WPPWIE Review Meeting, Jülich, 17-21 November, 2025

SP B status report 2025

Antti Hakola

On behalf of the SP B team and task holders

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Introduction – overview of SP B in 2025

SP B
Experiments on erosion, deposition and material migration

SP B.1 – Physics of erosion and deposition

Resources: 26.2 PM
Machines:
- MAGNUM-PSI (6 days)
- GyM (20 days)
- PSI-2 (10 days)
- Accelerators (11 days)

SP B.2 – Material migration in toroidal devices

Resources: 30.1 PM
Machines:
- Accelerators (16 days)

Others:
- 25 k€ for diamond saw cutting

SP B.3 – Characterization of plasma-exposed materials

Resources: 39.1 PM
Machines:
- Accelerators (33 days)

SP B.4 – Reference coatings for ITER and DEMO

Resources: 42.3 PM
Machines:
- Accelerators (15 days)

SP B.5 – Production of metallic dust in toroidal devices

Resources: 26.0 PM
Machines:
- Accelerators (8 days)

SP B.6 – B deposition on diagnostics mirrors

Resources: 8.0 PM

- Huge number of tasks and deliverables (altogether 53) – most of them will be completed by the end of 2025
- In many cases the work will continue in 2026-2027 within new tasks, with the scope and volume being re-adjusted

Overview of SP B in 2025 – high-level status of activities

Progress has been made in the following activity areas as follows

- **SP B.1: Physics of erosion and deposition - focus on cross-machine investigations**
  - ✓ Several B samples exposed to plasmas (PSI-2, MAGNUM-PSI, GyM) to study physical and chemical erosion; W programme proceeding more slowly
  - ✓ Erosion rates at varying incident angles measured for W and B reference layers, exposure of W layers to dust impacts scheduled
- **SP B.2: Material migration in toroidal devices - concentrate on samples from boronization studies and WEST monoblocks**
  - ✓ Results from WEST Phase 1 tiles and samples extensively reported (PFMC 2025), cutting of samples from Phase 2 PFUs ongoing
  - ✓ Several samples from AUG and WEST boronizations (uniform and non-uniform) analysed
  - ✓ Analysis of cavity samples from W7-X completed, measurements of divertor manipulator samples from AUG started
- **SP B.3: Characterization of plasma-exposed materials - samples coming from SP B.1 and SP B.2 (+ SP B.4)**
  - ✓ Focus on WEST samples as well as samples from boronization experiments
- **SP B.4: Reference coatings for ITER and DEMO - production of B and W layers**
  - ✓ Large programme to compare B layers produced by different labs by different techniques – all except VTT samples available (pure B layers)
  - ✓ W layers produced for targeted activities, highest interest for layers emulating re-deposits
- **SP B.5: Production of metallic dust in toroidal devices – re-scoping to primarily deal with dust analyses**
  - ✓ W7-X dust samples available and their characterization chain agreed
  - ✓ Formation studies of B and W dust particles continued; this subtask will be largely finished by the end of 2025
- **SP B.6: B deposition on diagnostics mirrors**
  - ✓ Mirrors exposed to AUG and W7-X boronizations/plasmas, analyses partly ongoing

In addition, meetings organized on (i) dust activities and analyses (March and September), (ii) production and analysis programme for B and W samples (July), and (iii) WEST analysis meeting (September)

Overview of SP B in 2025 – selected highlights per activity area

- **SP B.1: Physics of erosion and deposition**
  - ✓ Thick B layers produced (MAGNUM-PSI) and their erosion (incl. chemical erosion) investigated
  - ✓ Erosion of nano-columnar W samples shows different dynamics than bulk W or W fuzz samples
- **SP B.2: Material migration in toroidal devices**
  - ✓ Very thick deposited layers observed on WEST PFUs (up to 350 μm if never cleaned), erosion can reach values up to 20 μm (18 h of plasma)
  - ✓ Both on AUG and WEST, boronization layers show D/B fractions in the range of 0.1–0.3; B and D depleted upon exposure to air but at lower rates for the WEST samples
- **SP B.3: Characterization of plasma-exposed materials**
  - ✓ WEST data shows consistent picture for the complex structure for the deposited layers after Phase 1 and Phase 2 operations
- **SP B.4: Reference coatings for ITER and DEMO**
  - ✓ Pure B layers can be produced (impurity concentrations overall <10 at.%) but thicker ones required for linear machine experiments
- **SP B.5: Production of metallic dust in toroidal devices**
  - ✓ Several elements already identified on the analysed W7-X dust samples, including (besides C) B, Fe, Cr, W, Ti, Ni, and Cu; large (mm-sized) and thick flakes of deposits with varying morphology and layered structure observed on the samples
  - ✓ Of the studied seeding gases, Kr is most efficient in producing W dust; collected dust contains both nanoparticles and larger agglomerates
- **SP B.6: B deposition on diagnostics mirrors**
  - ✓ Reflectivities noticed to change following exposures, especially on the AUG case

High-level deliverables and milestones for SP B in 2025

- Erosion and deposition patterns at the divertor and main-chamber structures of toroidal fusion devices following operations with and without boronizations
- Reporting the role of fluence and pulse length in the erosion-deposition balance in toroidal fusion devices under reactor-relevant operational conditions

