EUROfusion

MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

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Overview of erosion/deposition patterns on WEST PFUs, including the role of magnetic ripple

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Content

- **Introduction and remarks to WEST**
  - Analyses of wall tiles to obtain erosion/deposition pattern of WEST
  - Some basic info's to WEST (inside views, ripple, tiles…)
- **Tiles and analyses**
  - Special marker tiles; standard tiles; ITER-like plasma-facing unit (PFU)
  - Some remarks on analyses of entire tiles and data evaluation
- **Results of ion beam analyses and microscopy**
  - Deposition pattern and erosion on marker tiles
  - Erosion pattern by ripple
  - Further topics:
    - Strong deposition variation by ripple ?
    - Arcing
    - Deposition into poloidal gaps
    - Remarks to small sample analyses
- **Take home messages**
  - Main results & future work

Introduction

- **Determine the erosion/deposition patterns on tiles exposed in WEST**
  - **Entire** W-coated graphite tiles
    - Erosion: by coating thickness measurement with IBA (RBS) and SEM on FIB-cuts
    - Deposition: by IBA (RBS & NRA) and SEM with EDX
  - **Segments** of ITER-like plasma-facing units (**PFU**s)
    - Deposition: by IBA (RBS & NRA) and SEM with EDX

- **Part of a larger task in WP PWIE SP B**
  - Many labs involved

→ Mostly on smaller samples cut from the graphite and ITER-like PFUs
→ More detailed, complimentary and confirming analyses
→ Behaviour of W monoblock, e.g., cracking

IBA = Ion Beam Analysis
NRA = Nuclear Reaction Analysis
FIB = Focused Ion Beam

RBS = Rutherford Backscattering Spectrometry
SEM = Scanning Electron Microscopy
EDX = Energy Dispersive X-ray spectroscopy

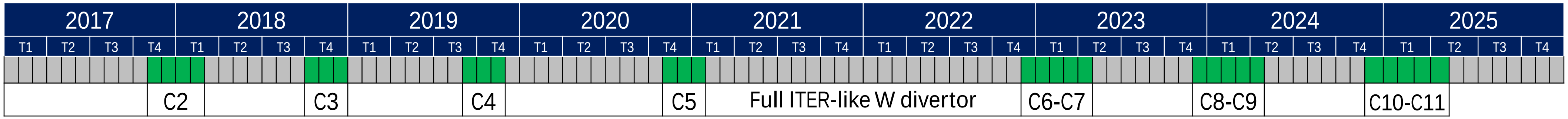
Remarks to WEST

- **WEST project**
  - Devoted to test W divertor technology for ITER [1-3]

[1] **T. Hirai 2013** Fusion Eng. Des. 88
[2] **J. Bucalossi 2014** Fusion Eng. Des. 89
[3] **B. Bourdelle 2015** Nucl. Fusion 55

- **Reconstruction of “Tore Supra” (major changes)**
  - Located at CEA, Carderache, France
  - Operation: 1988–2012 as carbon-based limiter tokamak in L-mode
- **1st operational phase of WEST project**
  - 2016–2021 in 5 campaigns **C1–C5**
- **2nd operational phase of WEST project**
  - 2022–ongoing

C1 – C3: ~2.5 h
C1 – C4: ~6 h
C1 – C5: ~7.5 h



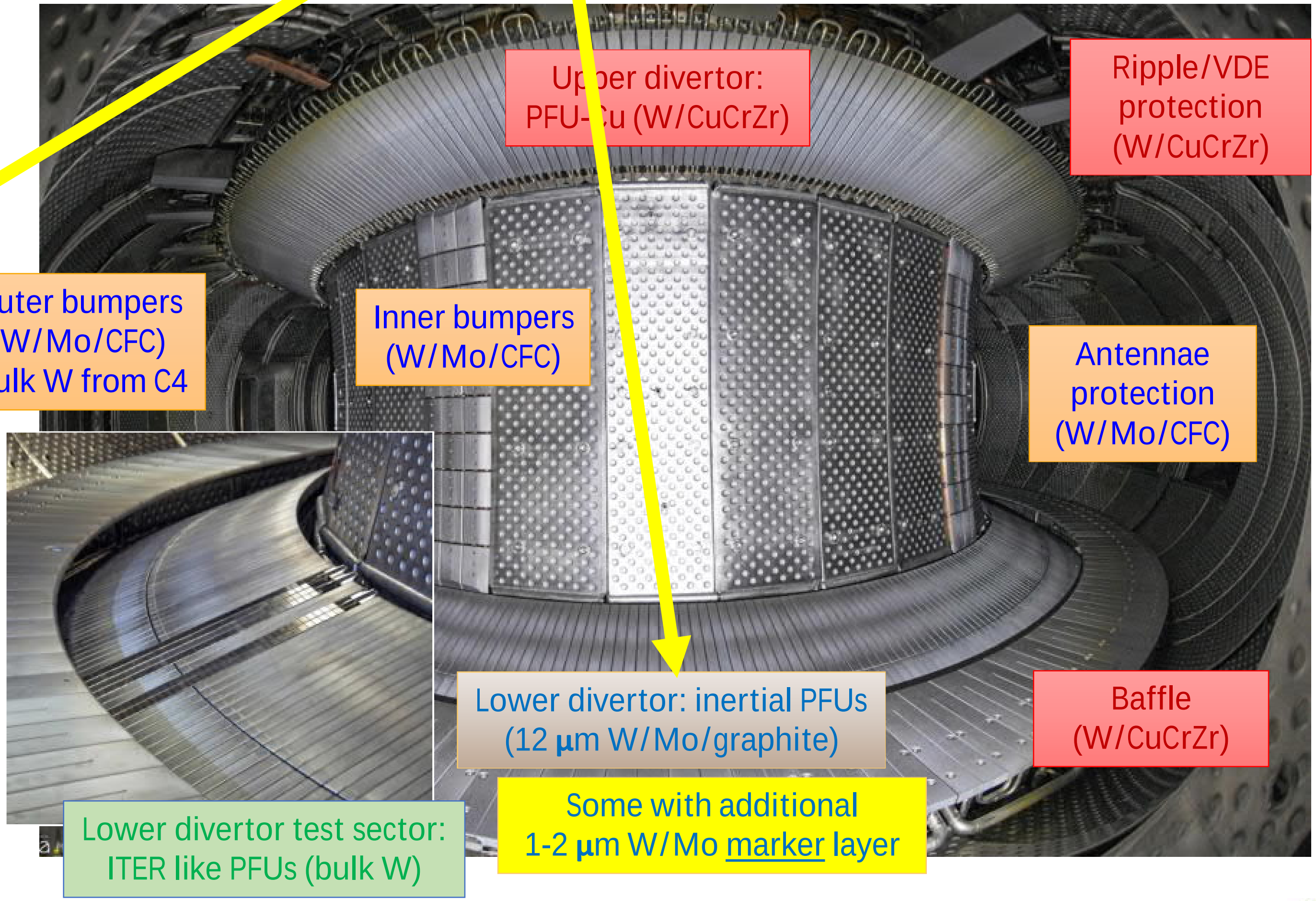
~1500 s **~7500 s** **C4-D: ~10000 s** **~4500 s**

C4-He: ~3000 s

Remarks to WEST

- **WEST project**
  - Start 2016 with all plasma-facing surfaces covered with **tungsten**
- **Divertor**
  - Inertially cooled W-coated graphite tiles *(bevelled !)*
  - Successively increased number of ITER-like PFUs with campaigns
- **Structure**
  - 12 sectors *(Q1..6A/B)*
  - Each composed of 38 PFUs
  - PFUs:
    - *- ITER-like: 35 W monoblocks*
    - *- W-coated graphite PFUs: **2 tiles***

Opportunity of mounting special marker tiles



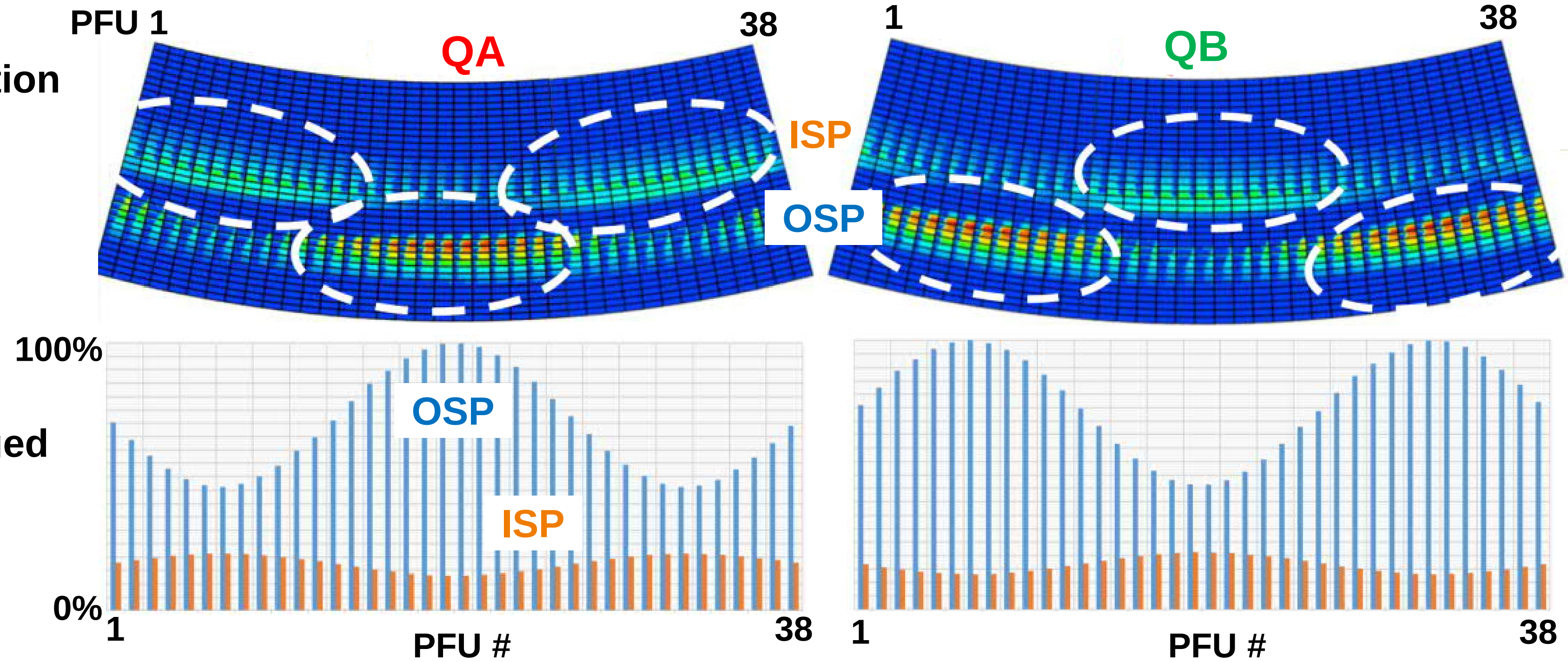
Remarks to WEST

- A <u>ripple</u> on magnetic field exist due to pre-existing arrangement of coils (Tore Supra)
  ⇨ Toroidal modulation of particle & power flux along strike lines

- "PFCFlux" simulation of heat load deposition [1,2]

  → 18 peroiodes around the torus

- Normalized averaged incident flux over wetted area



- Choice of positions of marker tiles and special ITER-like PFUs depends on ripple!

