WP PWIE

Overview of plasma-tungsten surfaces interactions on the divertor test sector in WEST during the C3 and C4 campaigns

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WEST : paving the way to ITER actively-cooled tungsten divertor operation

WEST Phase 1

2017-2021				
C1	C2	C3	C4	C5

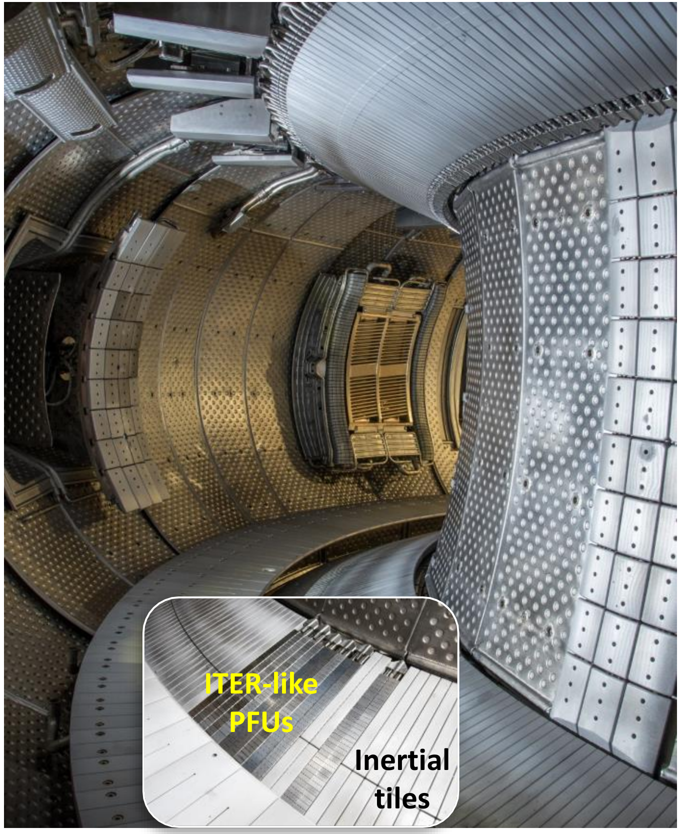
inertially cooled W coated tiles
\+ actively cooled bulk W ITER-like PFUs

WEST Phase 2

2022-			
C6	C7	C8	…

full ITER-like divertor

Now available for post-mortem analysis !



Divertor test sector

14 ITER-like PFUs having their own history

- Specific features :
    - W grade and manufacturing processes
    - Chamfered/unchamfered poloidal edge
    - No toroidal bevel in phase 1 as foreseen in ITER
- Different campaign/plasma exposure
- PFUs exposed with vertical misalignment > ITER specifications (up to 0.8mm)

1. Divertor configuration and operating conditions during WEST phase I

- Divertor heat load pattern modulated by magnetic field ripple
- Significant plasma exposure of the targets during C3 and C4

2. Post-exposure PFCs characterization

- Local modifications of W (cracking, melting, optical hot spots)
- Material migration

3. Summary and perspectives

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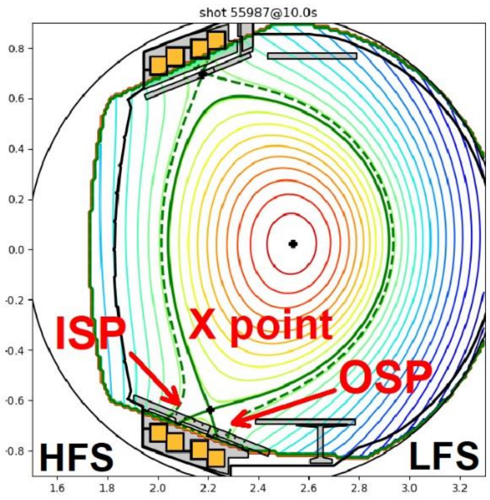
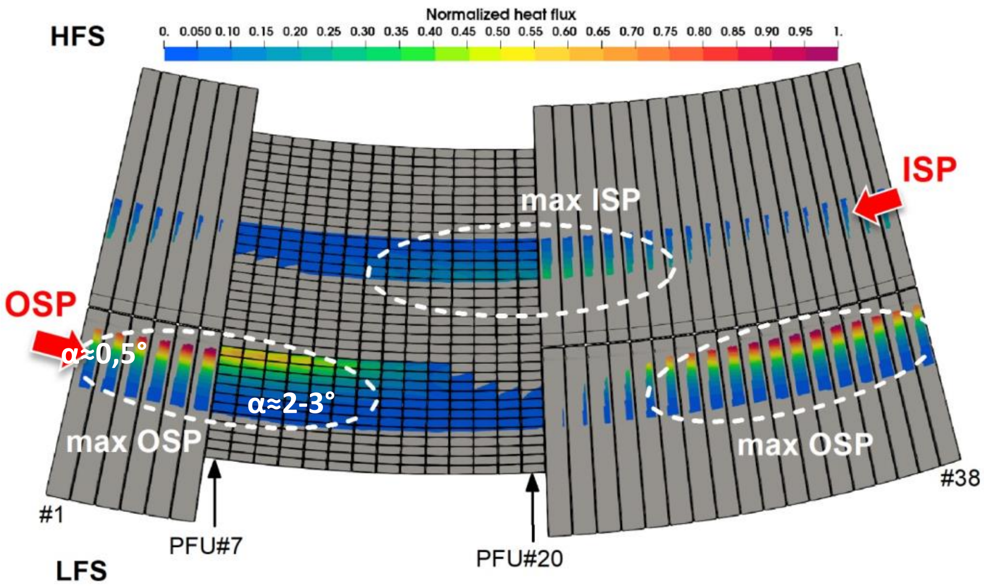
Divertor heat load pattern modulated by magnetic field ripple