WMxx	SP B	Erosion rates of co-deposited/re-deposited W layers at reactor-relevant particle fluxes and fluences determined. (ITER+DEMO)	31.12.2025
WMxx+1	SP B	Material migration pathways elucidated for W and B in toroidal devices (AUG, WEST, W7-X) during and after boronizations. (ITER)	31.12.2025
WMxx+2	SP B	Erosion and deposition patterns on PFUs removed after Phase 1 and Phase 2 operations on WEST compared. (ITER)	31.12.2025
WMxx+3	SP B	Co-deposited boron layers with varying oxygen contents and surface morphologies delivered and characterized. (ITER)	31.12.2025
WMxx+4	SP B	W dust samples from toroidal fusion devices (AUG, WEST, W7-X) characterized and extrapolations made towards fusion reactors. (DEMO)	31.12.2025
WMxx+5	SP B	B contamination determined on diagnostics mirrors after AUG and W7-X boronization experiments. (ITER)	30.06.2025

SP B.1 - Physics of erosion and deposition

SP B.1 deliverables 2025

Activity	Deliverable ID(s)	Title
SP B.1	D001 3 PM	Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions as well as the formation and erosion rates of thick re-deposits in MAGNUM-PSI with flux and fluence (DIFFER)
SP B.1	D002 4 PM	Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in GyM with flux and fluence (ENEA)
SP B.1	D003 7 PM	Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in PSI-2 with flux and fluence (FZJ)
SP B.1	D004 5 PM	Erosion rates of co-deposited W- and B-based model systems following exposure to controlled ion beams (ÖAW)
SP B.1	D005 1 PM	Erosion rates following high-energy dust impacts on W model systems and comparison to data from tokamaks (ENEA)

SP B.1: Production and erosion of thick re-deposition layers (DIFFER)

Task and questions to be addressed

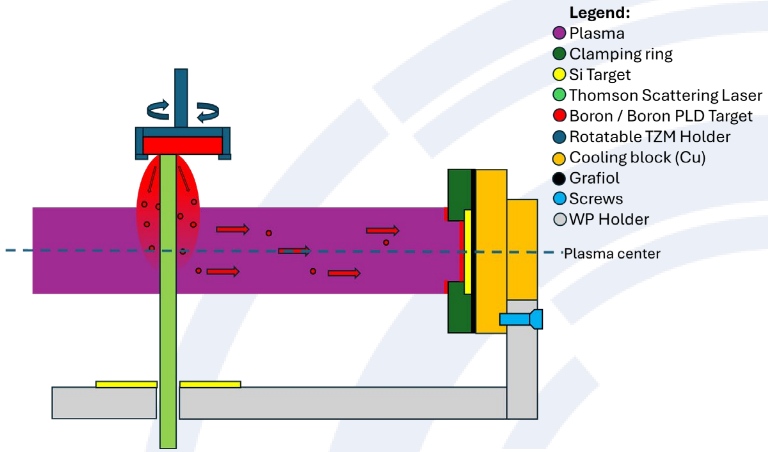
1. Production of thick re-deposited B-containing layers as expected in ITER
2. Investigate chemical erosion of B

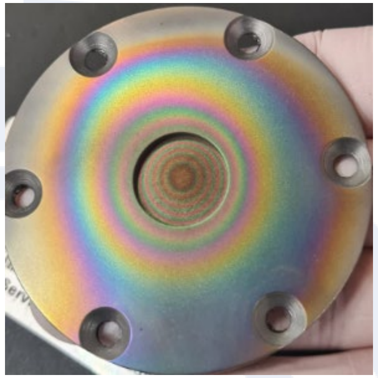
Approach

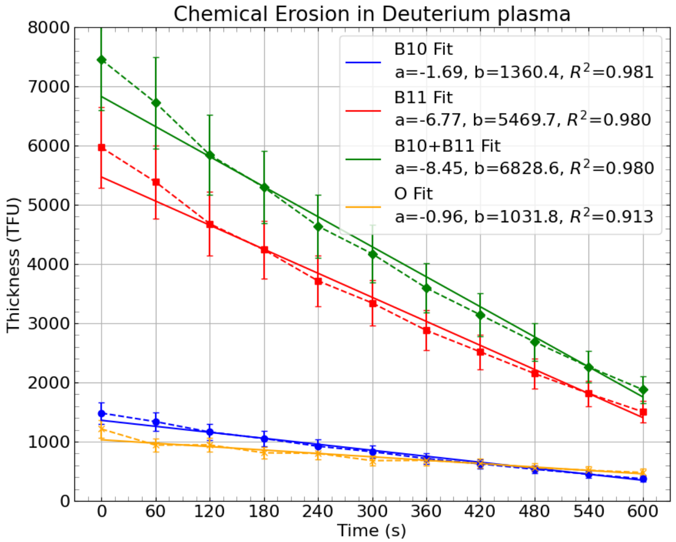
1. Use in-house developed plasma-assisted pulsed laser deposition (PLD) to grow thick B layers
2. Use lab-grown (PoliMo) 1-um thick B layers to study chemical erosion

Results

1. Using He plasma demonstrated for **growing thick (~1 μm) B layers**
   i. Studied as a function of the deposition energy, pressure, and B-field
   ii. Impurity content ~20% O, some C and N
2. **Chemical erosion dominant at low E_{ion}**
   i. Erosion rate for E_{ion} = 5 eV determined as 0.75 nm/s, Y=2.34×10^{-3}
   ii. Erosion as function of ion energy experiments Nov 2025







Deliverable: **PWIE-SP B.B1.T-T005-D001**
Status: ***ongoing (to be completed Dec 2025)***
Facilities: **Magnum-PSI 6 days, UPP 3 days (0 granted), Accelerator 13 days**
Linked WP or TSVV: **SP B.4**

T.W. Morgan, J.G.A. van Kesteren, C.J.D. Robben, B. Tyburska-Pueschel

SP B.1: Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in GyM with flux and fluence (ENEA-CNR)

Task aims to broaden the understanding of W and B erosion physics, using linear device GyM. The work focuses on assessing erosion characteristics of different W or B-based materials or reference layers.