[1] Firdaouus 2013 JNM 438, [2] Firdaouus 2015 FED 98-99

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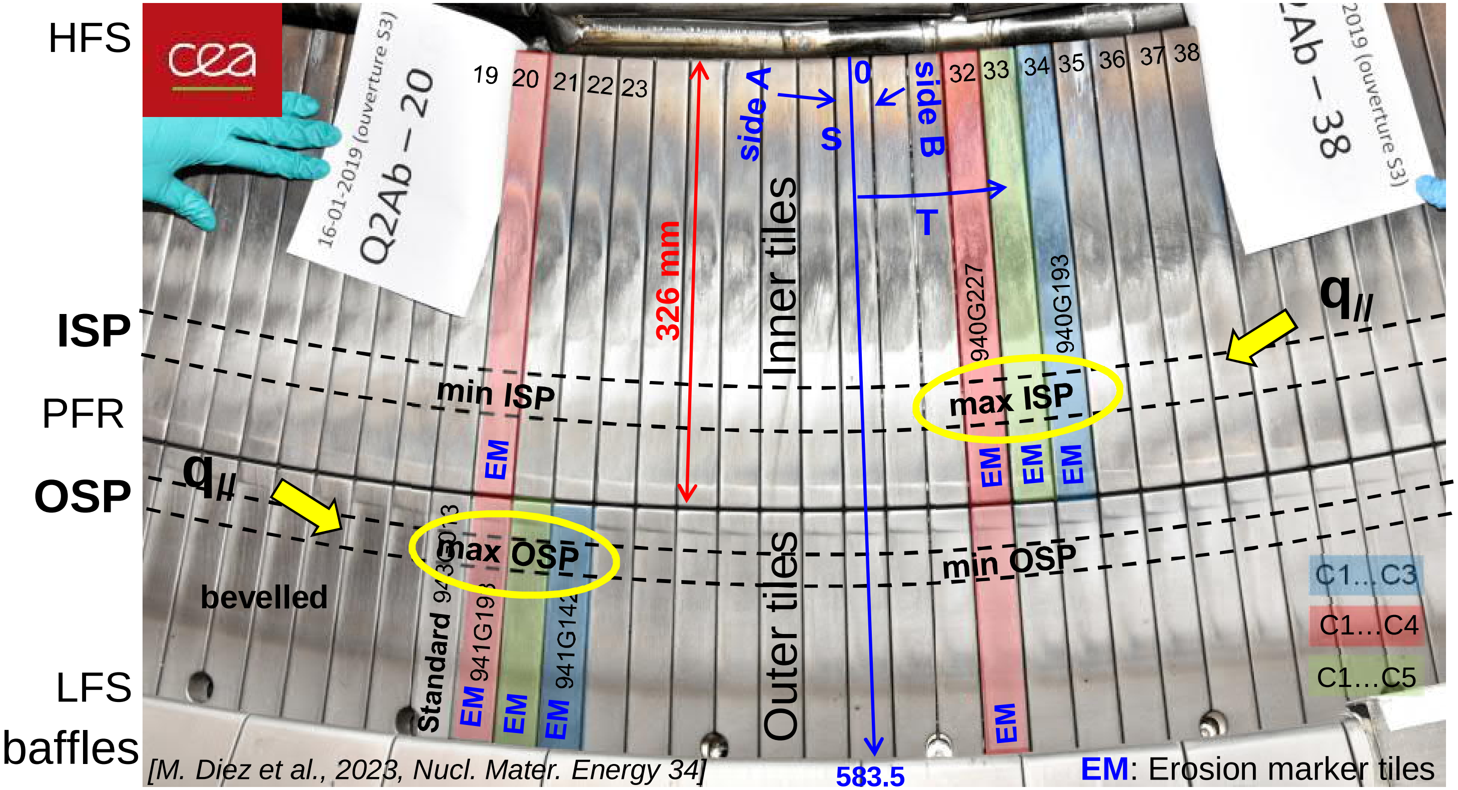
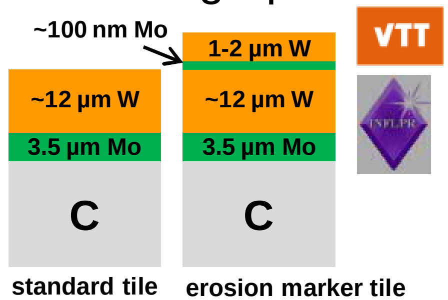
Tiles for analyses: A) C3, C4 & C5 marker tiles

➢ **Divertor sector equipped with marker tiles after C3 campaign**



- Inertially cooled W-coated standard graphite tiles

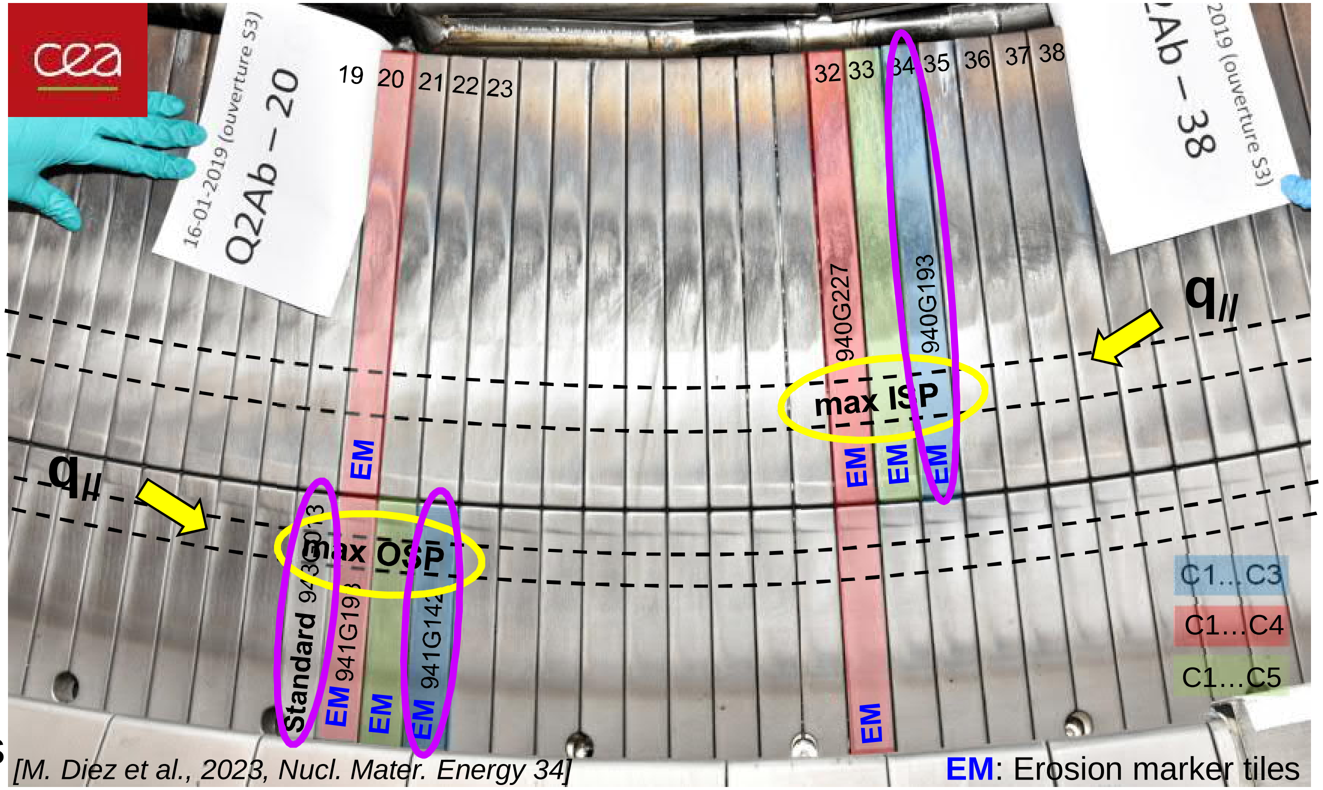


- 8 erosion marker tiles installed in WEST phase 1
- Successively dismounted
  - "**C1-3**": 2
  - "**C1-4**": 4 *(only 2 analyzed)*
  - "**C1-5**": 2
- IBA along central line (T=0)

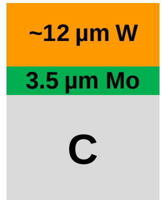
➢ **Position of marker tiles at max flux area of strike line (ISP & OSP) due to the ripple**

Tiles for analyses: B) C4 standard tiles

➢ **Divertor sector equipped with marker tiles after C3 campaign**



- Inertially cooled W-coated standard graphite tiles



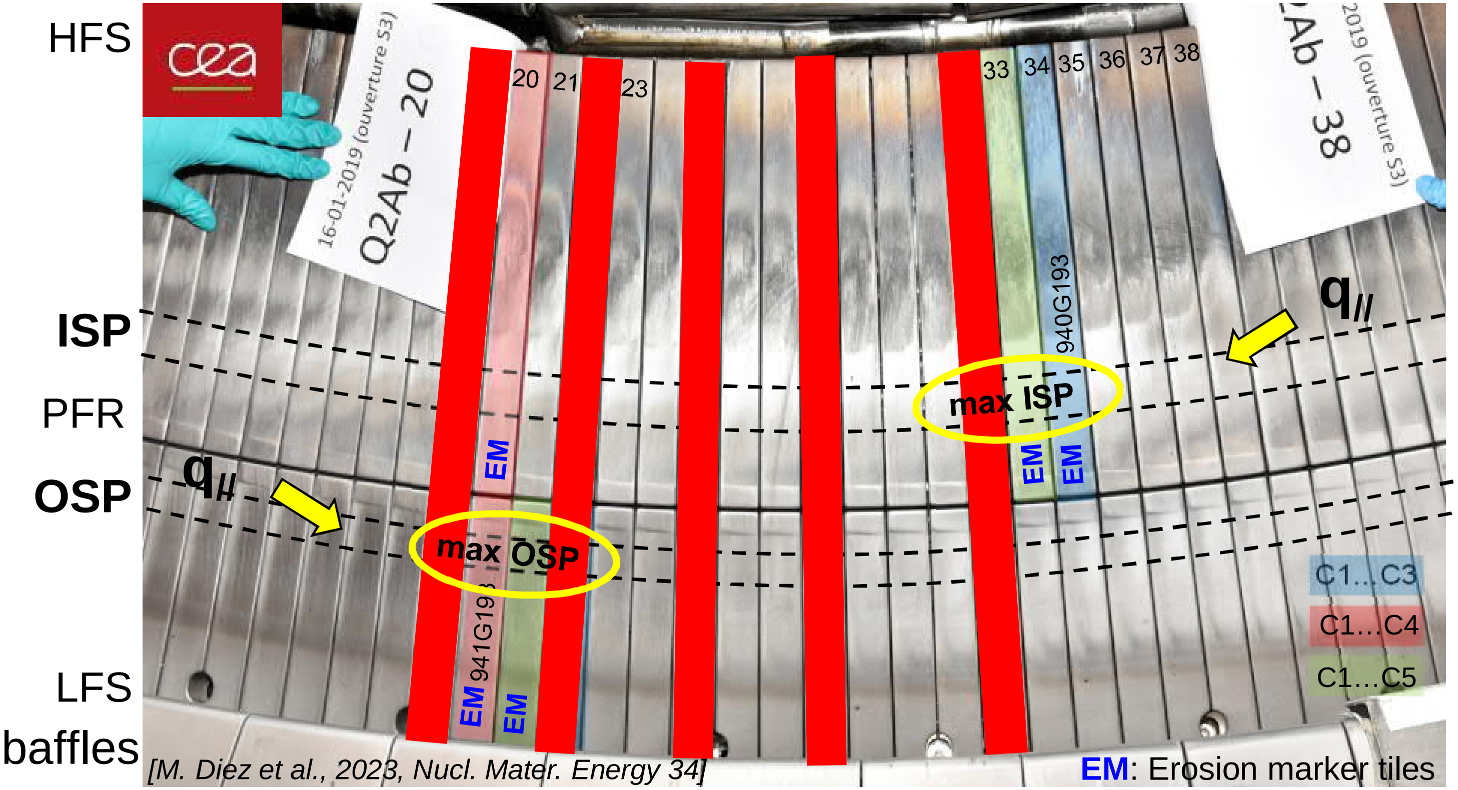
standard tile

- 2 standard tiles exposed to **only C4**
  (same position as C3 marker tiles)

