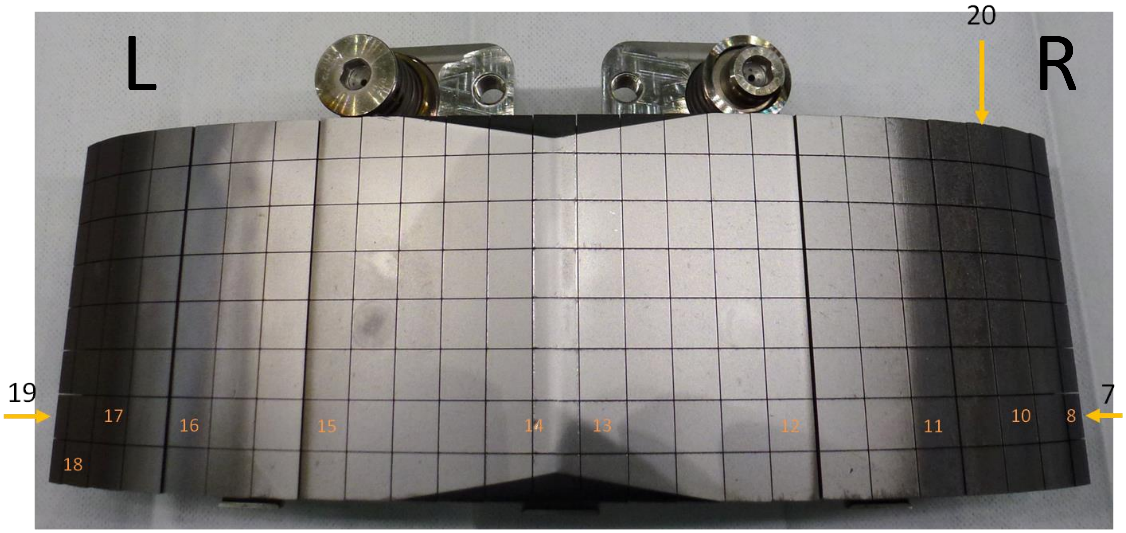
Tile 5, bulk W lamellae, IWL-1 + ILW-3

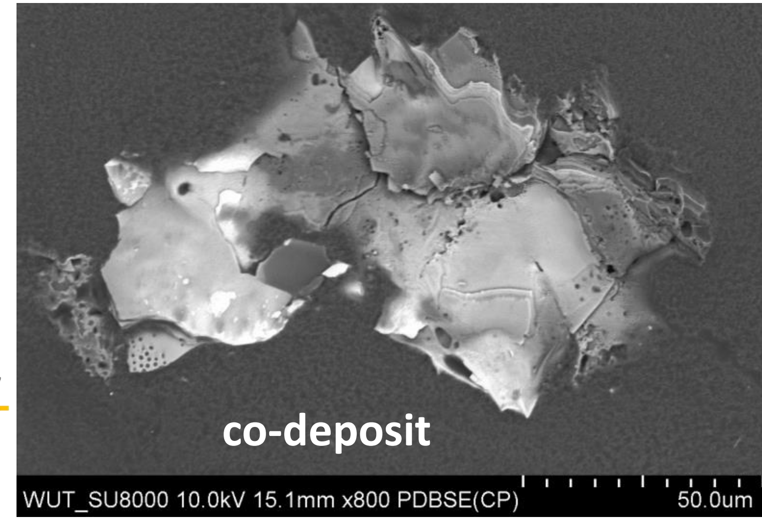


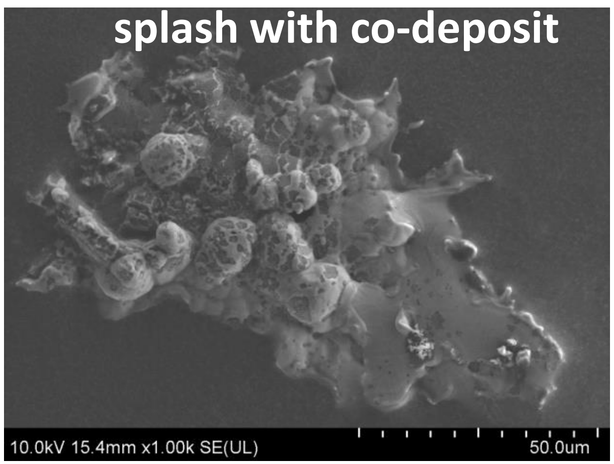