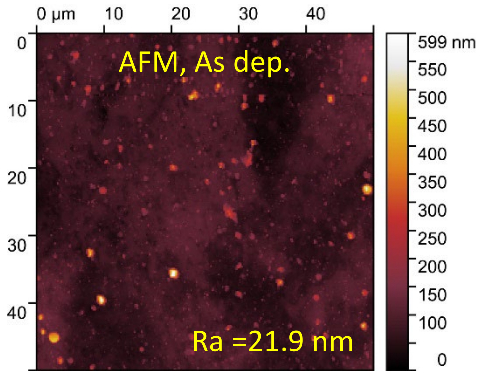
Task and questions to be addressed: Determine erosion characteristics of B films mimicking boronisation layers deposited on PFCs

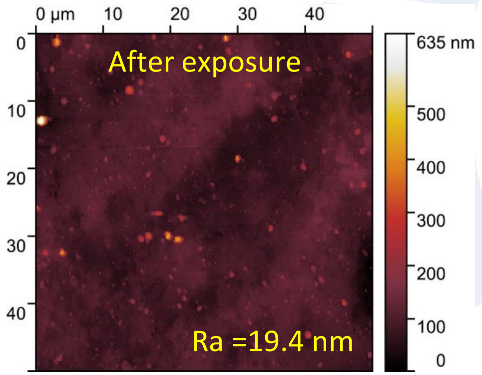
Approach

- D plasma exposure of 3 ns-PLD 100 nm-thick compact B films at Γ =3.4e20 $D^+ m^{-2}s^{-1}$
- E_{ion} =76 eV according to PSI-2 experiments [1]
- Φ =4e23 D^+m^{-2} (t_{exp} =20 min) chosen based on $Y_{D\rightarrow B,SDTrimSP}$, to avoid full erosion of B films

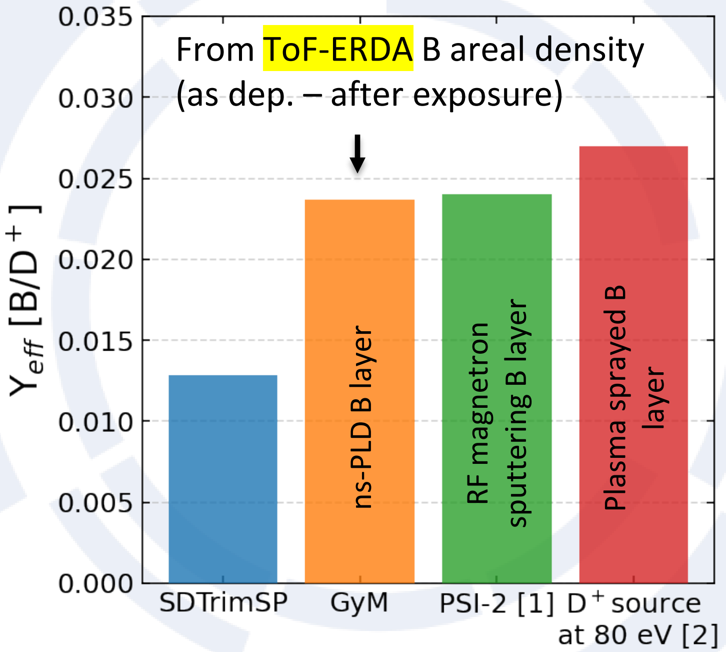
Characterisations

- Y_{eff} from mass loss: ***done***
- Surface topography by AFM: ***done***
- Surface composition by
  - ToF-ERDA, EBS+NRA+PIXE, ToF-MEIS
    - ✓ at Uppsala University: ***done***
      (see E. Pitthan's slide)
  - SIMS at CIEMAT: ***ongoing***
  - Raman and XPS at Aix Marseille Université: ***ongoing***





Results



[1] M. Sackers, et al., Nucl. Mater. Energy **45** (2025) 102003

[2] E. Hechtl, et al., J. Nucl. Mater. **196-198** (1992) 713-6

Deliverable: **PWIE-SP B.B1.T-T005-D002**
Status: ***completed***
Facilities: **GyM (20 days)**
Linked WP or TSVV: **SP B.4, SP D.1, SP D.3**

POLITECNICO DI MILANO

A. Uccello, A. Cremona, F. Ghezzi, M. Pedroni, G. Alberti, D. Dellasega, M. Passoni

SP B.1: Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in GyM with flux and fluence (ENEA-CNR)