- 2 strike points (ISP,OSP) in one target
- Modulated plasma pattern due to the ripple effect and variation of the angle of incidence
- Inner/outer asymmetry : OSP most loaded area (heat load distribution 1/4 ISP, 3/4 OSP)

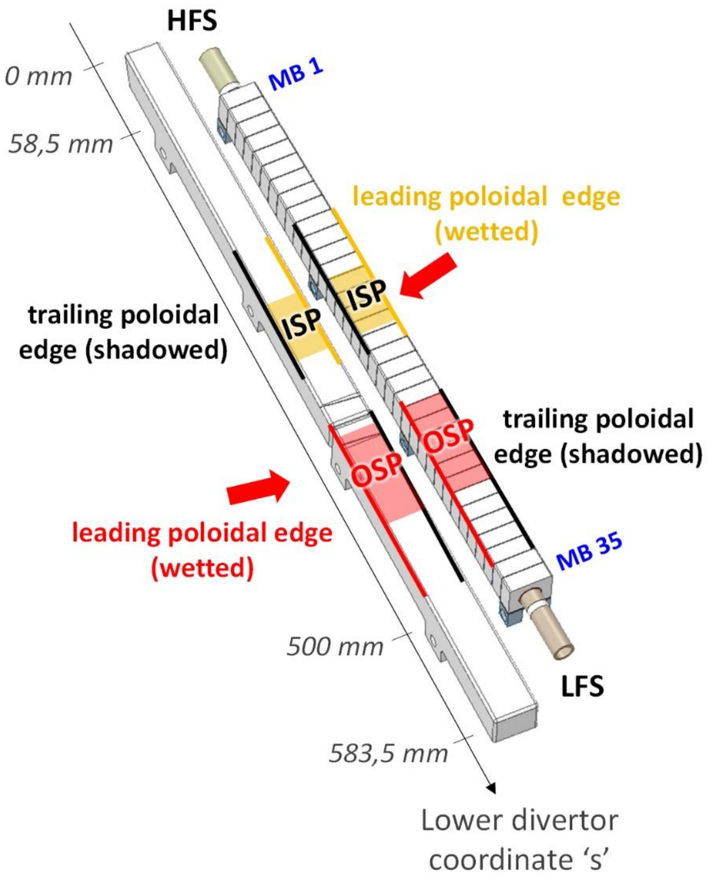
  → ITER-like PFUs exposed to 1 max ISP/OSP





Divertor heat load pattern simulated by PFCFlux for C4 (shot#55987 at 10s)

Significant plasma exposure of the targets during C3 and C4



Operating conditions during C3 and C4

- About 5,5 hours of plasma (2113 shots > 1s)
- Including a dedicated helium campaign (45min)
- L mode but with significant nb of transients (>2000 disruptions)
- 16 boronizations in total (3 in C3 ; 13 in C4)
- Heating power from 1 to 8 MW

From the point of view of the targets

- Subjected to heat loads up to 6 MW/m² (top surface)
- Base temperature : 70°C
- T_{surf} (bulk ITER-like PFU) < T_{surf} (inertial W coating tiles) = 300-700°C
- Thermal cycling from 70°C up to/above DBTT temperature (300-400°C for W)

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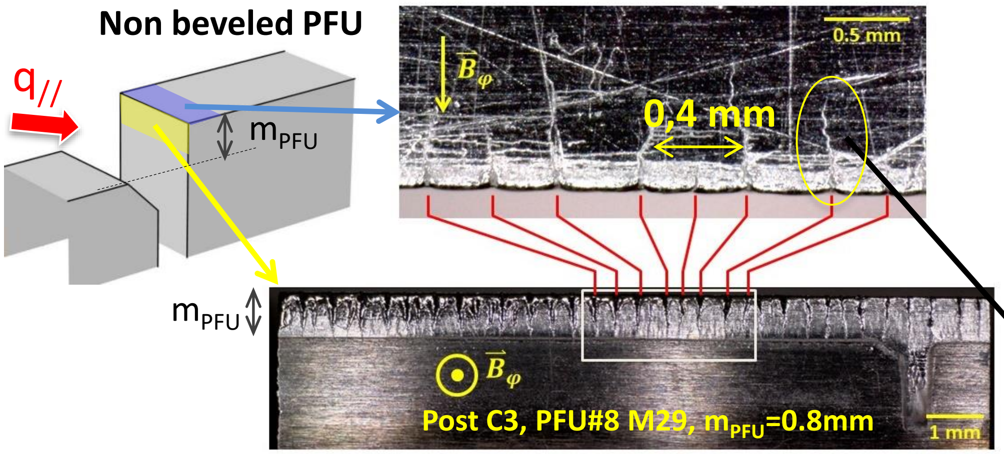
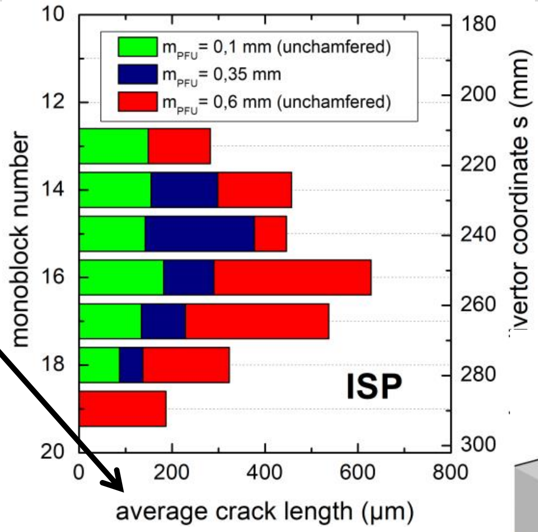
Misaligned edges directly exposed to plasma are prone to local cracking/melting