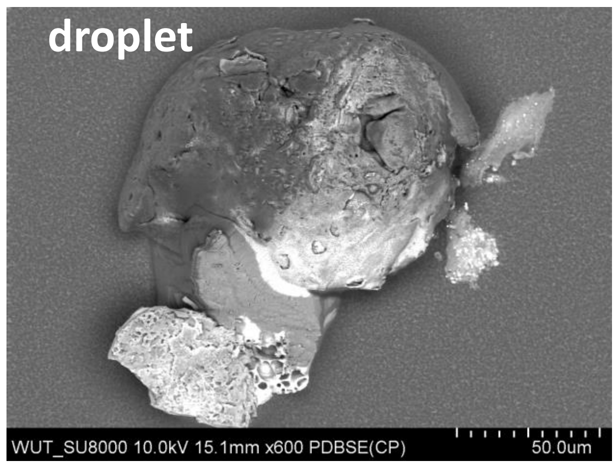
E. Fortuna, IPPLM-WUT

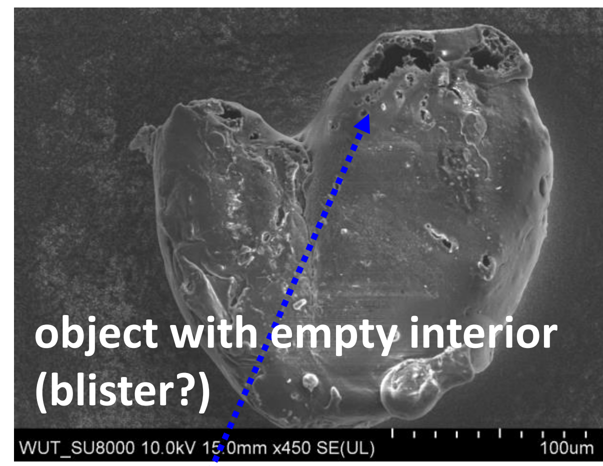
Dust: Inner Wall Guard Limiter 2XR11 ILW1-3