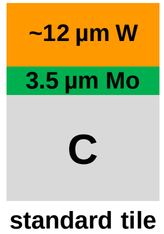
- 1 standard tile exposed to **C1-C4** beside marker tiles

Tiles for analyses C) C5 standard tiles ("ripple samples") + spare tile

➢ **Divertor sector equipped with marker tiles after C3 campaign**



- Inertially cooled W-coated standard graphite tiles



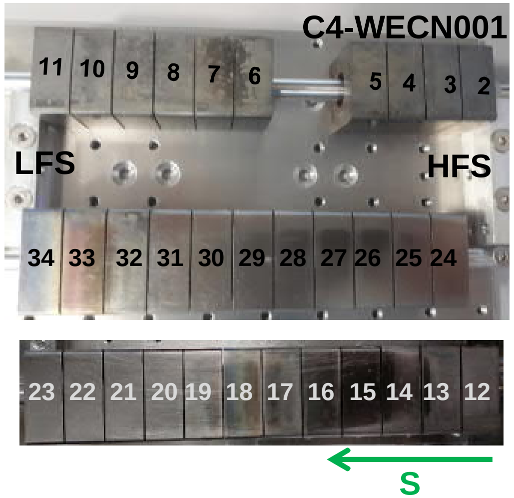
- 10 standard tiles from sector 3QA: "C1-5" → **study ripple effect**

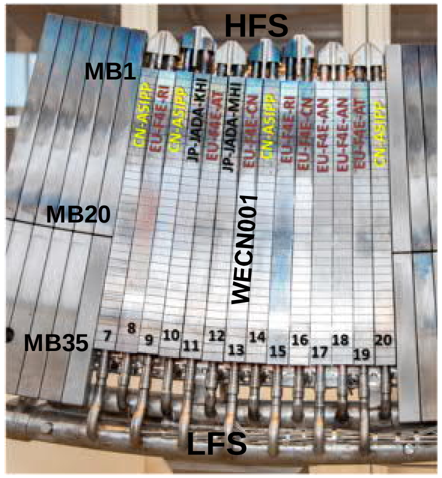
- Inner and outer unexposed **spare** tiles

➢ **5 position of standard tiles over one period of the ripple** (1/18 of full circumference)

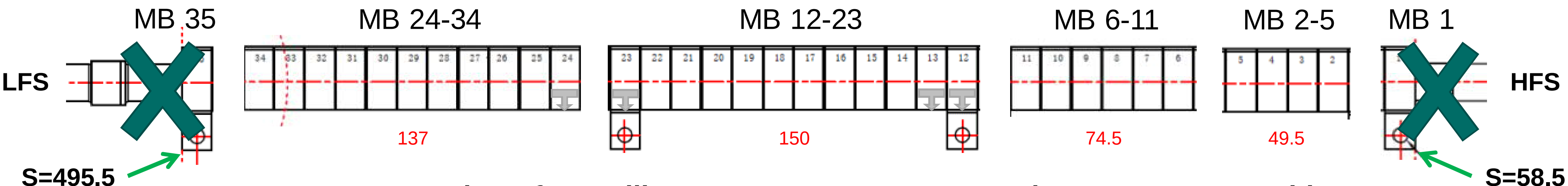
Tiles for analyses: D) segments from ITER-like PFU

- **ITER-like PFU from phase 1**
  - Exposed to C3-C4
  - Cut in segments *(and smaller sample)* by CEA
  - Measurement of deposits (& D)
    → *other labs: smaller samples* → *He content*
    Note: cracking studied
- **Future: ITER-like PFUs from Phase 2**
  - Plus: Erosion measurement only at special prepared/pre-characterized W monoblocks → *see M. Diez invited talk at PFMC*
  - Cutting small sample + detailed analyses





View on side B



$S = MB\#_{mid} \times 12.5 + 52$

Segmenting of ITER-like PFU "WECN001" mounted C3-C4 at PFU position #13

Tiles and analyses

➢ Which information should be gained?

- Erosion and deposition pattern on WEST tiles:
  - *- **Quantification of <u>erosion</u>** & determination of **composition and thickness** of deposited material*
  - *- Are the expectation from **optical inspection** regarding regions of erosion and deposition correct?* **Not always !**
  - *- Do other astonishing features exist?* **Yes, arcing !**
  - *- Is **"fuzz"** formed during the He-phase end of C4 campaign?* **No ! (only bubbles)**
  - *- Can something be learnt about the progression (C3 – C4 – C5) of erosion/deposition* **Yes ! (mainly between C3 an C4)**
  - *- What can be learnt for the deposition onto side of tiles, i.e., into the gaps?* **??**

➢ Which methods used for analyzing entire tiles?

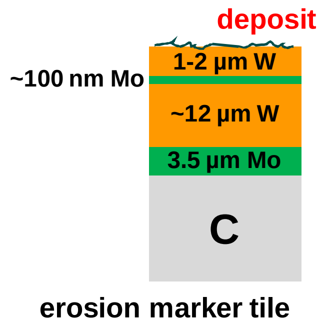
Entire/large tiles

- **I**on **B**eam **A**nalyses (**IBA**):
  Rutherford **B**ackscattering **S**pectroscopy (**RBS**) and
  Nuclear **R**eaction **A**nalyses (**NRA**)
  } **<u>Quantified</u>** amounts of W, B, C, O, D (N) (depth profiles)
- **S**canning **E**lectron **M**icroscopy (**SEM**) assisted by
  Energy **D**ispersive **X**-ray spectroscopy (**EDX**) and
  Focused **I**on **B**eam cutting (**FIB**) of cross-sections
  } Surface & layer morphology and elemental composition on microscopic length scale
- **C**onfocal **L**aser **S**canning **M**icroscopy (**CLSM**) } Height profile on microscopic length scale

Ion beam analyses: RBS & NRA

➢ Measurement positions

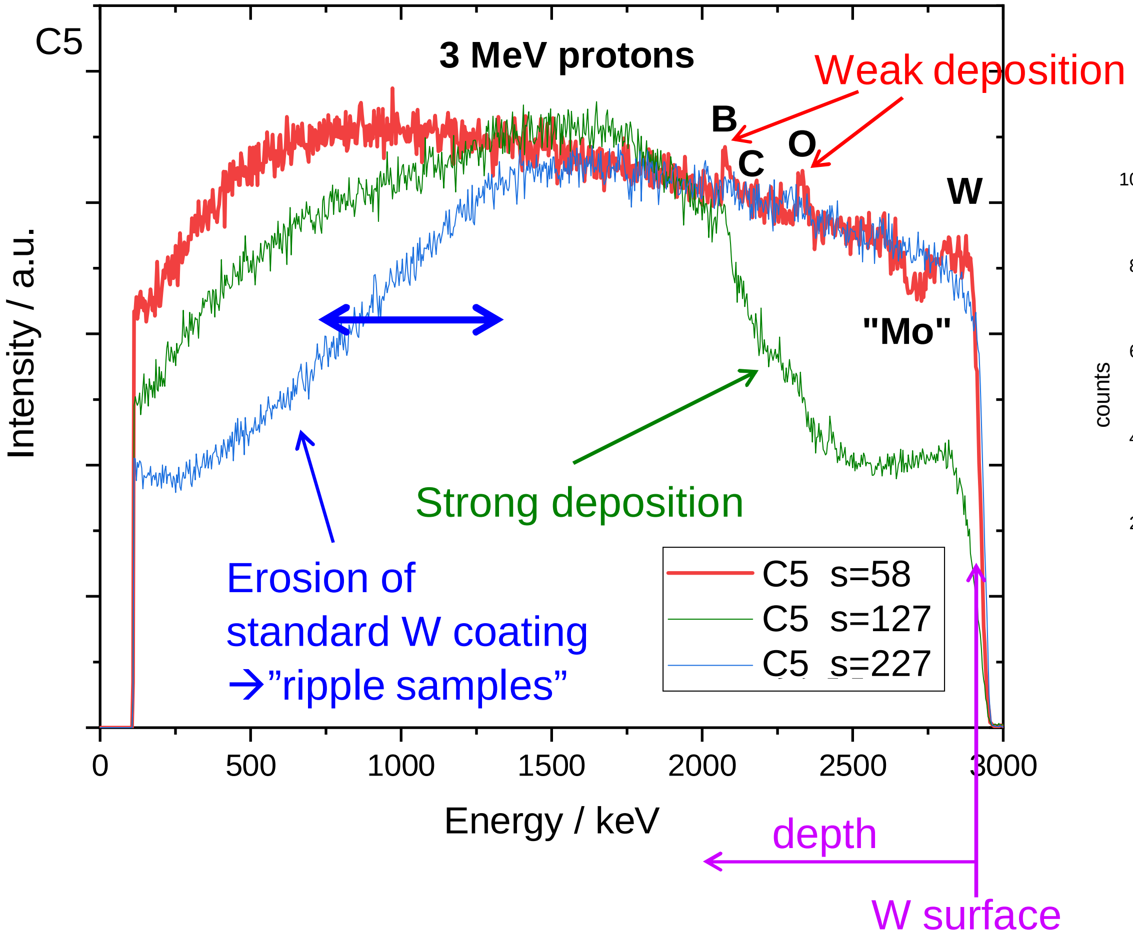
- At least, poloidal scan along **central line** (T=0) **every 12.5 mm** (MB-width)
- Additional toroidal and poloidal scans, especially on “ripple” samples
- Spot size area **~2 mm²** *(positioning accuracy ~1 mm)*

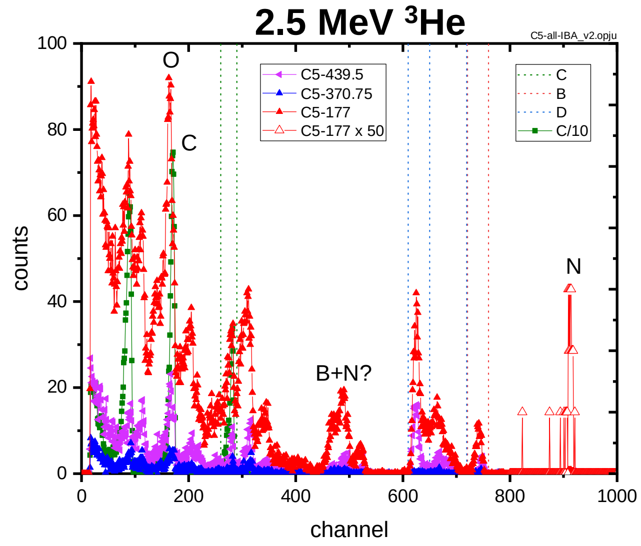


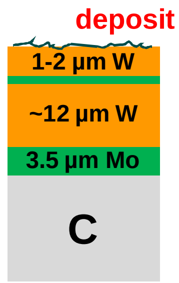
➢ IBA conditions

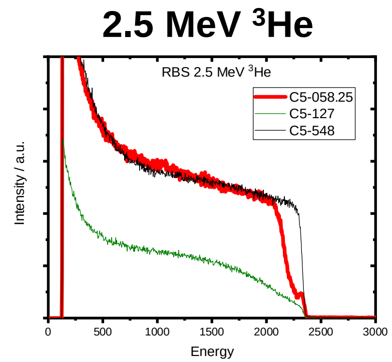
- Combination of RBS/NRA **3 MeV protons** at 165° & **2.5 MeV ^{3}He** at 150°
  → Thickness of W above Mo-marker layer and thickness + composition of deposit
- Only RBS with **4 MeV protons** at 165°
  → Thickness of everything above graphite substrate