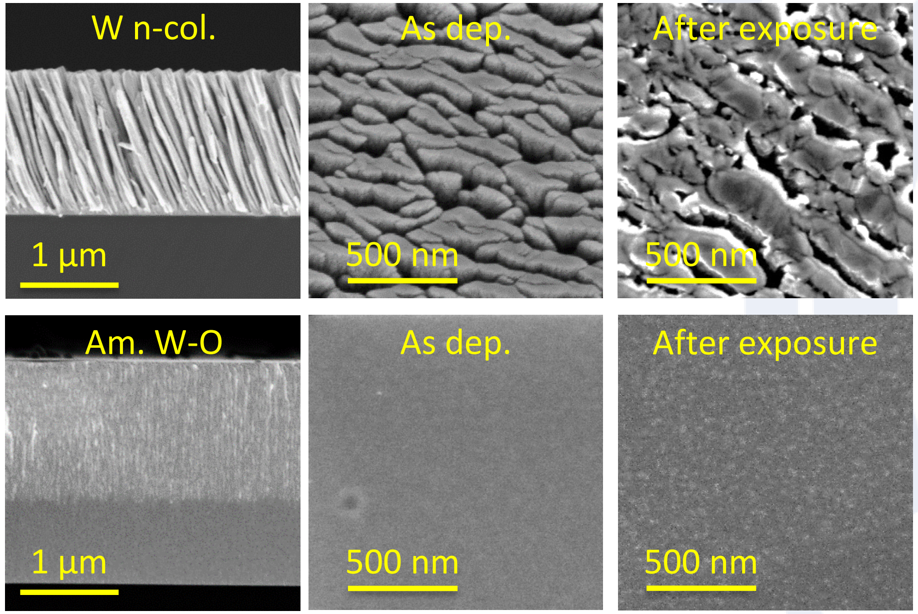
Task aims to broaden the understanding of W and B erosion physics, using linear device GyM. The work focuses on assessing erosion characteristics of different W or B-based materials or reference layers.

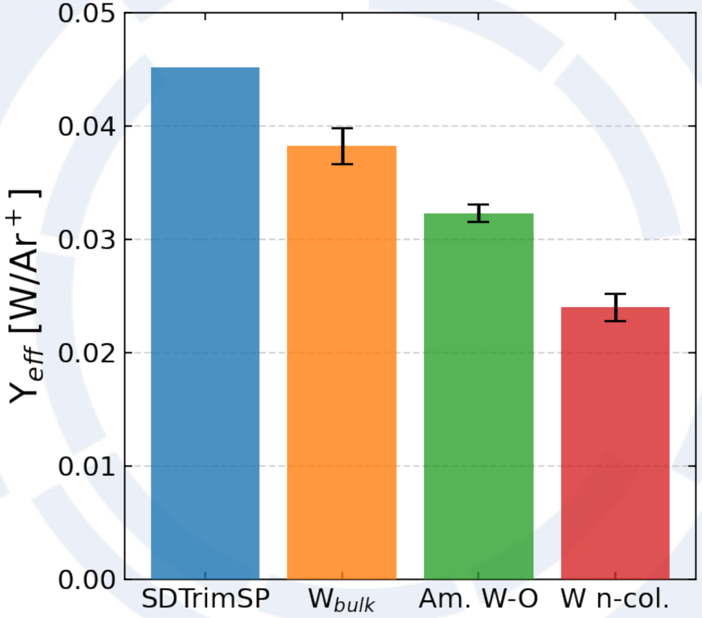
Task and questions to be addressed:

Determine the impact of plasma flux and sample morphology in erosion characteristics of W model systems (cross-machine experiment)

Approach

- Ar plasma exposure at Γ =1.5e20 $Ar^+m^{-2}s^{-1}$
  - Φ =5.4e23 Ar^+m^{-2} and E_{ion} =90 eV, of:
  - Compact W films on Si w/ pyramids
  - W nano-columns
  - Amorphous W-O films (PoliMi)
  - W-O films (IAP)
- Y_{eff} from mass loss: ***done***
- Surface topography by AFM: ***done***
- Surface structure by SEM: ***done***





Main result

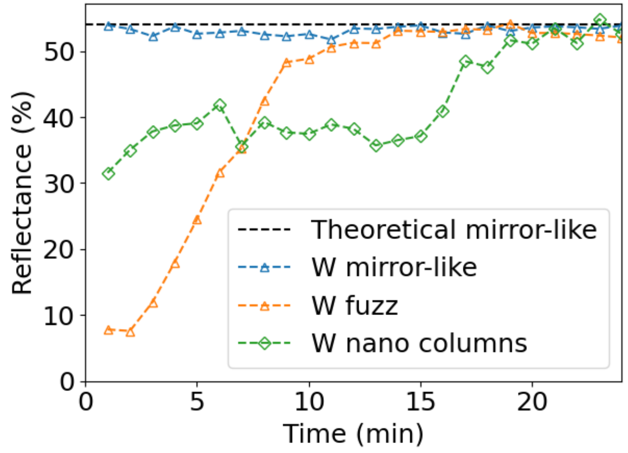
W nano-columns $Y_{eff} \cong$ 40% W_{bulk} Y_{eff} ← Microscale morphology modelling with ERO2.0 carried out under SP D.3 *(see G. Alberti's talk)*

Deliverable: **PWIE-SP B.B1.T-T005-D002**
Status: ***completed***
Facilities: **GyM (20 days)**
Linked WP or TSVV: **SP B.4, SP D.1, SP D.3**

POLITECNICO DI MILANO

A. Uccello, A. Cremona, F. Ghezzi, M. Pedroni, G. Alberti, D. Dellasega, M. Passoni

SP B.1: Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in PSI-2 with flux and fluence (FZJ)