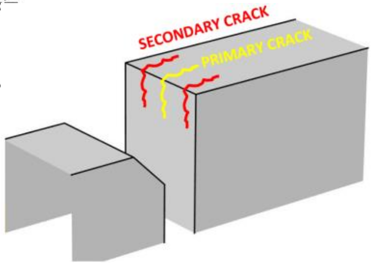
Non beveled PFU





[J.P. Gunn, NME 2021]

(see P. Reilhac at SOFT 2022)



- Regularly spaced cracks (≈0.4mm) and visual evidence of local melting at cracks edges on misaligned edges
- Crack length (top surf) consistent with misalignment m_{PFU} at ISP
- No crack propagation between C3 and C4
- Possible cause : brittle cracking of "cold" W (<DBTT) due to transients

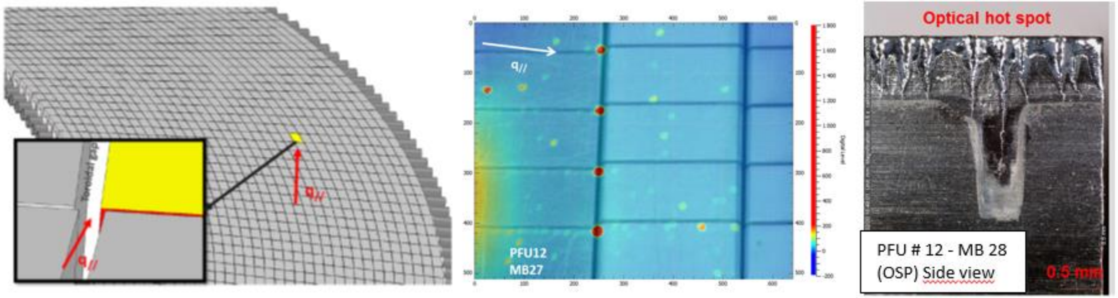
- In good agreement with simulation **[Durif, Phy Scripta 2022]**
  - Predict the number of thermal cycles to reach brittle fracture
  - Formation and propagation of cracks
- Next step for confirmation: post-mortem
- Leading edges in ITER protected by bevel -> WEST phase 2

Optical Hot Spots (OHS) predictions confirmed experimentally in the WEST tokamak !

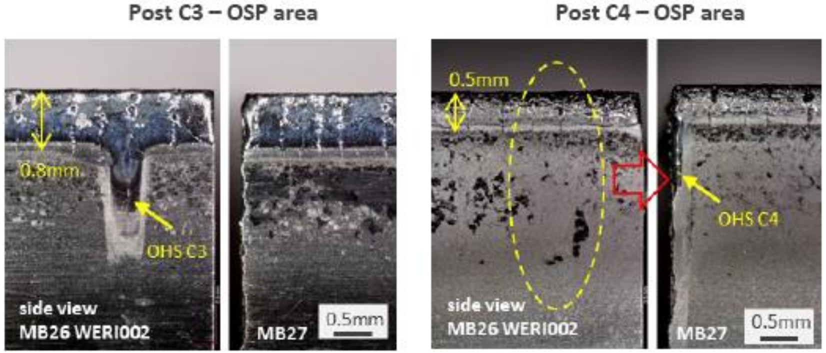
Optical Hot Spot = localized plasma-wall interaction (heat deposition on an isolated point) resulting from penetration of charged particles into the toroidal gaps

Observations

- Occurred where it was predicted by ion orbit modelling **[Gunn, NF 2017]**
- More likely caused by transient high flux events **[Gunn, NME 2021]**



[Diez, NF 2020]



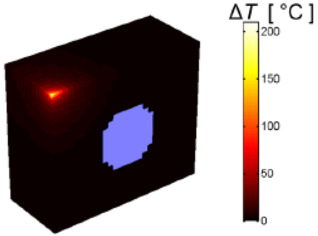
[Diez, NF 2021]

Evolution between C3 and C4

- Based on C3 observations, efforts were made to better align toroidal gaps in C4
- But new OHS formed on MB corner
- In SP areas : OHS formed in C3 did not evolve but were covered by thick deposits into the poloidal gaps

Impact for ITER ?