IBA evaluation: Examples of RBS & NRA spectra









- **Fitting all three data consistently**
  - Ratio of light element extended <u>beyond</u> information depth of NRA to fit proton RBS
  - He-RBS only useful for thin deposition

  → quantified depth profiles

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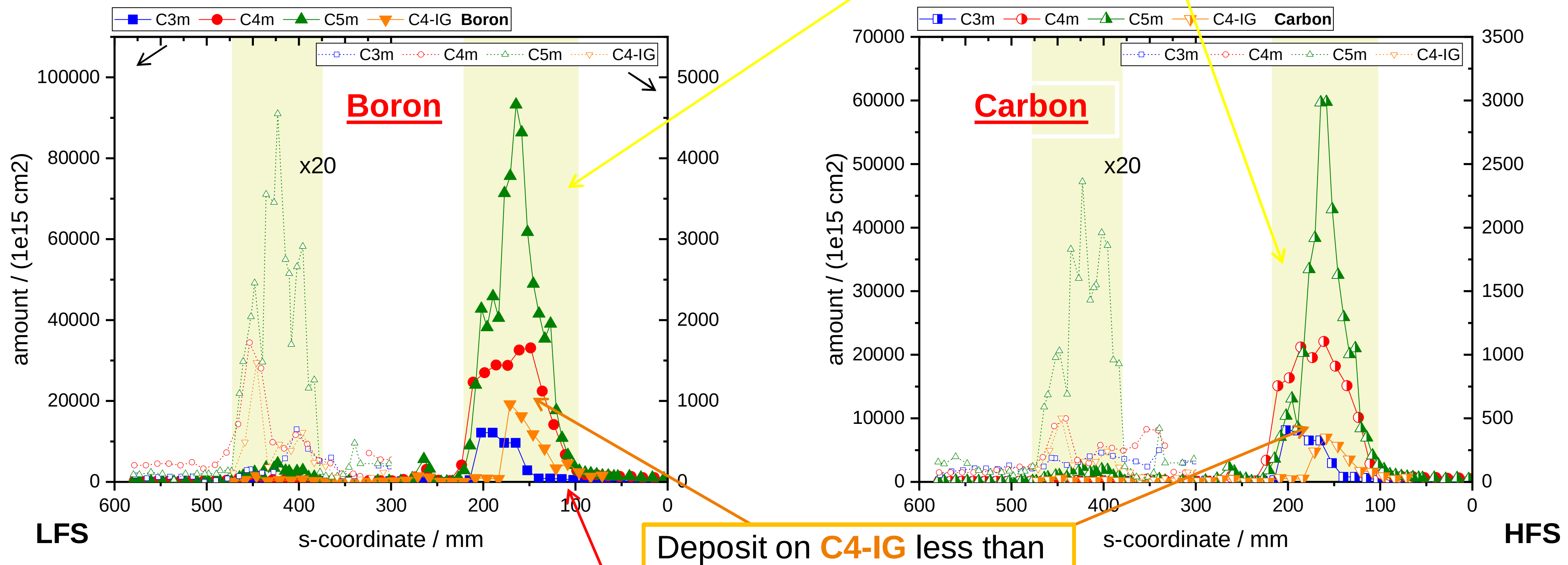
IBA results: Deposition pattern

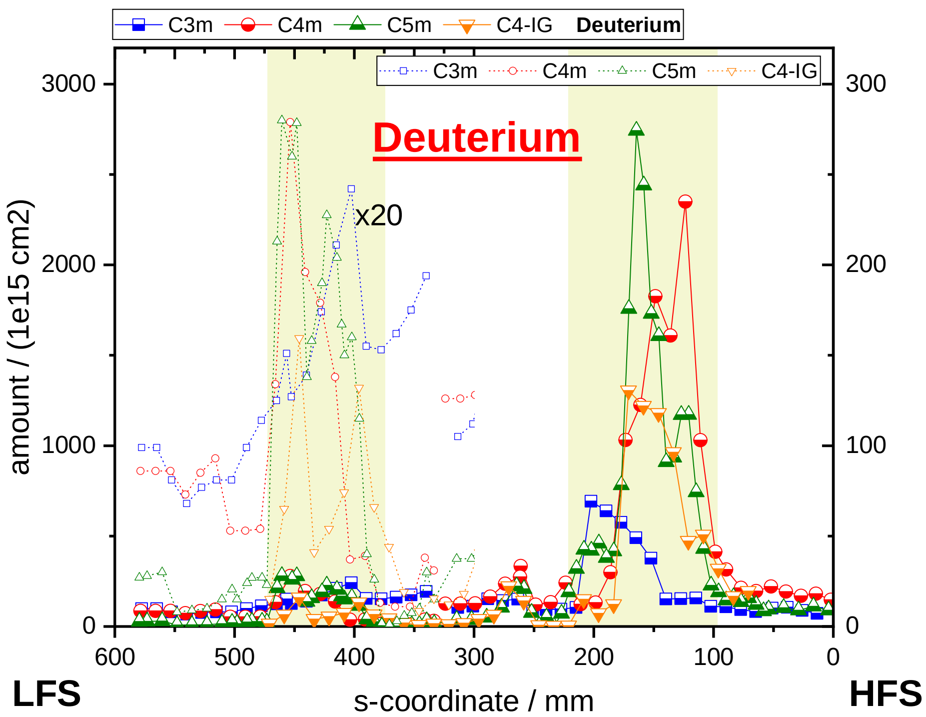


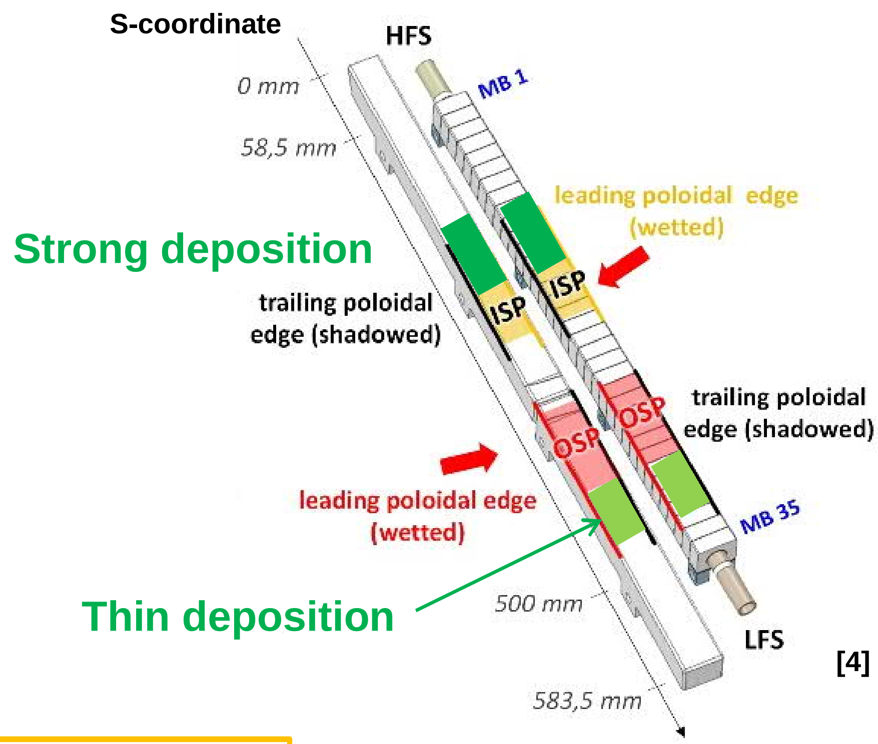
C1 – C3: ~2.5 h
C1 – C4: ~6 h
C1 – C5: ~7.5 h

- C3/C4 marker data: published [1-4]
- C4 ITER-like PFU: published [4,5]
- C5 unpublished / in preparation

[1] **Balden 2021** Phys. Scr. 96
[2] **Hakola 2021** NF 61
[3] **Bucalossi 2022** NF 62
[4] **Diez 2023** NME 34
[5] **Martin 2021** Phys. Scr. 96

IBA results: Deposition pattern – Deuterium



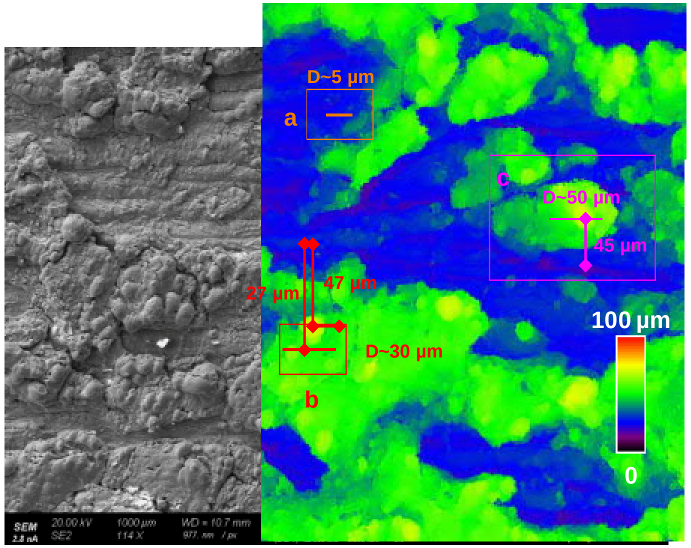


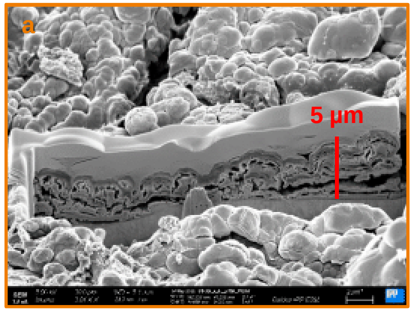
- C3/C4 marker data: published [1-4]
- C4 ITER-like PFU: published [4,5]
- C5 unpublished / in preparation

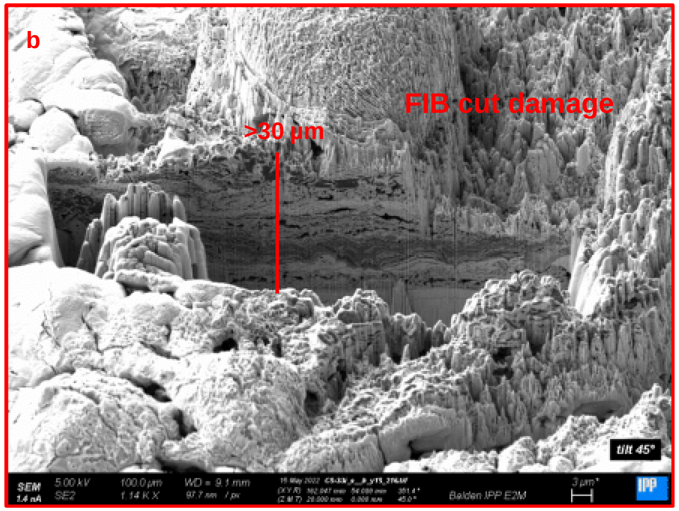
- Deuterium mainly follows deposit
- Tail into W layer visible

[1] **Balden 2021** Phys. Scr. 96
[2] **Hakola 2021** NF 61
[3] **Bucalossi 2022** NF 62
[4] **Diez 2023** NME 34
[5] **Martin 2021** Phys. Scr. 96