Task and questions to be addressed

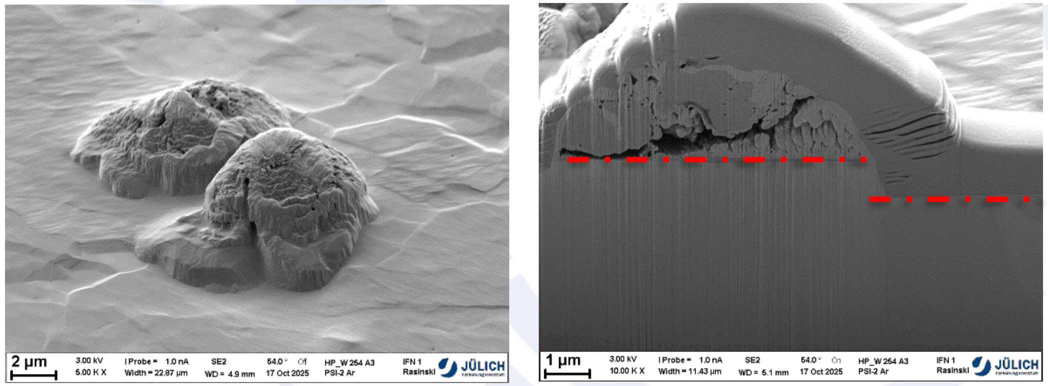
- Establish the erosion rates for nano-columnar W coatings

Approach

- Exposure of nano-columnar W coated samples in PSI-2 to Ar plasma for 25 min
- Measurement of erosion rate by spectroscopy studies
  - Variation in intensity - sputtering yield
  - Variation in reflectance - optical properties

Results

- **Lower erosion rate of the coating compared to bulk W**, confirmed by spectroscopy as well as post-mortem SEM/FIB analysis



SEM image of the surface and cross-section after PSI-2 exposure. Spot with coating leftover presents lower erosion rate as compared to bulk surrounding.

Deliverable: **PWIE-SP B.B1.T-T005-D003**
Status: ***completed***
Facilities: **PSI-2 (2 days)**
Linked WP or TSVV: **SP B.4**

O. Marchuk

SP B.1: Erosion rates of co-deposited W- and B-based model systems following exposure to controlled ion beams (ÖAW)

Boronizations produce mixed tungsten-boron layers on plasma-facing surfaces, thereby influencing the erosion properties of the first wall

Task and questions to be addressed

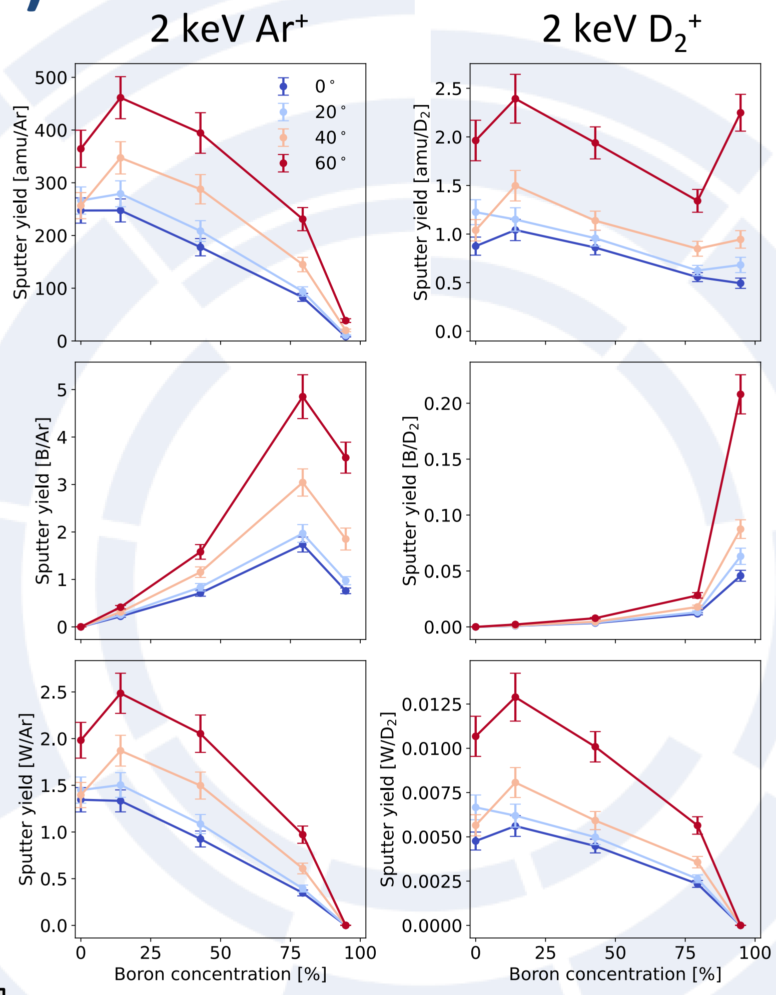
- Assess the erosion characteristics of co-deposited W- and B-based model systems upon exposure to different ion beams under laboratory conditions

Approach

- Utilization of a Quartz Crystal Microbalance (QCM) to perform angle-dependent sputter yield measurements of samples with different tungsten-boron mixing ratio (W:B ≈ 1:0, 4:1, 1:1, 1:4, 0:1) under 2-keV Ar^+ and 2-keV D_2^+ irradiations

Results

- General **decrease in sputtered mass for increasing boron concentration** for 2 keV Ar^+ and 2 keV D_2^+ irradiation
- **Decrease in sputtered tungsten particles and increase in sputtered boron particles** with increasing boron concentration for 2-keV Ar^+ and 2-keV D_2^+ irradiation



Deliverable: **PWIE-SP B.B1.T-T005-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **ENR-MAT.02.VR**

R. Gurschl, M. Fellinger,
B. Burazor Domazet, J. Brötzner,
G. Nagy, R.A. Wilhelm, F. Aumayr

SP B.1: Erosion patterns on W model systems at high-energy dust impacts (ENEA)

Following the previous studies on the erosion patterns and material migration of W model systems upon dust impacts *for normal impacts* (i.e. at 0°), this task focuses on the erosion patterns *at different dust impact angles*.