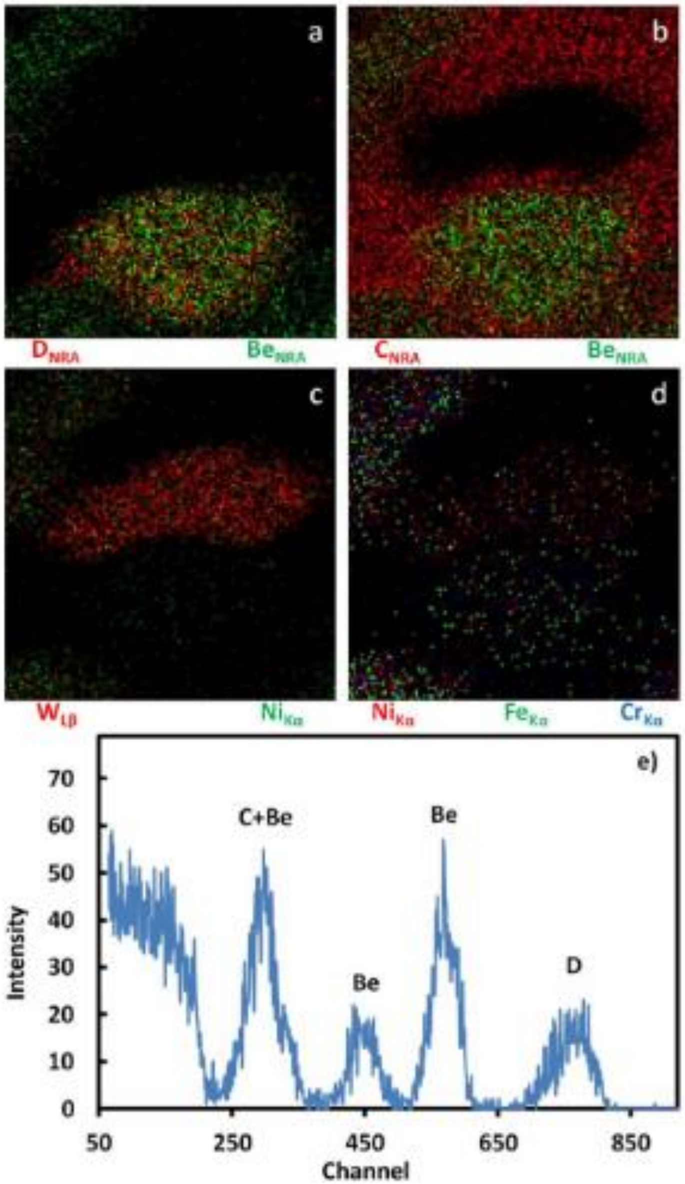


Messages:

- *Numerous splashes, co-deposits and irregular objects with empty interior.*
- *Strong adherance of particles to the substrate.*

E. Fortuna, IPPLM-WUT

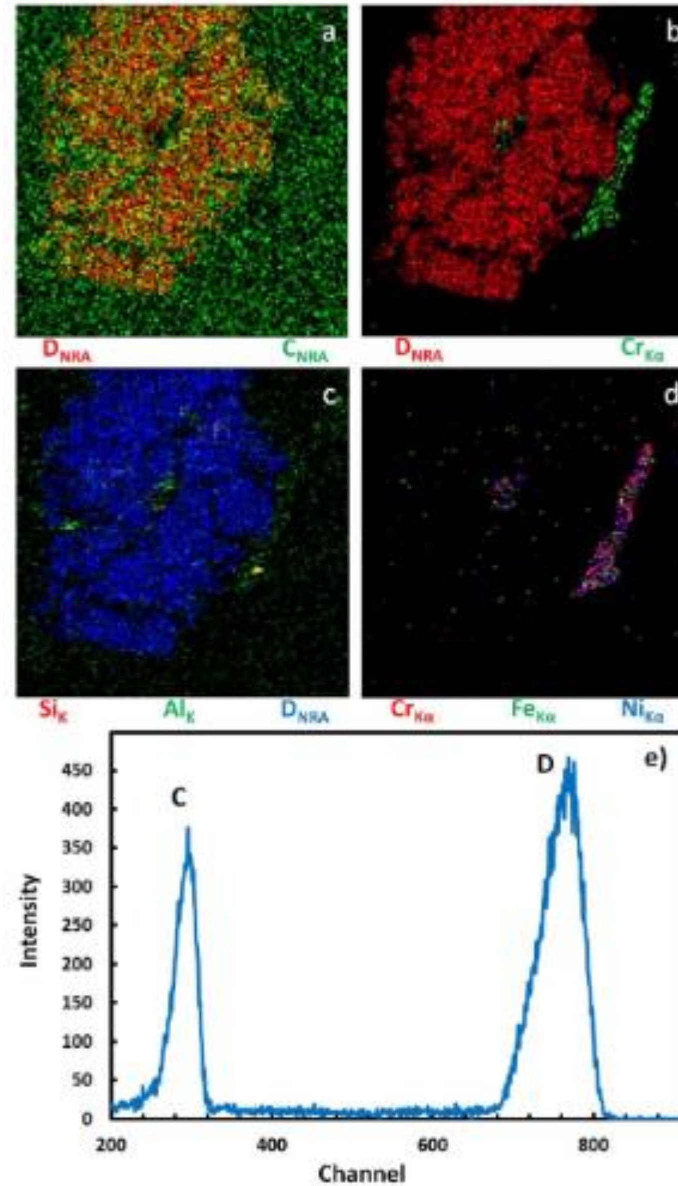
Dust collected by vacuum cleaning after ILW-3: Ion Micro-beam Analysis



Main message:

D retention is associated mainly with C:

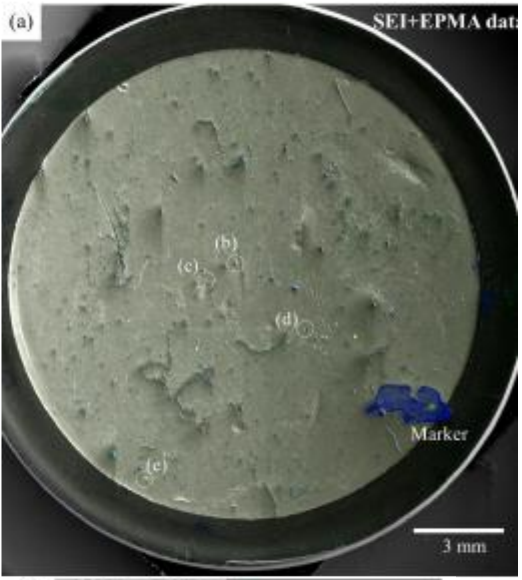
~ 10–20 times greater than in metal-based particles.

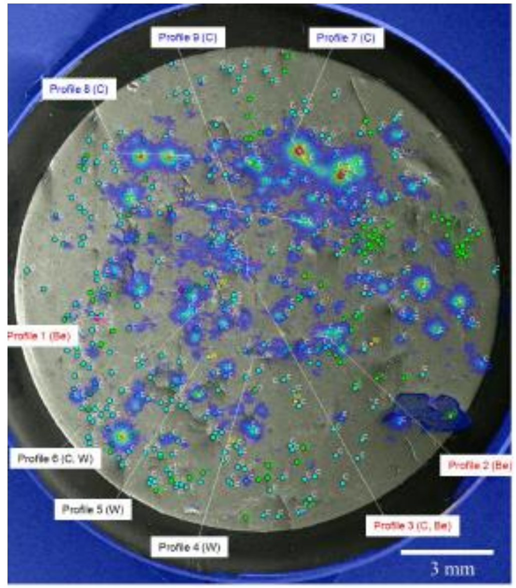


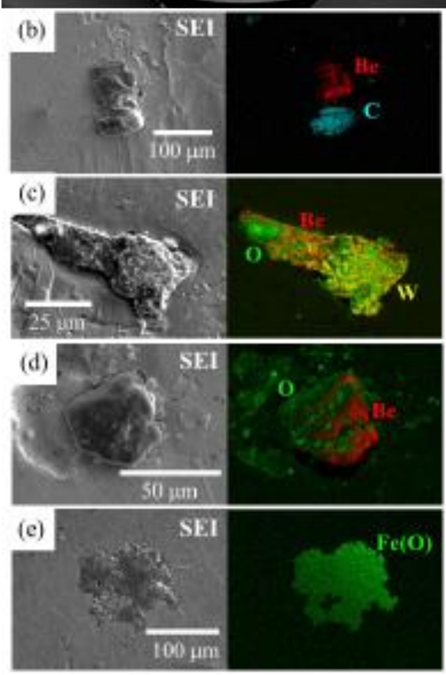
S. Fazinic et al. Nucl Fusion 60 (2020) 126031

S. Fazinic et al., RBI, Croatia

DUST:
Radiography of T in different particles (ILW-1)