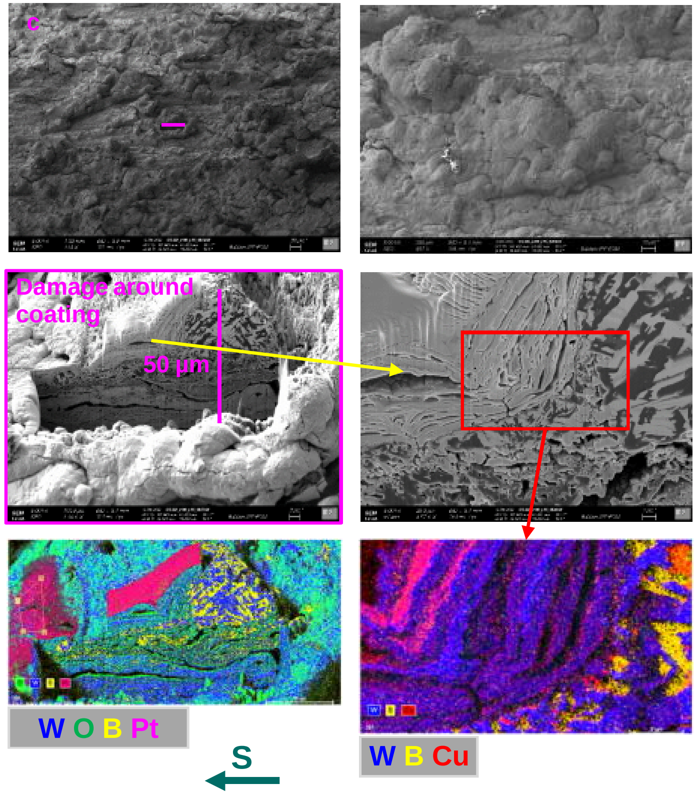
SEM results of inner divertor marker tile: Example C5-marker, S=200

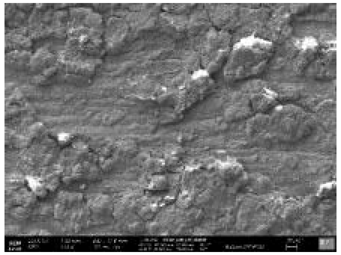


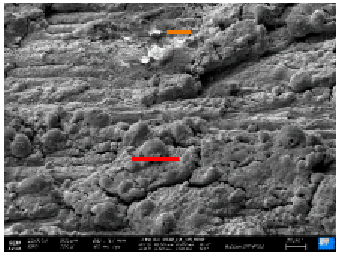




Confirmed by analyses on small samples





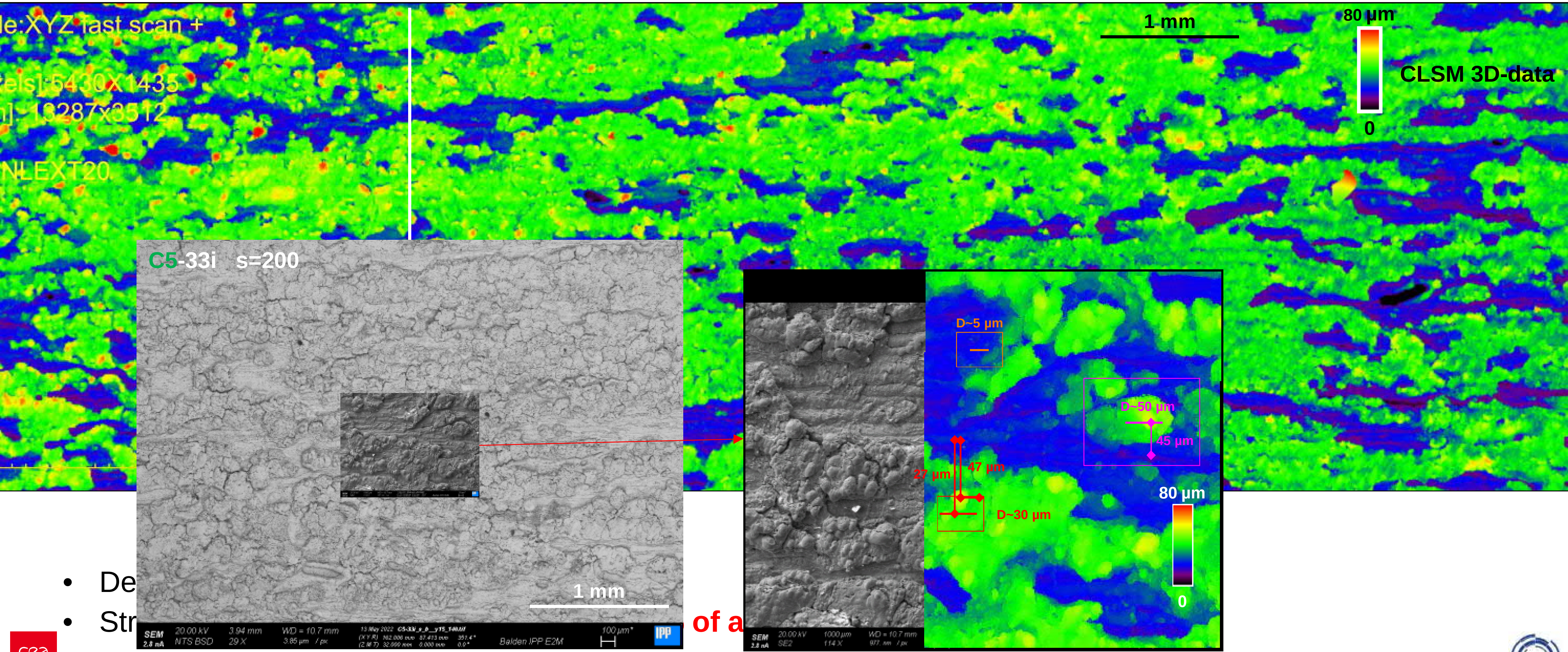


- Deposit thickness: Around **50 µm**
- Strong delamination of thick deposit (**25-30% of area**; 30-40 µm)! → **by arcing**

Arcing – delamination deposit + deposition

S

C5-33i s=200 toroidal center



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- Str … of a

Thickness of deposit from FIB cuts

- **Increase of thickness with accumulated fluence ?**
  - Thickness of deposit for "**C4only**" same as for C1-C4 on C4-marker tile
  - Thicknesses measured with IBA are a factor of 2 (to 4) lower than on FIB cuts → **further assessment needed**

C1 – C3: ~2.5 h
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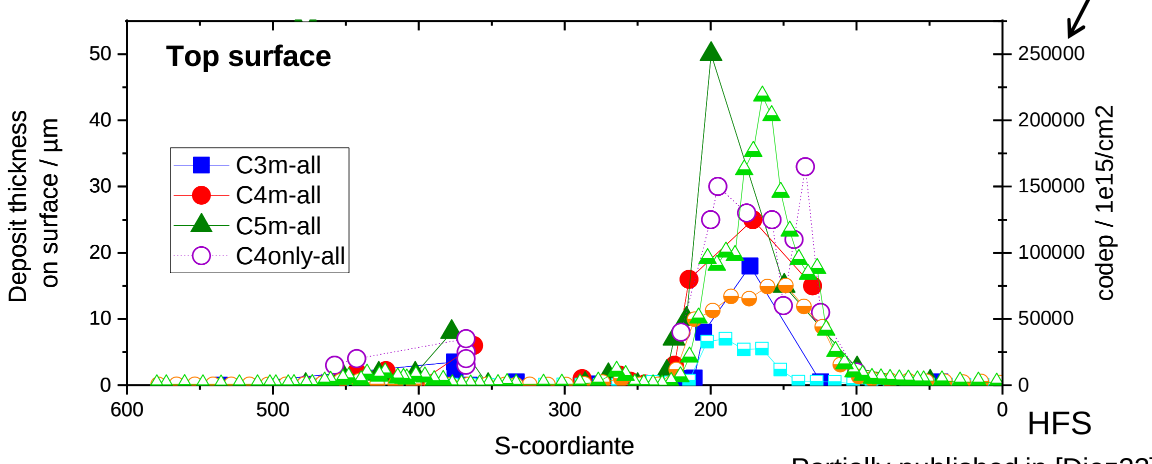


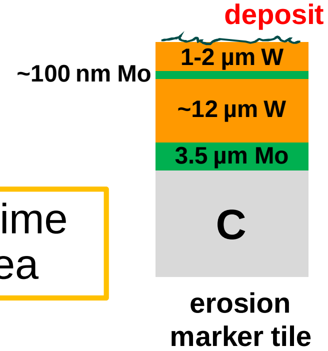
Partially published in [Diez23]

- **Appetizer: Study deposition on tile sides** i.e. into **poloidal gaps** (IBA + SEM/FIB)