- Local melting expected on MB corner at every ELM **[Gunn, NF 2017]**
- Area of research during WEST phase 2



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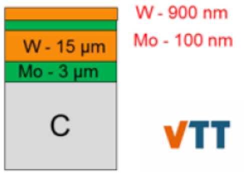
Type of targets

- W-coated erosion marker tiles
- Bulk W ITER-like PFUs

W-coated erosion marker tile



An international post-mortem program

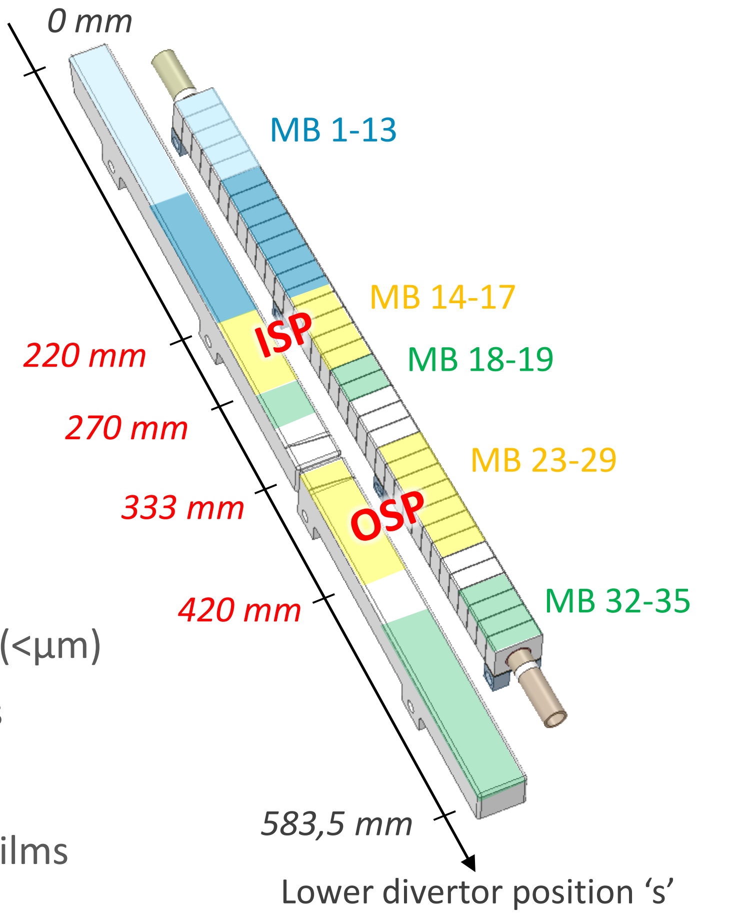
- Coordinated within WPPWIE
- 2020-2022: entire targets (ND tests)
- 2021-20XX: targets cutting (-> samples) + samples analysis

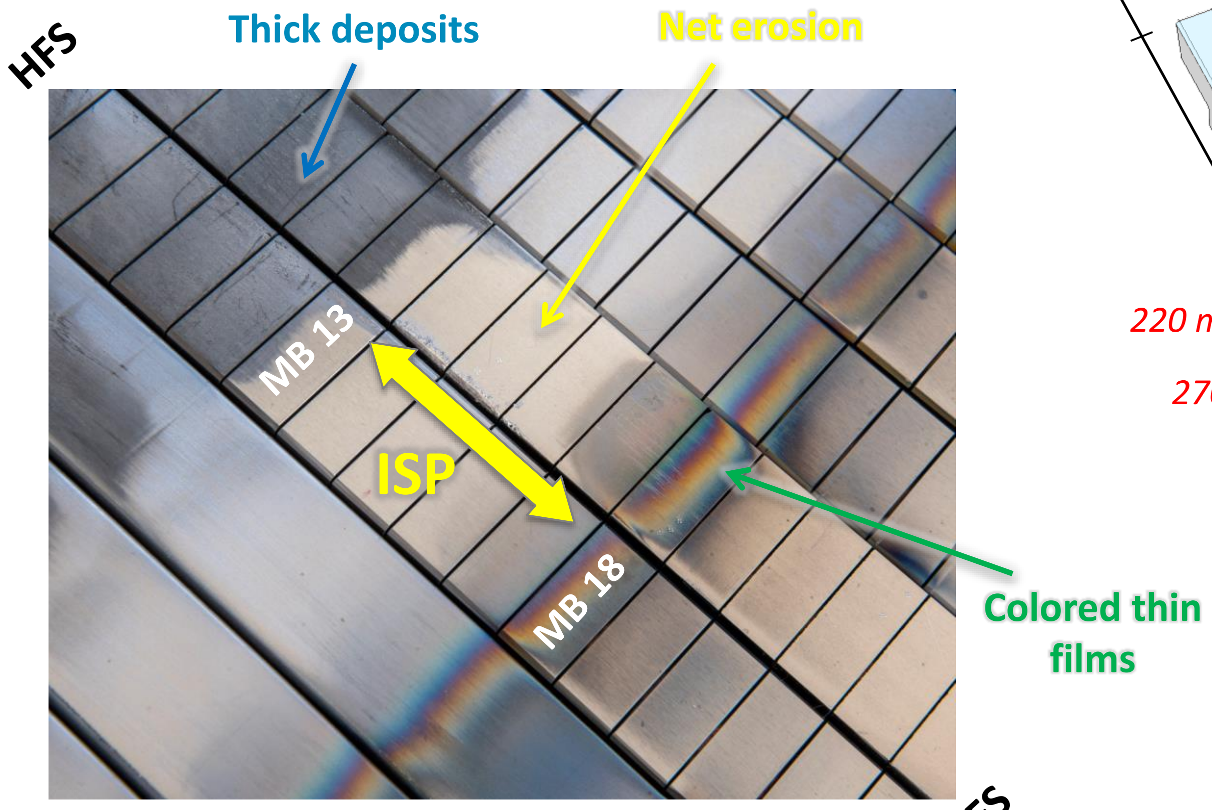
So far, the investigation has focused on:

- Thickness of the deposits
- Surface modification
- B,O,C,D inventory

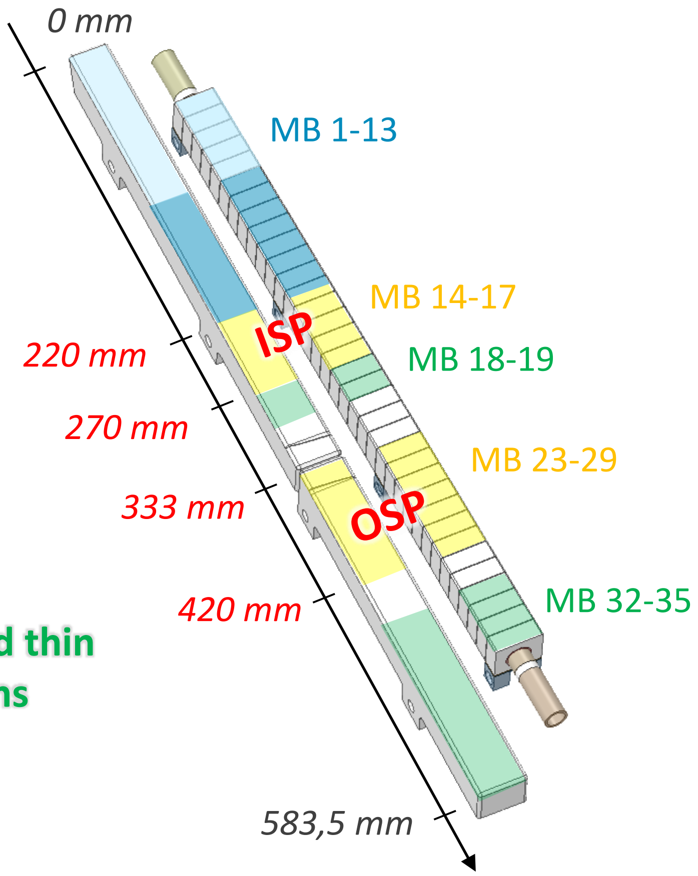
Aix*Marseille université · EUROfusion · VTT · Politechnika Warszawska · IPP · CORIA (UMR 6614, Complexe de Recherche Interprofessionnel en Aérothermochimie)

Thin deposits (<µm)
Thick deposits
Erosion
Colored thin-films





Photograph of the test divertor sector taken after C4



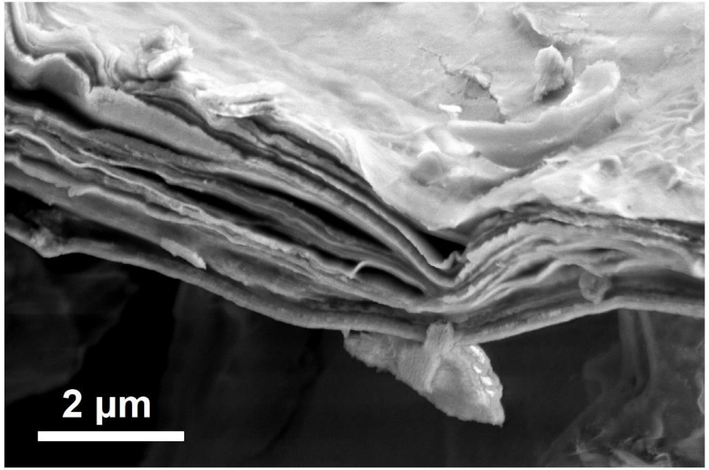
Thick deposits with a stratified structure mainly composed of W, O, C, B

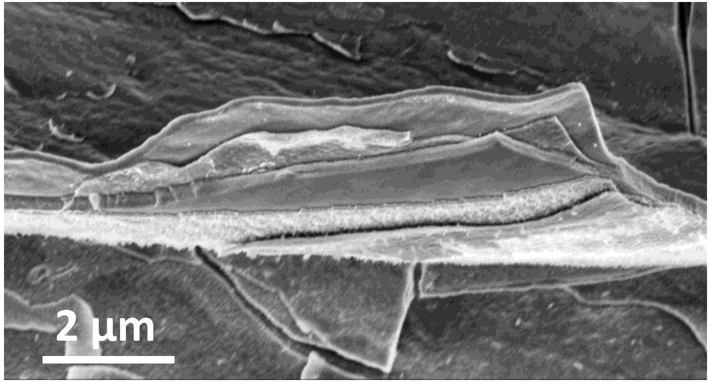
Morphology

- Multilayer structure
- Each layer has a different morphology, thickness and composition
- Same type of deposits on W-coated tiles and ITER-like PFUs

Content

- Main elements : W, O, C, B + oxides
  - B: 16 boronizations in C3+C4
  - C: PFCs substrate
  - O: during plasma exposure or/and air exposure
- Traces of :
  - stainless steel Fe, Ni, Cr (walls)
  - Ag (Faraday screen of the ICRH antenna)
  - Cu (LH antennas, PFC substrate)





Images of deposits found on the ITER-like PFUs

Multi-scale techniques to measure the thickness of the deposits (top surface)