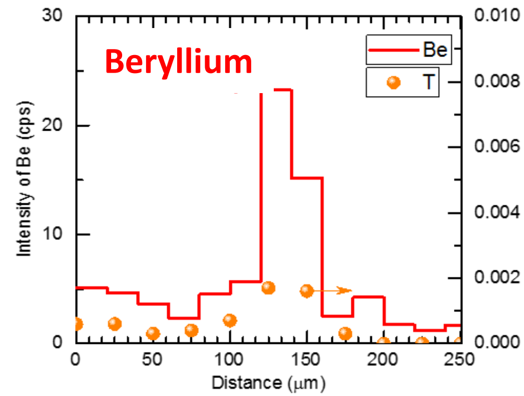


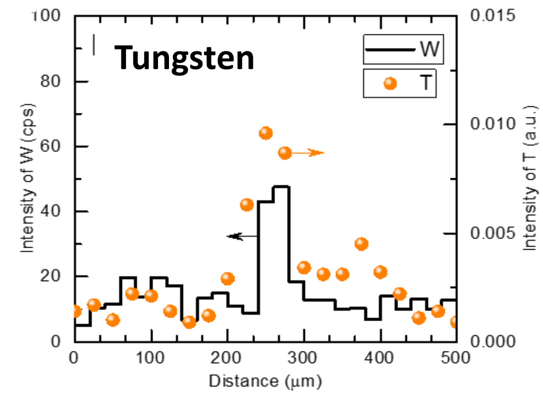
- *Dust particles are placed on In disk.*
- *Composition of individual particles is identified with EPMA (WDS).*
- *β^- (T) recorded by radiography.*
- *Superposition of profiles.*

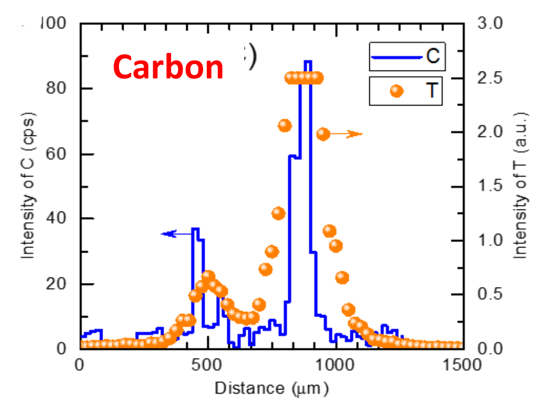
Message:

Tritium presence associated with C.