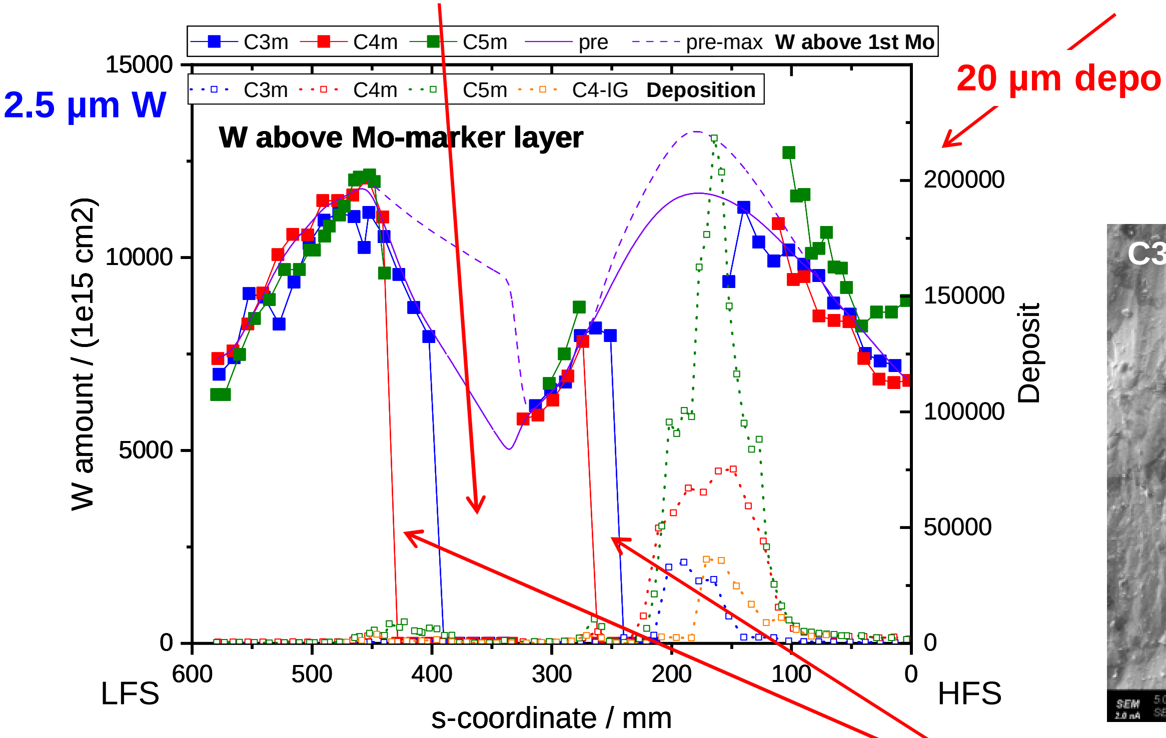
IBA results: Erosion

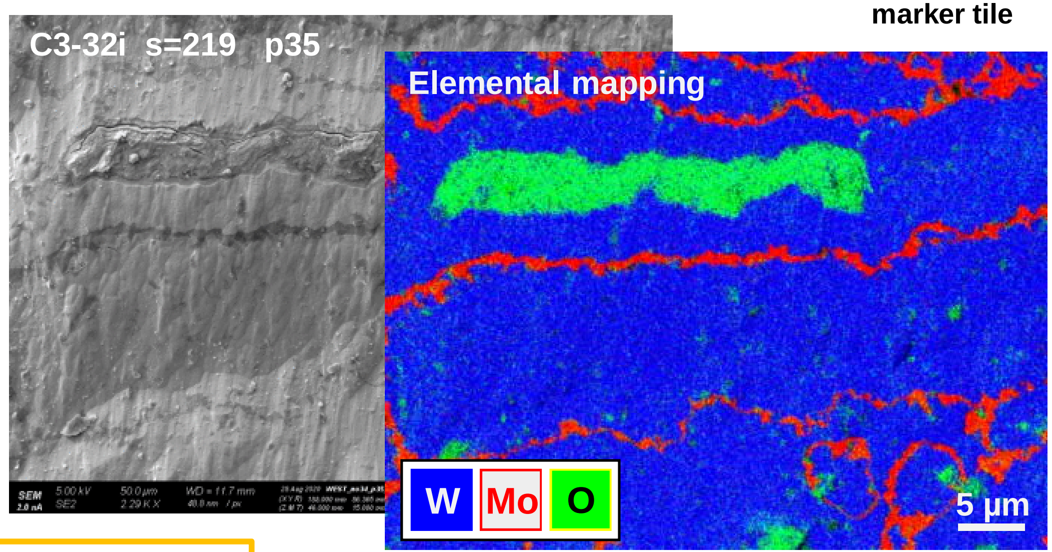
Complete erosion of the top W already after C3 (& Mo marker layer), i.e. 2 µm → **C5: ~ 6 µm!**

Conversion factor of thickness:
atomic density **0.6**…**1**e23 at/cm³ for **W** & **C**
1e15 at/cm² → 0.1 nm



Erosion & deposition at same time
+ shift of erosion/deposition area





- **C3**/**C4** marker data: published [1-3]
- **C5** unpublished / in preparation

Erosion area enlarges from **C3** to **C4** and stays for **C5**

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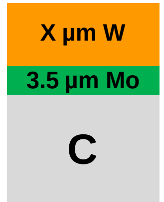
Results: Erosion pattern by “ripple”

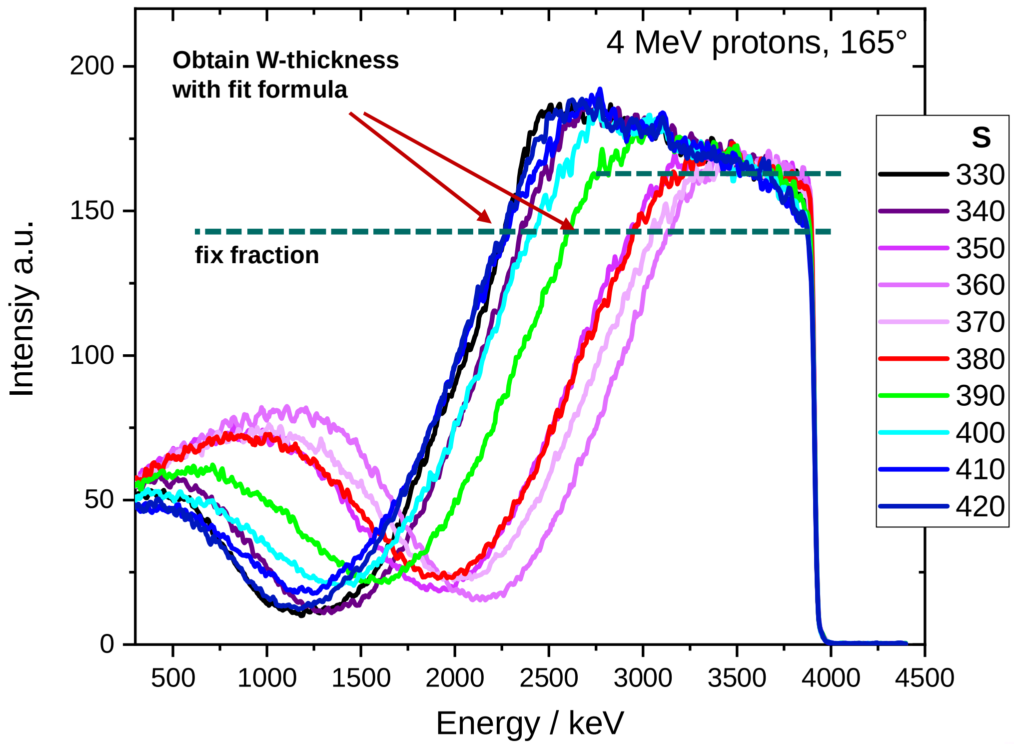


standard tile

➢ Examples of RBS spectra

- Strong deposition (large O,B peaks) → **sorted out**
- Along central line on tiles, as on marker tiles, but…
- **More** (2D maps)

Poloidal scan along central line (T=0)
on outer tile #19



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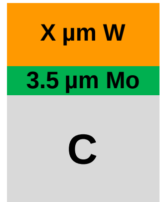
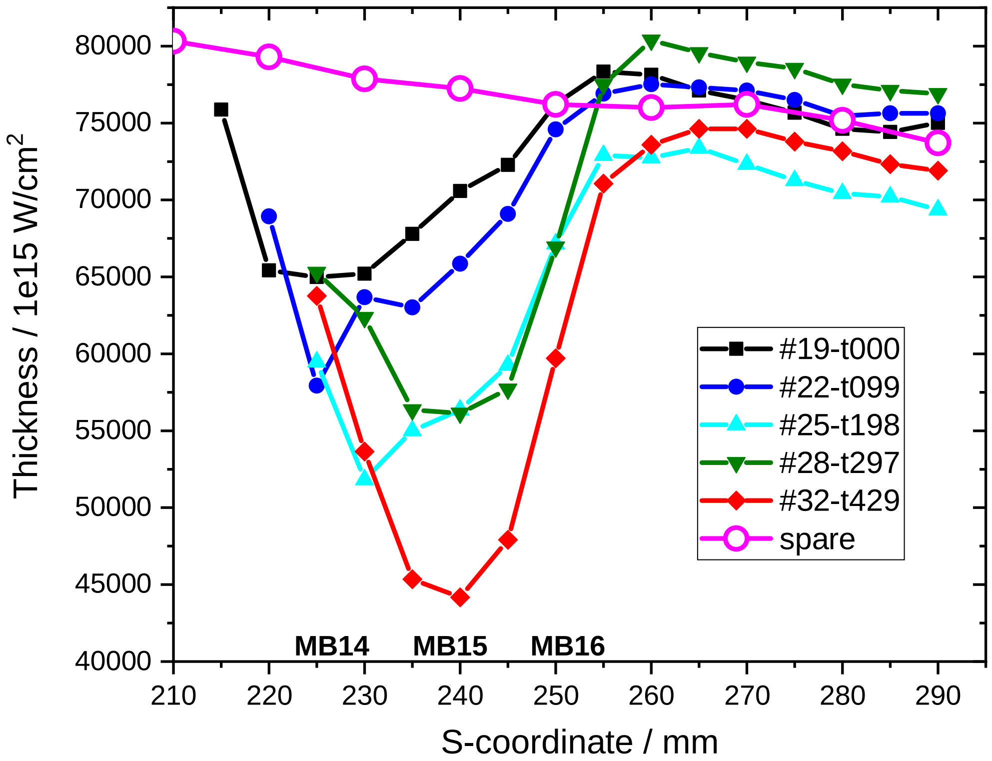


standard tile

➢ Data treatment

- Spread at nearly unaffected area on tiles
  by difference of initial coating thickness *(10%)*
  → No pre-characterization
- **Scale** data of spare tiles before subtraction
  to unaffected area

Central line on inner tiles (T=0), as measured on marker tiles



Results: Erosion pattern by "ripple"

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➢ Data treatment

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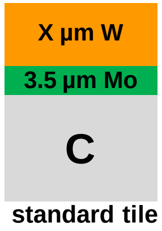
  by difference of initial coating thickness *(10%)*
  → No pre-characterization
- **Scale** data of spare tiles before subtraction
  to unaffected area

➢ Difference of thickness

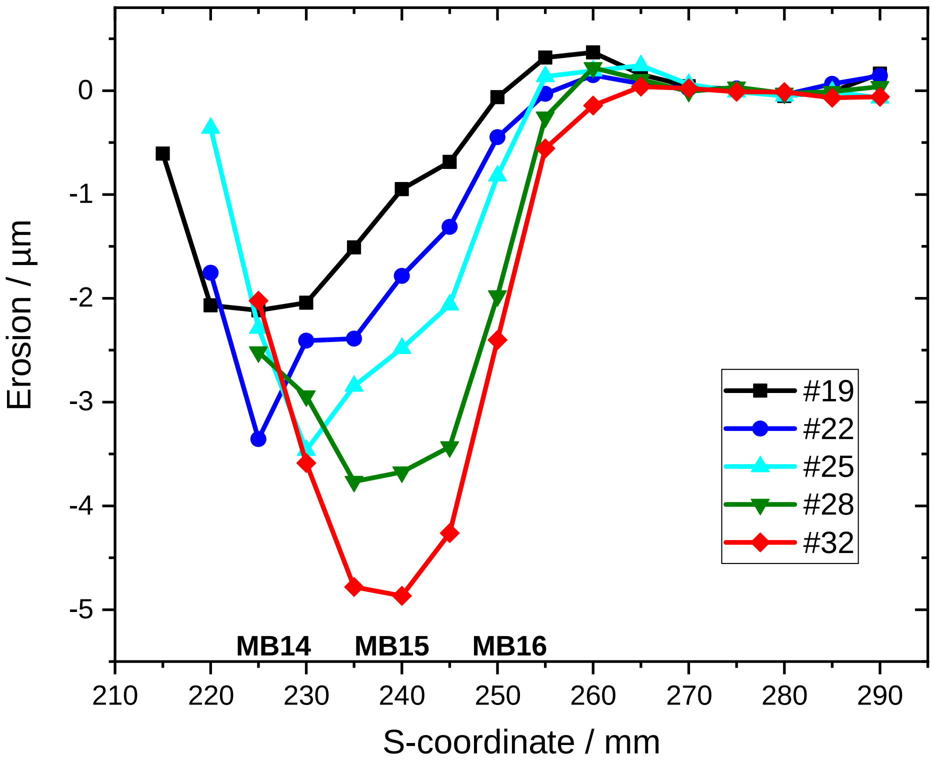
between spare tiles and "ripple samples"