Task and questions to be addressed

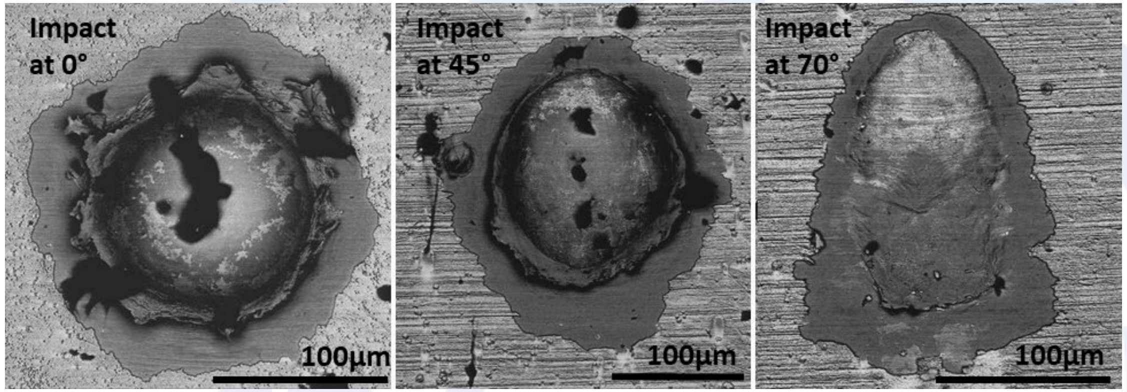
- Determine the erosion and morphology of W systems impacted by high-speed dust *at different angles*

Approach

- Shoot dust at three velocities (1, 2, 3 km/s) and three different impact angles (0, 45, 70°) on W model systems on Mo substrates
- Analyse the damaged surfaces

Preliminary results

- The eroded surface at 0° impacts are in line with previous investigations
- The eroded surface is larger for samples 45° tilted respect to normal incidence
- The **eroded surface decreases at shallow dust impact angles**



SEM images showing examples of delaminated surfaces of W model systems upon dust impacts for different impact angles. Dark color: Mo substrate and impurities; light color: W deposit.

Deliverable: **PWIE-SP B.1.T-T005-D005**
Status: ***ongoing (to be completed by the end of 2025)***
Facilities: -
Linked WP or TSVV: **SP B.4**

M. De Angeli (ENEA), D. Ripamonti (ENEA), G. Daminelli (ENEA), P. Tolias (VR)

SP B.2 - Material migration in toroidal devices
SP B.3 - Characterization of plasma-exposed materials

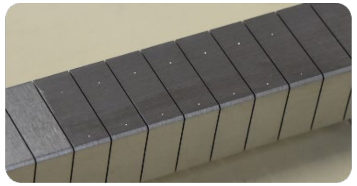
SP B.2 deliverables 2025

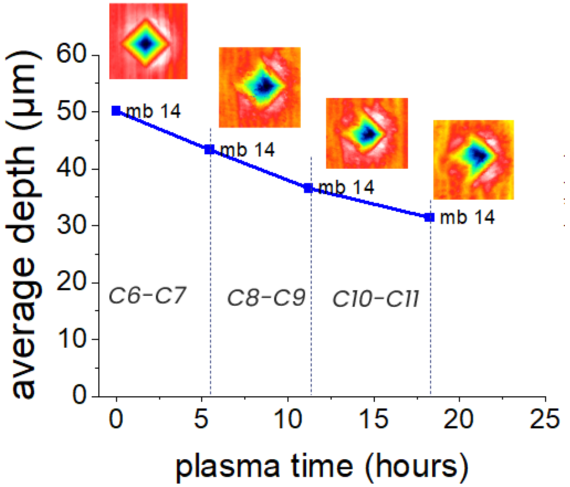
Activity	Deliverable ID(s)	Title
SP B.2	D001 6 PM	WEST campaigns: erosion and deposition patterns on PFUs after WEST Phase 1 (C1-C5) and Phase 2 (C6-C10) operations and thickness profile of layers originating from boronizations (CEA)
SP B.2	D002 2 PM	WEST campaigns: microscopy investigations of He-exposed PFUs after Phase 1 and Phase 2 operations on WEST (CEA)
SP B.2	D003 2 PM	WEST campaigns: detailed investigation of selected PFUs, including side faces of marker tiles, for their erosion, deposition, and surface-modification patterns at different locations with respect to magnetic ripple (MPG)
SP B.2	D004 5 PM	AUG manipulator experiments: pre- and post characterization of samples exposed to AUG plasmas and/or boronizations on AUG for their erosion and surface-modification patterns as well as boron deposition profiles (MPG)
SP B.2	D005 3 PM	AUG manipulator experiments: deposition profiles of B and D on samples exposed to AUG plasmas and/or boronizations on AUG at high spatial and depth resolution (VTT)
SP B.2	D006 2 PM	AUG campaigns: deposition profiles on samples originating from boronizations on AUG (RBI)
SP B.2	D007 2 PM	AUG campaigns: changes in the surface properties of samples exposed to AUG plasmas and/or boronizations on AUG (FZJ)
SP B.2	D008 2 PM	W7-X manipulator experiments: erosion and deposition characteristics on manipulator and other samples exposed to OP2 plasmas on W7-X (FZJ)
SP B.2	D009 3 PM	W7-X manipulator experiments: erosion and deposition patterns on manipulator samples and wall components from OP2 experiments and/or boronizations on W7-X (MPG)