T. Otsuka, Osaka-Kindai U. / IFERC

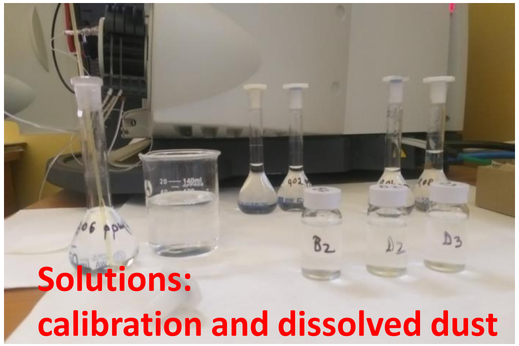


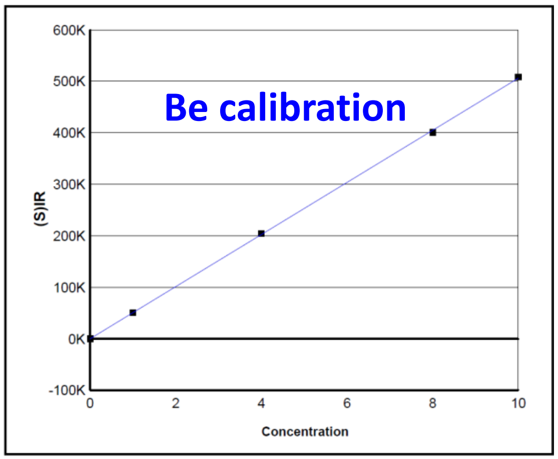




Note the scale

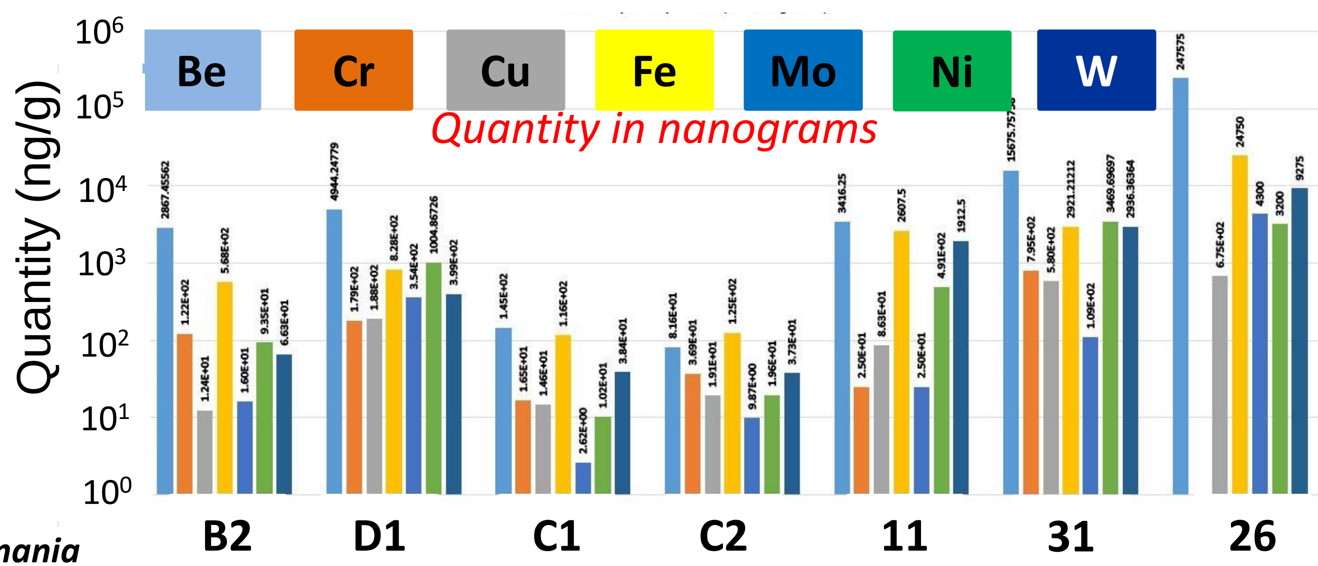
Dust: Analyses of metals* in dust by ICP-OES





Sample	B2	D1	31	C1	C2	11	26
Be Wt ratio	0.766	0.626	0.592	0.422	0.248	0.399	0.854
Cr Wt ratio	0.032	0.023	0.030	0.048	0.112	0.003	0.000
Cu Wt ratio	0.003	0.024	0.022	0.043	0.058	0.010	0.002
Fe Wt ratio	0.152	0.105	0.110	0.338	0.379	0.304	0.085
Mo Wt ratio	0.004	0.045	0.004	0.008	0.030	0.003	0.015
Ni Wt ratio	0.025	0.127	0.131	0.030	0.059	0.057	0.011
W Wt ratio	0.018	0.051	0.111	0.112	0.113	0.223	0.032

- *Carbon and other non-metals cannot be analysed by ICP-OES.*
- *Be is the major metal constituent of dust.*



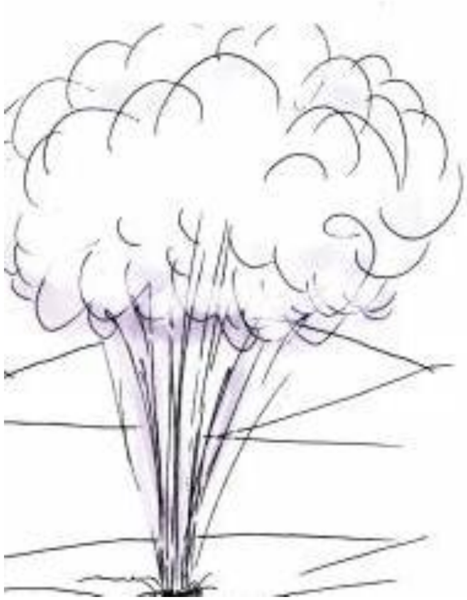
***B2** – swab (with vacuumed dust)*
***D1** - divertor 2014-11*
***31** - HFGC tile (2014)*
***C1** - 15BNG6D -2010-2014*
***C2** – 14BWG6B –2010-2014*
***11** - SEM stubs*
***26** - SEM stubs*

C. Lungu, C. Porosnicu, IAP, Romania

Impact of moisture on Be dust generation

ITER wants to know:

What happens to beryllium-rich deposits when hot water/steam enters the vessel?