➢ Obtain 2D erosion "maps"

by inter- & extrapolation *(W/cm² convert in µm)*



Central line on inner tiles (T=0),
as measured on marker tiles

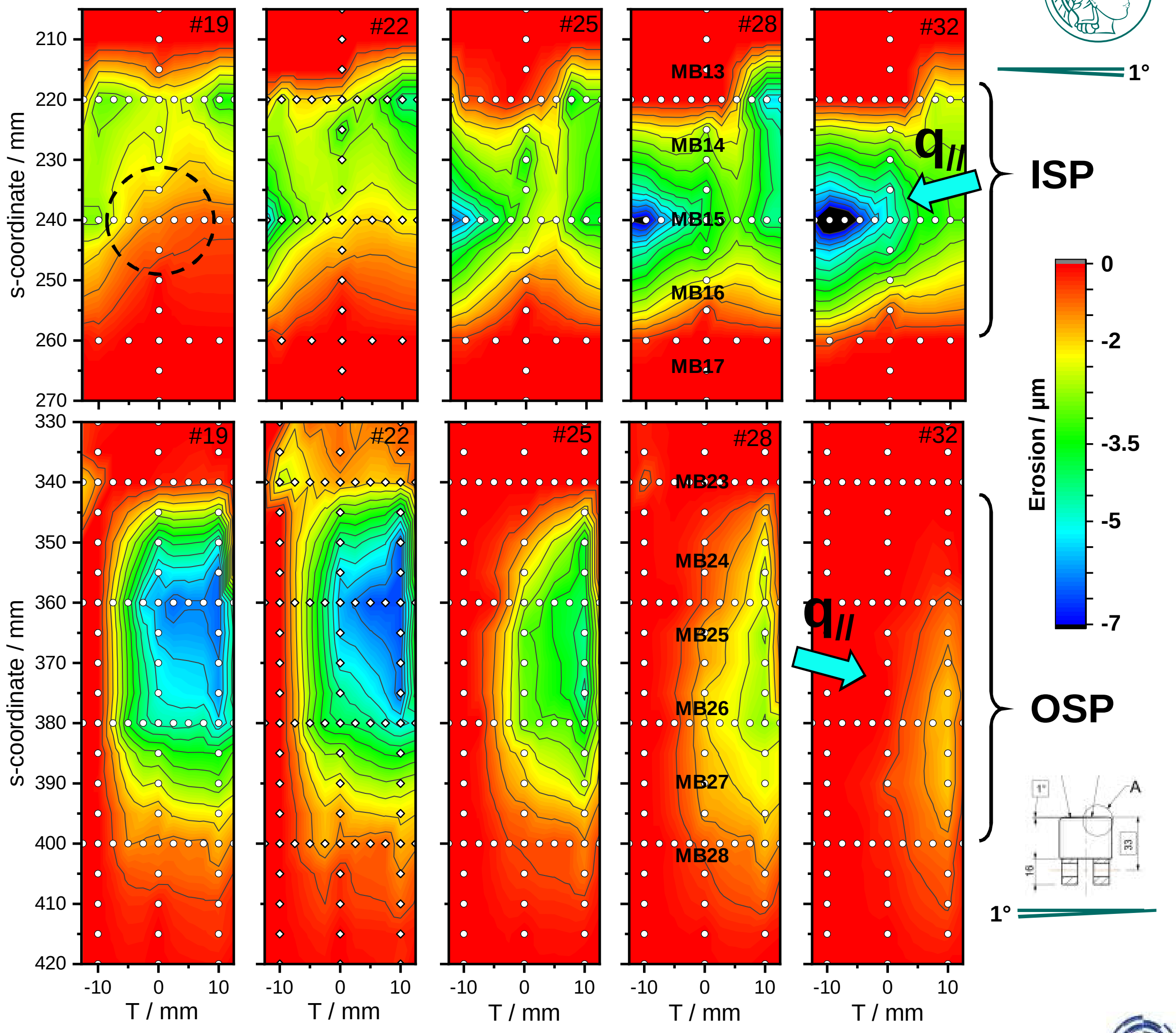


Results: “ripple” erosion maps

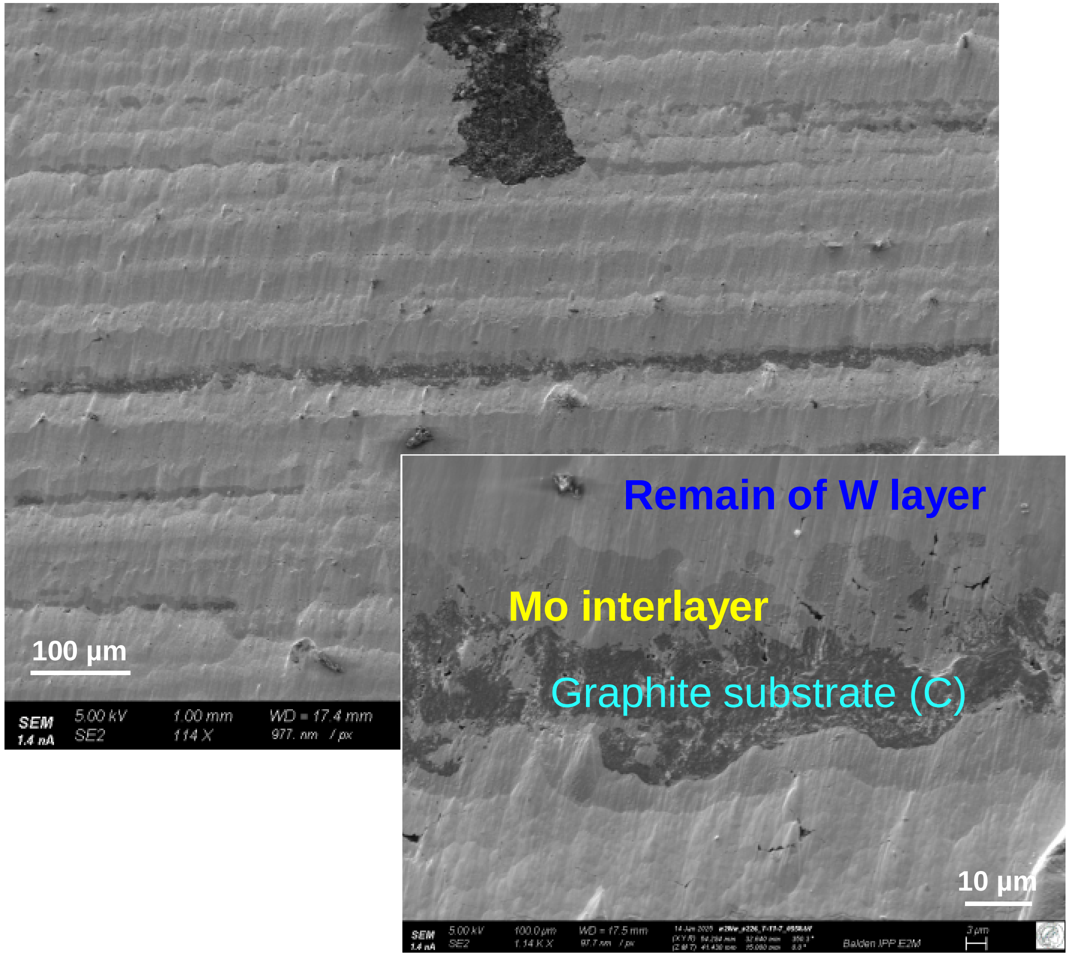
➢ **Contour plot of the interpolated data together with positions of measured data**

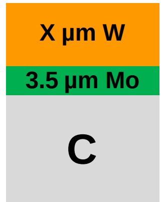
- Maximal erosion on tiles not at central line (toroidally shift) probably due to beveling *(+ misalignment)*
- Maximum shifts poloidally by 20 mm
- Erosion varies, as expected, with position in respect to ripple, but also patterns vary
- Overall highest erosion of edge of inner tiles at ripple max (*confirmed by SEM*)
- ISP: increased higher erosion at both toroidal edges *(beveling + misalignment)*

Note: beveling + misalignment probably “measurable” by comparison of photos



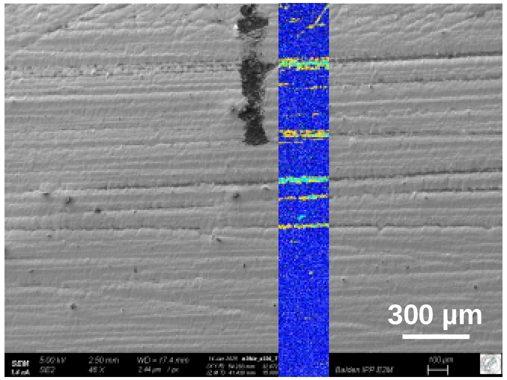
Results: Highest erosion at toroidal edge at ISP





standard tile

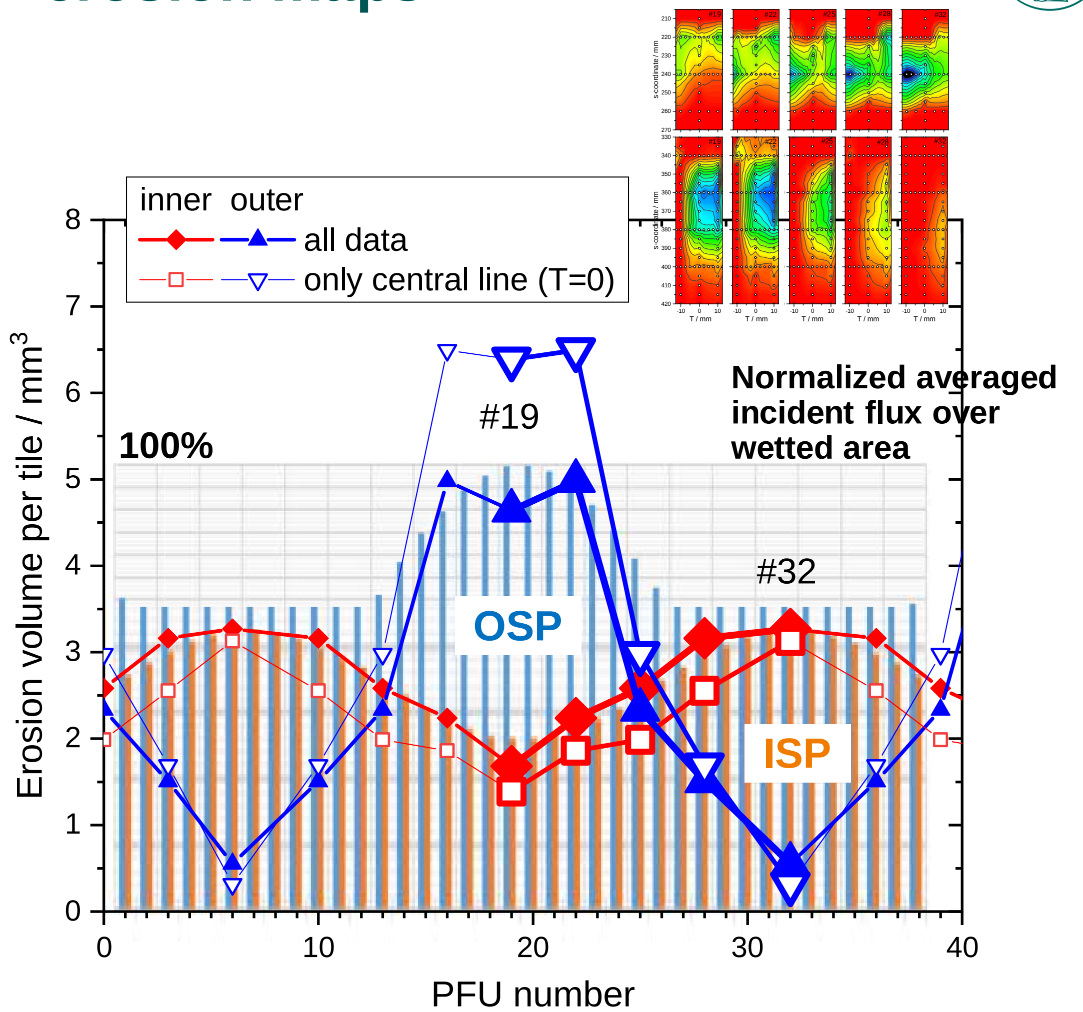
- Complete coating eroded at small areal fraction → graphite visible!
- Initial same coating thickness eroded respective to surface roughness unequal
- Remark: Take local measurements with care
  → representative vs. averaging
  → uncertainty of extrapolation!