SP B.3 deliverables 2025

Activity	Deliverable ID(s)	Title
SP B.3	D001 2 PM	Depth profiles and surface morphology of selected B or W layers (CIEMAT)
SP B.3	D002 4 PM	Surface modifications and fuel content of selected AUG, WEST, W7-X, and PSI-2 samples (FZJ)
SP B.3	D003 2 PM	Composition of layers on selected WEST monoblock samples (IAP)
SP B.3	D004 3 PM + 2 PM (AR)	Surface modifications of selected WEST, W7-X, MAGNUM-PSI, PSI-2, and GyM samples (IPPLM)
SP B.3	D005 3 PM	Composition and fuel content of layers on selected WEST monoblock samples and on SP B.1 or SP X samples (IST)
SP B.3	D006 3 PM	Micro- and macroscale composition of layers on selected AUG, WEST, MAGNUM-PSI, PSI-2, and GyM samples (JSI)
SP B.3	D007 2 PM	Surface modifications and erosion/deposition profiles of samples and wall tiles from AUG, WEST, and W7-X (MPG)
SP B.3	D008 5 PM	Surface modifications and composition of layers on selected WEST, MAGNUM-PSI, PSI-2, and GyM samples (NCSRD)
SP B.3	D009 2 PM	Micro- and macroscale composition of layers on selected AUG, WEST, MAGNUM-PSI, PSI-2, and GyM samples (RBI)
SP B.3	D010 1.5 PM	Erosion and deposition patterns on selected WEST samples as well composition of plasma-exposed B and W layers (VR)
SP B.3	D011 2 PM	Depth profiles and composition of deposited layers of selected samples from AUG, WEST, W7-X, MAGNUM-PSI, PSI-2, and GyM (VTT)
SP B.3	D012 2 PM	Depth profiles for layers on selected WEST monoblock samples (UT)

SP B.2: WEST analysis: erosion and deposition patterns on PFUs (CEA)





Task and questions to be addressed

- Assess erosion of divertor PFUs phase 2

Approach

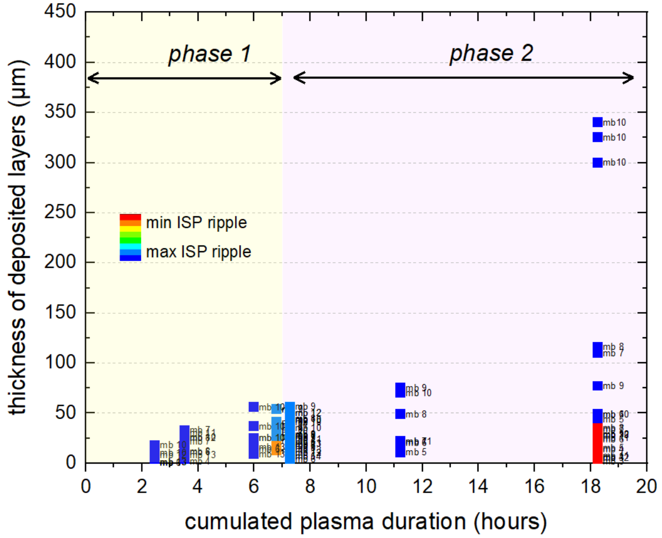
- Fiducials on the surface of 4 PFUs (CEA)
- Measurement of their depth using confocal microscopy – monitoring after each campaign (CEA)
- FIB analyses of the fiducials (MPG)

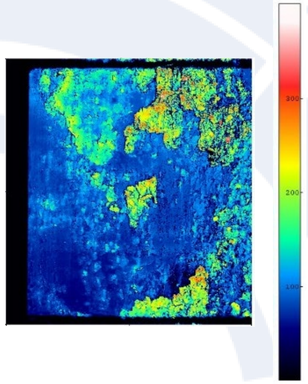
Results

- Fiducials clearly modified by plasma (change of depth, change of shape)
- ***Erosion might reach 20 µm at ISP after 18h of plasma***

Deliverable: **PWIE-SP B2.T-T005-D001**
Status: ***completed***
Facilities: **20 k€ consumables**
Linked WP or TSVV: **WPTE**

M. Diez et al.





Task and questions to be addressed

- Evaluate deposition behaviour on PFUs during phase 2

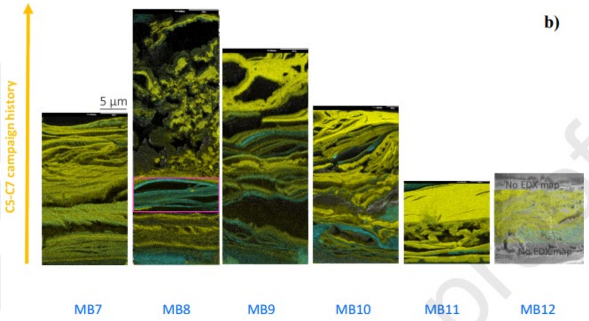
Approach

- Confocal microscopy on PFUs after C9 and C11 to determine thickness of deposited layers