Impact of moisture on dust generation: Experiment

Task requested by ITER:

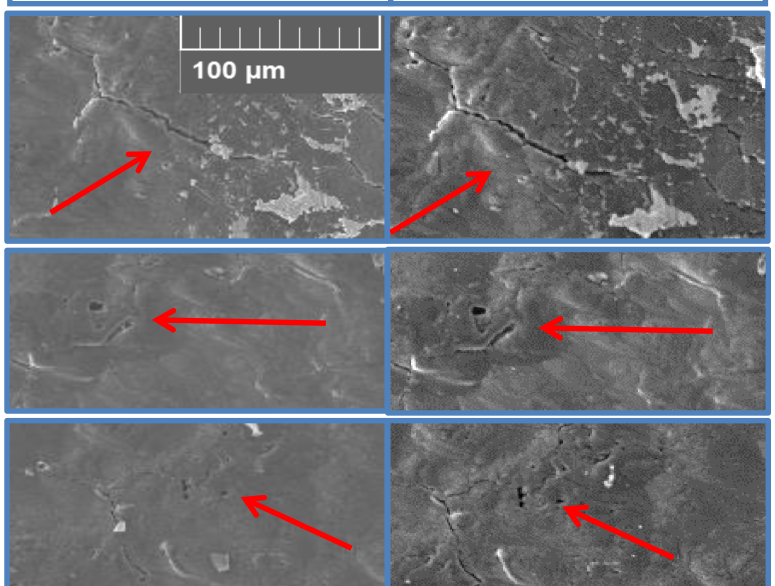
Determine dust generation under off-normal events like water and air leaks.

Experiment:

- "Cook" Be limiter samples with/without deposits for some hours.
- Prevent water evaporation (use of cooler)
- Determine T content in H_2O (tritium transfer).
- Determine surface properties before and after exposure to hot water.
- Investigate a solid residue to check for the released dust.

Current status: One sample with deposit (cut from 2XR10 tile IWGL) "cooked" for ~4 h.

Before	After



Y. Zayachuk et al., CCFE, UK

Main messages:

a. *Exposure of Be with deposit doesn't lead to "mechanical" damage to the layer: no cracking or large-scale flaking.*

b. *No flakes/dust found in the flask → mechanical stability of the deposit exposed to boiling water.*

c. *Agreement (a & b)with data obtained in earlier experiments. (P. Petersson, E. Fortuna, 2019)*

d. *Tritium detected in water: ~6 x10^{11} atoms (~10 % of total T inventory within the sample)*

Where are we NOW?

- **The original scope of WPJET2 (2014) has been vastly broadened by new projects:**
  (i) identified research needs, (ii) own ideas; (iii) ITER needs/requests.
- **The majority of work has already been done or it is a very advanced stage.**
- **Most results have alredy been published.**

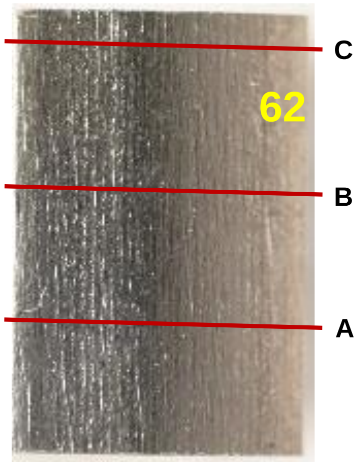
Samples to be distributed *(delay caused by Covid):*

- **Be castellation samples from tiles exposed to ILW 1-3**
- **Sample of filter in JET exhaust ventilation system**
- **Langmuir probe – non-exposed**

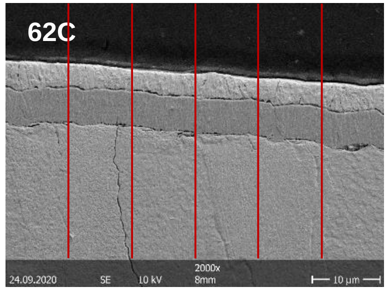
Anna with tell more tomorrow.