1- 30 cm
resolution 0.1 µm

~ µm
resolution < 0.1 µm

~ µm
resolution nm

Aix Marseille université

Chromatic confocal microscopy

LIBS

CORIA

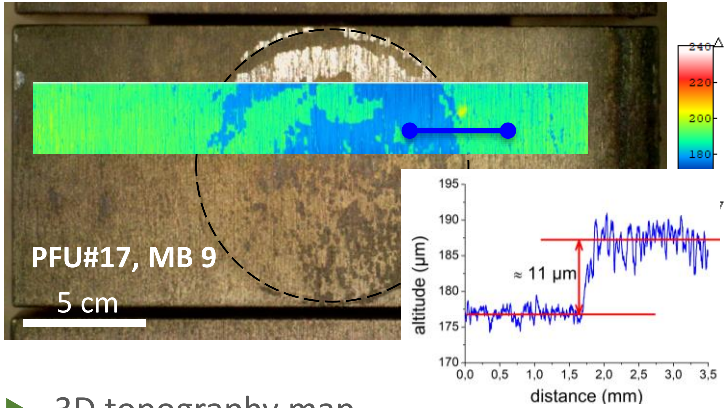
measurements on going

FIB/SEM

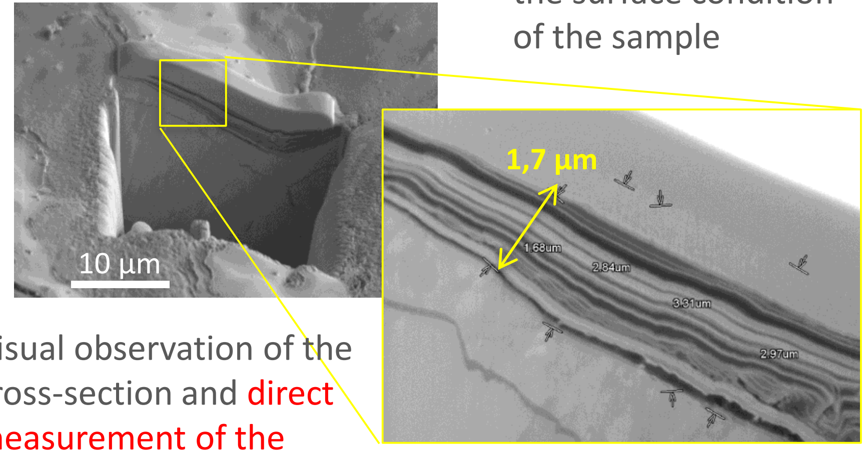
Politechnika Warszawska

IPP

- Very local, does not necessary represent the surface condition of the sample



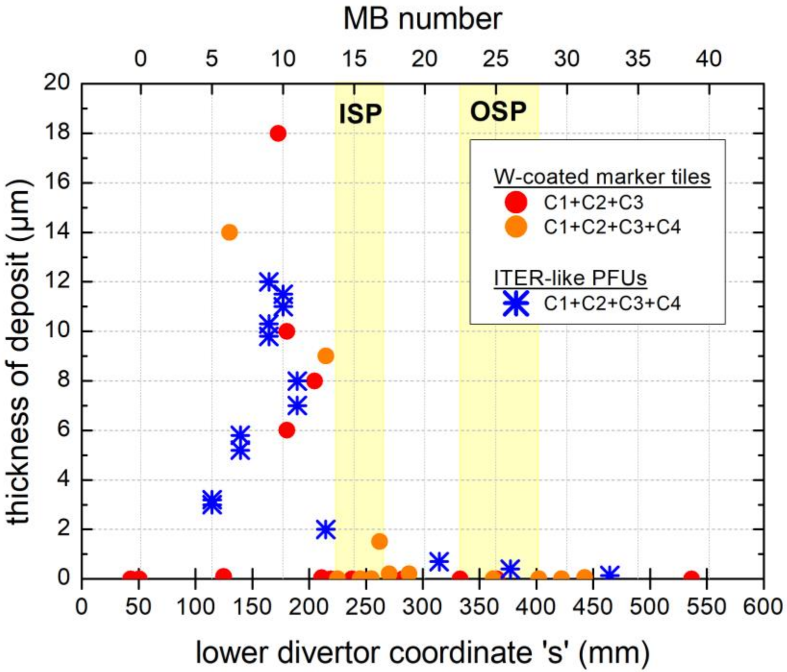
- 3D topography map
- May minimize the thickness

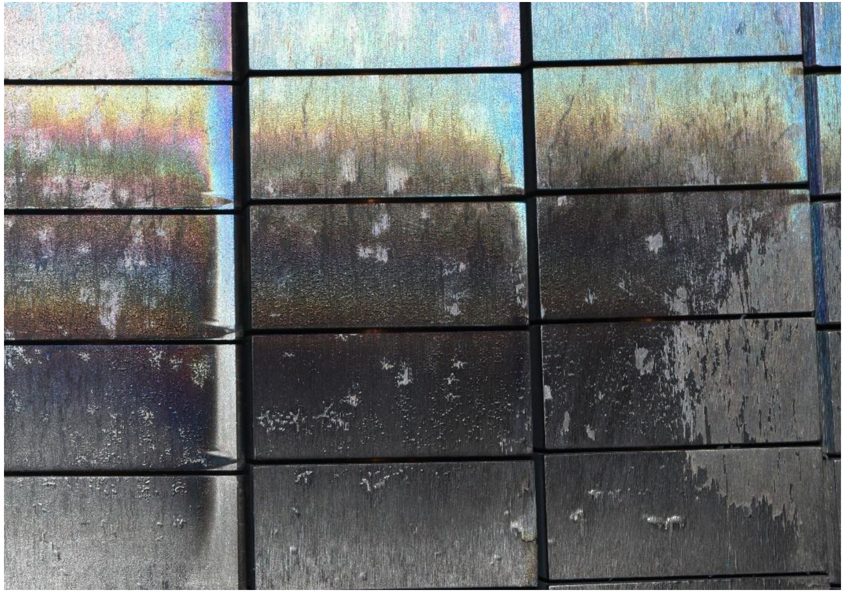


- Visual observation of the cross-section and direct measurement of the deposits thickness