Results: Extrapolation from “ripple” erosion maps

- Get “total” erosion per tile by inter- & extrapolation of 2D erosion “map” *(all map data vs. only central line (T=0))*
- Erosion follows ripple, but different amplitude
  → Ratio of cal. incident flux ISP/OSP
  not reflected in measured data
  (max/min: ~10 OSP; ~2 ISP)
- Extrapolate around all 12 sectors
- Obtaining one value for “total” erosion of ISP and OSP useful for balancing
  → OSP higher to ISP by 2% *(only central 35%)*

	vol. eroded around torus /cm³	
	full	*central line*
ISP	**1.24**	*1.04*
OSP	**1.27 (102%)**	*1.60 (135%)*



Content

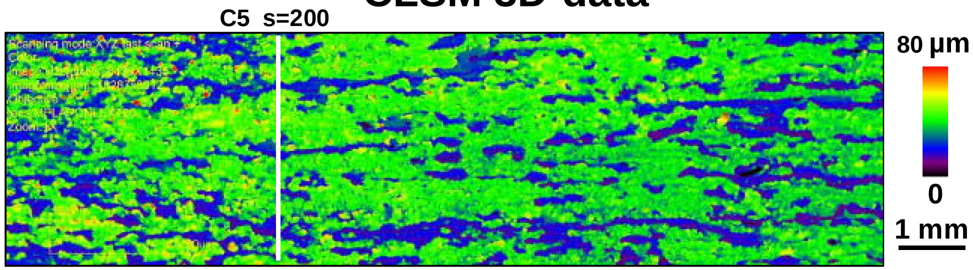
- **Introduction and remarks to WEST**
  - Analyses of wall tiles to obtain erosion/deposition pattern of WEST
  - Some basic info’s (inside views, ripple, tiles…)
- **Tiles and analyses**
  - Special marker tiles; standard tiles; ITER-like plasma-facing unit (PFU)
  - Some remarks on analyses of entire tiles and data evaluation
- **Results of ion beam analyses and microscopy**
  - Deposition pattern and erosion on marker tiles
  - Erosion pattern by ripple
  - Further topics:
    - Strong deposition variation by ripple ?
    - Arcing
    - Deposition into poloidal gaps
    - Remarks to small sample analyses
- **Take home messages**
  - Main results & future work

Further topics: Strong deposition variation by the ripple ?

- CLSM 3D-data for the “ripple” tiles
  → not conclusive jet
  → 1st impression: **NO** variation
  (same depth of traces regardless PFU #)

- Further SEM/FIB needed

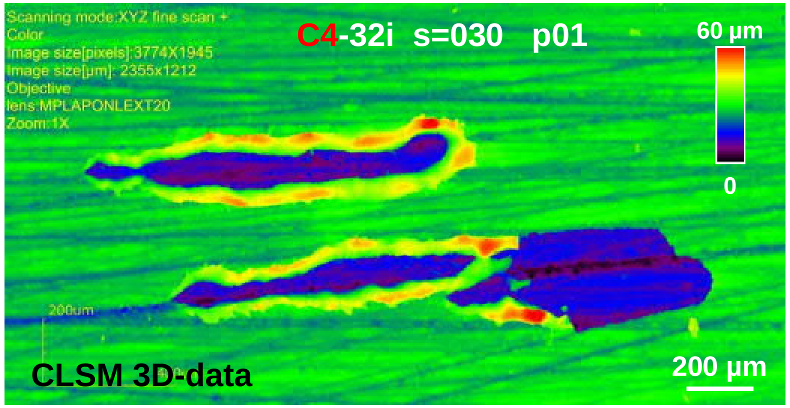
CLSM 3D-data

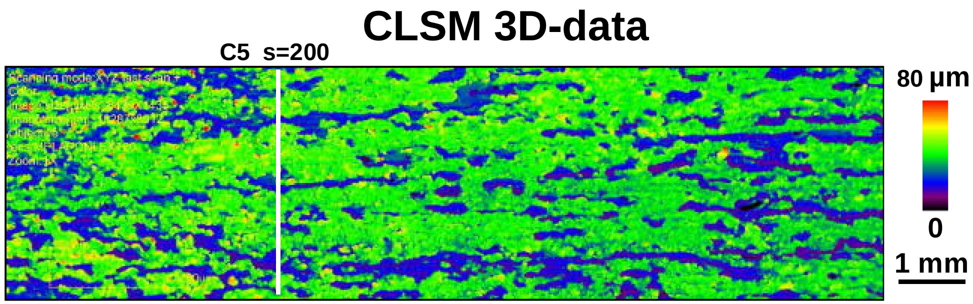


→ *Evaluation of data*

Further topics: Arcing & deposition into poloidal gaps

- Appetizer: Arcing





→ *Evaluation of data*

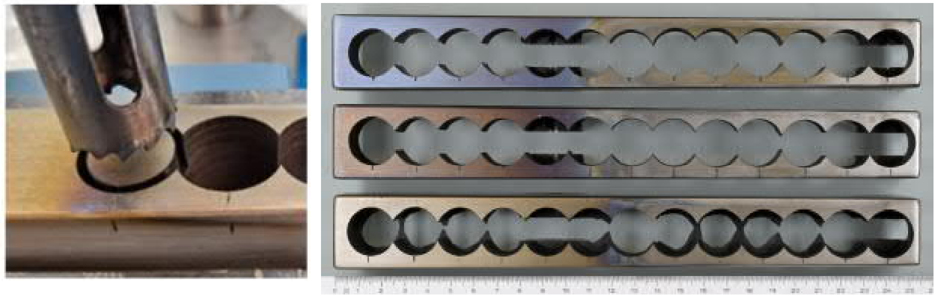
- Appetizer: Study deposition on tile sides, i.e., into **poloidal gaps** *(IBA + SEM/FIB)*

→ *Evaluation of data*

Further topics: Some remarks to “small” sample analyses

➢ Sample preparation

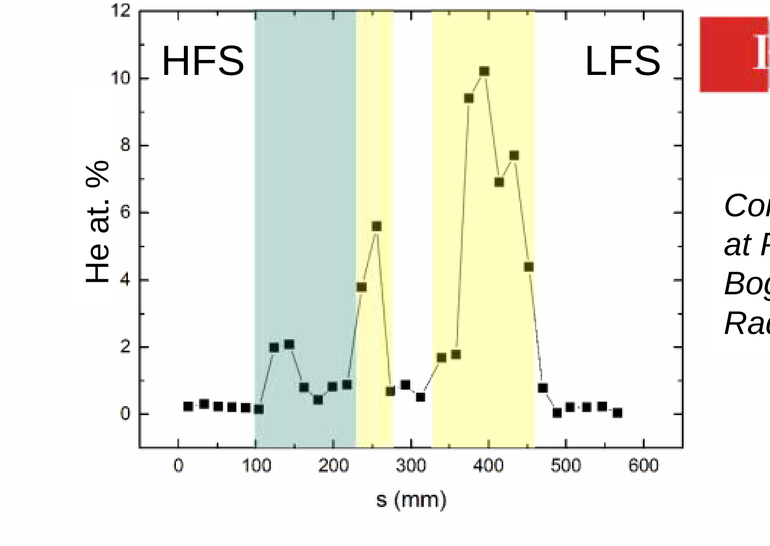
- Core drilling for graphite PFUs by VTT
- Cut of ITER-like PFUs by CEA



➢ Analyses

- IBA, SEM, SIMS, LIPS, GDOES …
  → confirm presented data
  → more detailed insight
- Example of additional information: **He content**

TOF ERDA on core-drilled samples from C4 marker tiles



Contribution at PFMC by Bogdanović-Radović

➢ Future

- Pick-up bits of information from cut samples to obtain conclusive picture, as done for one ITER-like W monoblock *(paper ready to submit* **[Tsavalas 2025]***)*

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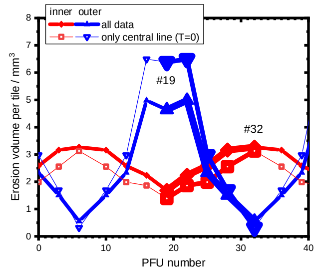
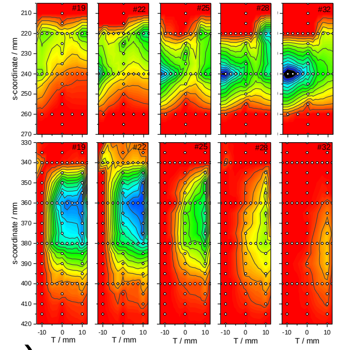
Take home massage: Main results & future work





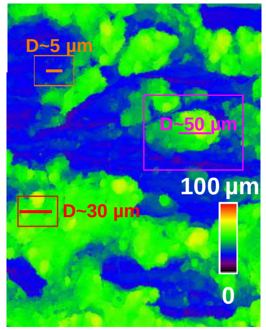
➢ Erosion & deposition pattern of WEST phase determined

- Most data along poloidal central line on tiles *(marker tiles)*

➢ Erosion maps

- Poloidal variation of erosion pattern due beveling (+ misalignment)
- Deepest erosion on ISP close to tile edge
  → W coating just thick enough to survive phase 1 (only a few holes; i.e. 15 µm erosion)
- Tile integrated erosion of ISL and OSL follows ripple, but…
  → Full-toroidal-integrated erosion of ISP and OSP do reflect simulated heat/particle loads due to ripple
  → OSP slightly higher; **~1.2 cm³** eroded there

➢ Deposition



- Strong deposition at HFS of ISP → with ~ 50 µm *(stratified W/C/B/O/D layers with Cu/Fe/Ag)*
  → Increase with campaign / accumulated plasma time (?)
  → Correlation to dust ?

➢ Good data base for interpretation underlying physics

- Correlation with plasma scenarios/parameter

Take home massage: Future work

- **Publish more of the data**
  - A lot of data still under evaluation and not published jet *(several contributions at upcoming PMFC)*
  - Combine the bits of information from cut sample analyses to obtain conclusive picture

- **Study deposition into poloidal gaps**
  - Some data already exist, but not evaluated jet

- **Arcing & dust**

- **Analyses on segmented or small sample cut form ITER-like PFUs**

Thank you for your attention

[1] **Balden** *et al.,* **2021** Phys. Scr. 96, 124020
[2] **Hakola** *et al.,* **2021** Nucl. Fusion 61, 116006
[3] **Bucalossi** *et al.,* **2022** Nucl. Fusion 62, 042007
[4] **Tsitrone** *et al.,* **2022** Nucl. Fusion 62, 076028
[5] **Diez** *et al.,* **2023** Nucl. Mater. Energy 34, 101399
[6] **Martin** *et al.,* **2021** Phys. Scr. 96, 124035
[7] **Joji** *et al.,* **2023** J. Nucl. Eng. 4, 96
[8] **Martin** *et al.,* **2024** Nucl. Mater. Energy 41, 101764
[9] **Marin** *et al.,* **2025** J. Nucl. Mater. 604, 155525
[10] **Tsavalas** *et al.,* **2025** ready to submit

M. Balden[1], M. Mayer[1], M. Diez[2], E. Tsitrone[2], E. Bernard[2], A. Hakola[3], J. Likonen[3], E. Fortuna-Zaleśna[4], I. Jõgi[5], P. Paris[5], E. Grigore[6], I. Bogdanović-Radović[7], Z. Siketić[7], S. Markelj[8], M. Kelemen[8], P. Tsavalas[9], K. Mergia[9], A. Lagogiannis[9], C. Pardanaud[10], C. Martin[10], P. Petersson[11], R. Mateus[12], E.A. Alves[12] and the WEST team*

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* See http://west.cea.fr/WESTteam