Extra slides with detailed information

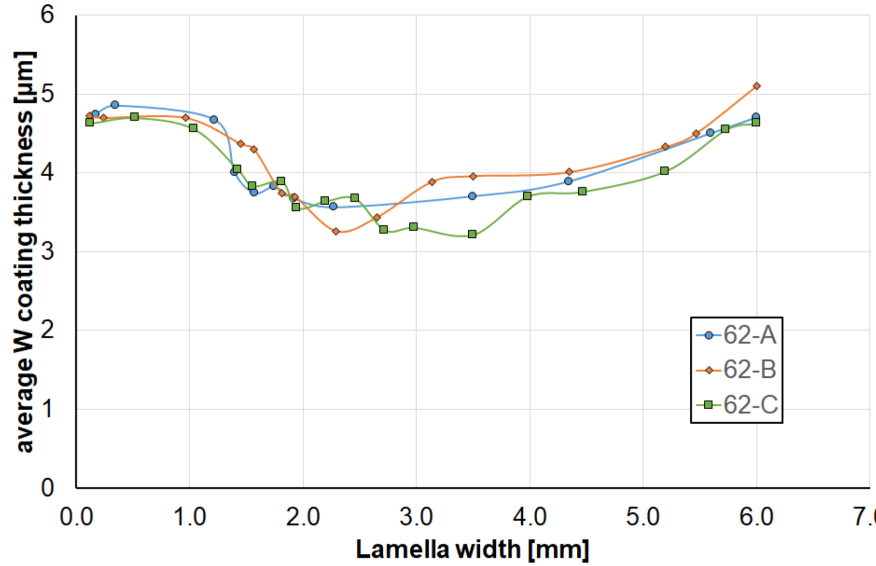
Tungsten lamellae with marker (ILW-2): W-Mo coating thickness

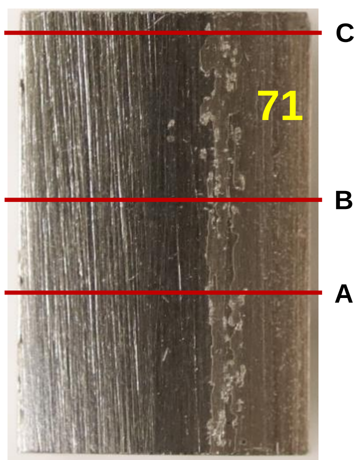


X

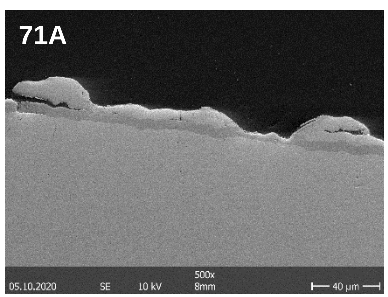


measurement @ ≥ 5 positions

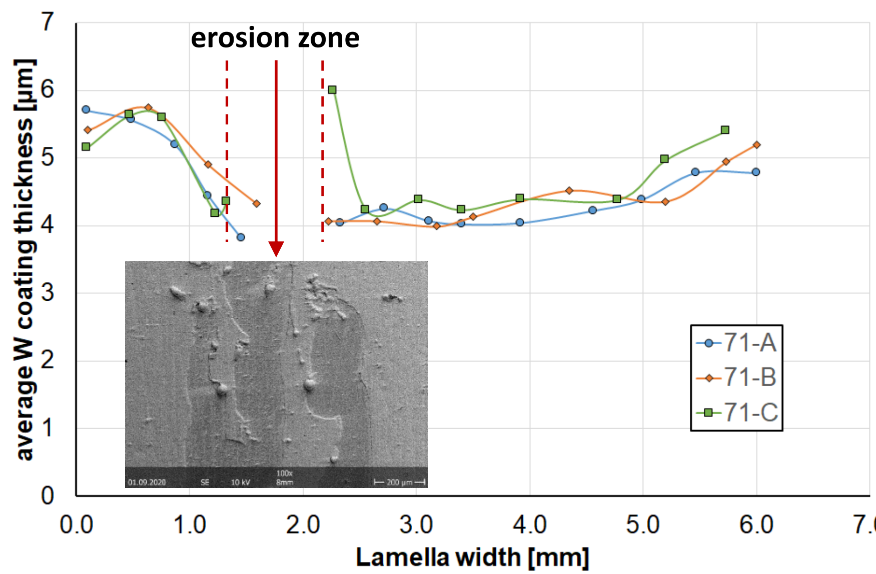




X



Measurement not always possible due to ablation/melting



X ... inner wall facing marking

G. Pintsuk, FZJ