FIB= Focused Ion Beam
SEM = scanning Electron Microscope

Deposition of thick layers in the shadowed HFS of the divertor ; moderate in LFS

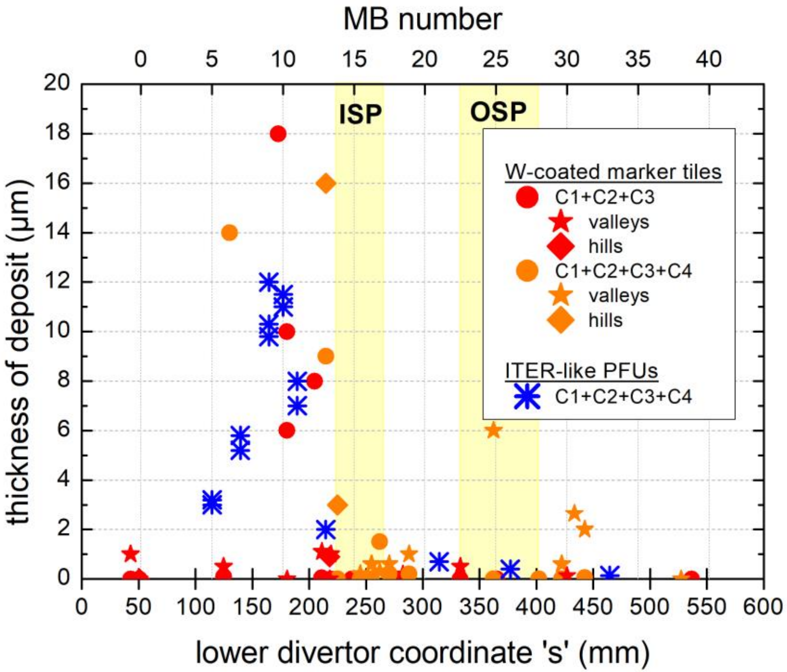




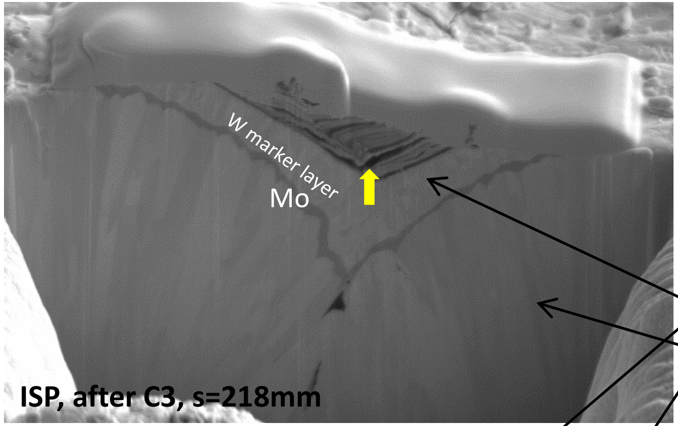
In-situ photograph of test divertor sector taken right after the end of C4

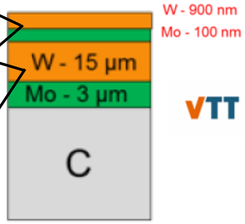
- Thickness > 10µm after ≈ 5.5 h of plasma
- Campaign-averaged deposition rate at least 0.5 nm/s
- Thick deposits may cause operational issues (flaking)

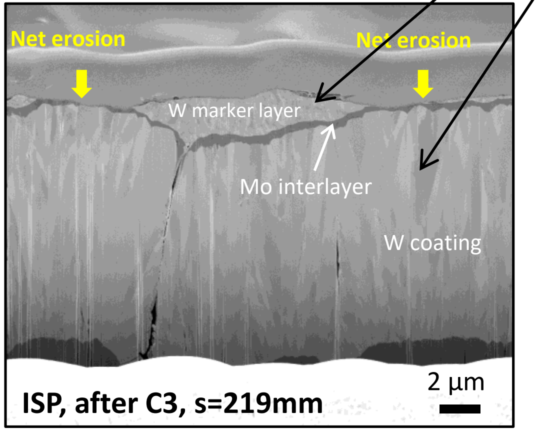
Local effects occur due to surface roughness



Surface roughness of W-coating tiles ≈ 2-3 µm







- Deposited layers found in the valleys
- Same type of deposits in the valleys as in HFS
- W marker layer (1-2µm) totally eroded at top of the hills

→ net erosion rate W coating at ISP/OSP: 0,1-0,5 nm/s (≈AUG)

Level of O, B and D in the redeposited layers in good agreement with the operation

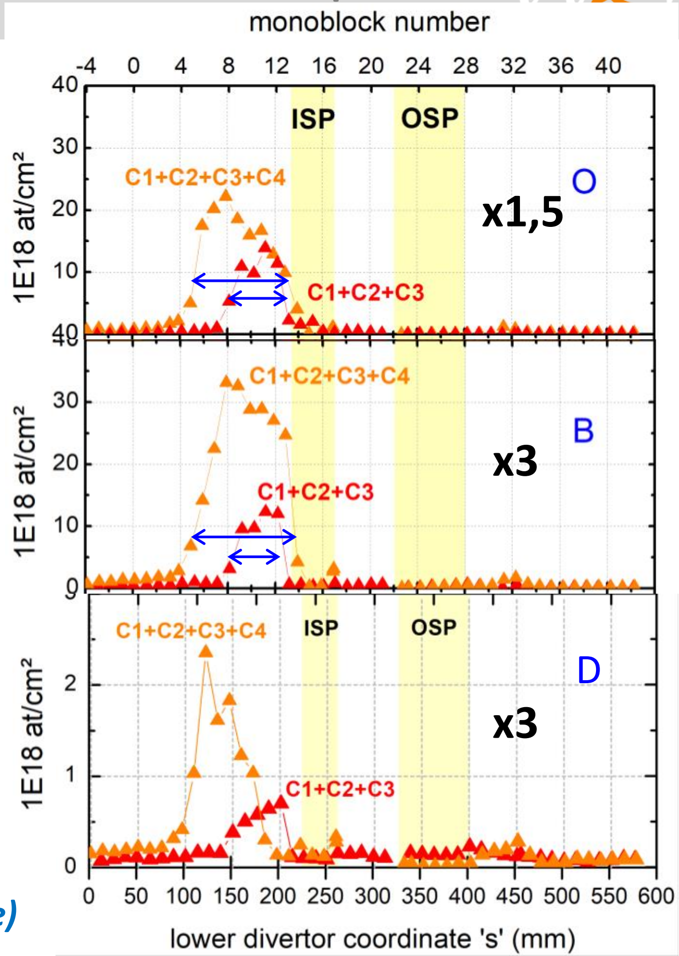
Impurities content

- O, B found in the HFS
  → good correlation with FIB/SEM and confocal microscopy results

- Expansion of redeposition area between C3 and C4
- Amount of B multiplied by 3 between C3 and C4
  → good correlation with the operation and conditioning

Deuterium content

- D inventory mainly found in the deposits
- Shift of D deposition between C3 and C4
- Amount of D multiplied by 3 between C3 and C4 in the deposits on the W coated tiles ↔ more porosity in C4 deposits, acting as traps for D?



Similar results obtained on ITER-like PFUs (work on going ; not shown here)

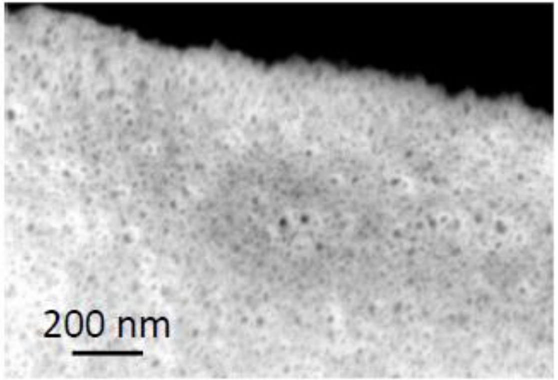
Helium campaign

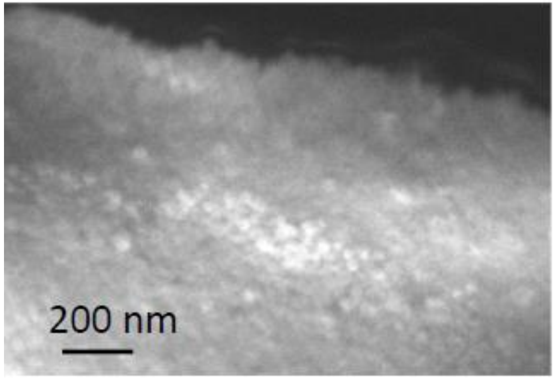
- 45 min He plasma exposure
- Goal : W fuzz formation at OSP on W-coated tiles
- Conditions required for W fuzz formation marginally reached (T, E_{inc} He fluence)

→ Observations so far:

- He implantation (10 at.%) in OSP erosion-dominated area (W-coated tiles)
- No indication of W fuzz or He nanobubbles so far in OSP area

- However, observation of nanocavities filled with gas in W dust collected after C4





[Private comm., C. Arnas, PIIM]

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Conclusion and perspectives

Local modifications

- Local cracking and melting were evidenced on exposed poloidal leading edges in addition to optical hot spots, although it was not detrimental for the operation of WEST.

→ will it be an issue for ITER with toroidal-bevelled targets ? Efforts on simulation are required ! WEST phase 2 will also give some answers

Material migration

- Deposition was mainly found in HFS of the divertor with W, O, B, C-rich layers with thickness >10 µm. The large source of light impurities (C,O) is not clearly understood. D has largely diffused into the deposits.

- A net erosion rate of 0,1-0,5 nm/s was found at ISP/OSP, despite local effects due to surface roughness.

- Although there is no clear evidence of W fuzz formation so far, helium is shown to be implanted in OSP eroded area in C4 marker tiles (≈10%)

→ investigation continues through samples analysis and future cutting of bulk PFU planned this year

- Thick deposited layers up to 10µm were found into the poloidal gaps while plasma-W interactions were observed into toroidal gaps (work on going, not presented here)

→ modelling of W transport needed !

Thank you for your attention