Results

- ***Layers > 100 µm during phase 2***
- If no cleaning is carried out, layers can even ***grow up to 350 µm***

SP B.2: WEST analysis: analysis after the high-fluence campaign (CEA)



Task and questions to be addressed

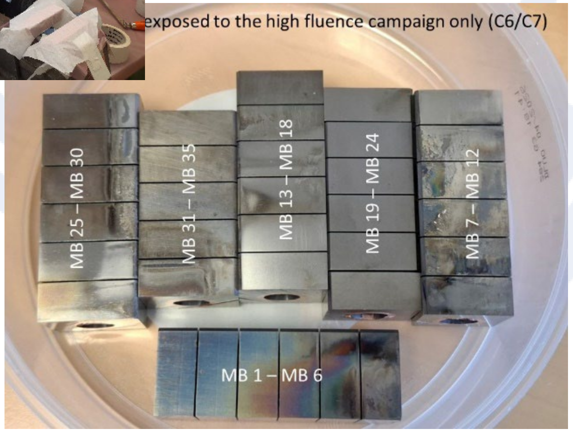
- Investigate/compare impact of high fluence campaigns (C7 and C12) on divertor targets

High fluence campaigns in WEST (C7, 2023 vs C12, 2025)

- Dedicated to reach particle fluence of ITER shots (W erosion /migration expected)
- Repetitive long discharges and 100s of pulses
- Cumulated plasma time 5 h 30 min (C7)

Characterization plan and results

- In-situ collection of deposits on 2 PFUs using sticky pads after C7 and analysis using SEM/EDX/FIB (CEA/AMU) – 2023/2024 → **Dense W layers of 5-40 µm thickness [1]**
- Identification of 1 PFU exposed to C7 and cutting into segments (CEA) – 2025 - **done**
  Plan : retention, morphology and thickness of deposits, cracks, morphology of flakes
- Identification of 1 PFU to be exposed to C12
  Pre-characterization using confocal microscopy (CEA/AMU) – 2025 **done**



Deliverable: **PWIE-SP B2.T-T005-D001**
Status: ***completed***
Facilities: **20 k€ consumables**
Linked WP or TSVV: **WPTE**

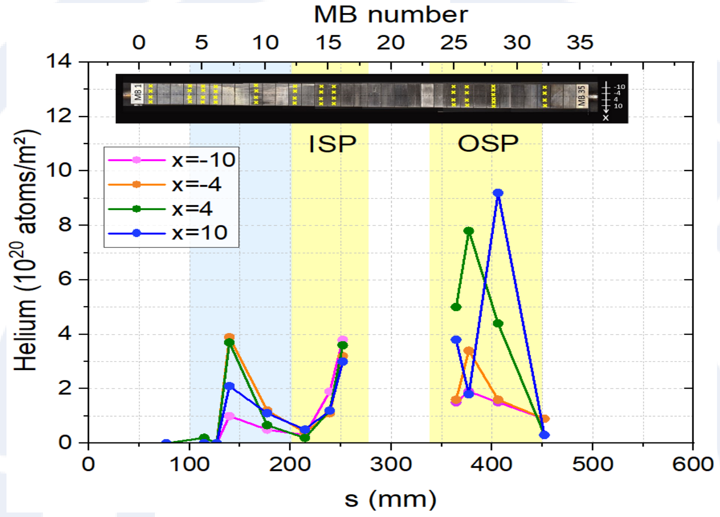
*[1] C. Martin et al., Nucl. Mater. Energy **41** (2024) 101764*

M. Diez, C. Martin et al.

SP B.2: Microscopy investigations of He-exposed PFUs after WEST Phase 1 (CEA)
SP B.3: Surface analyses of selected WEST monoblocks (RBI)

Task and questions to be addressed

- Carry out ion-beam analyses for samples exposed to the helium plasma operations on WEST and determine ***accumulation of He and B on the PFUs***
- Investigate changes in the surface state of the He-exposed PFUs



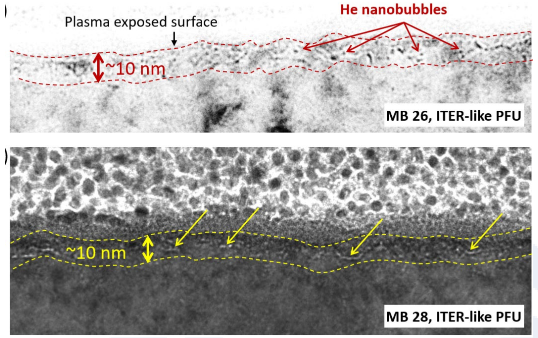
Approach

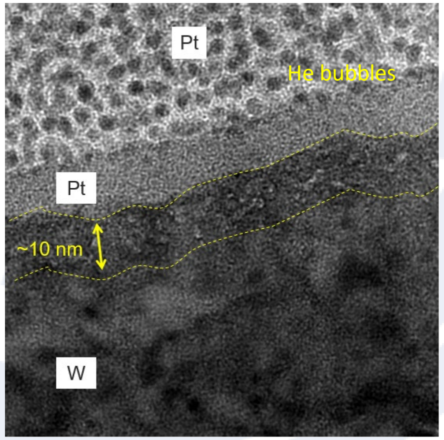
- TOF-ERDA analyses for samples from standard WEST Phase 1 PFUs as well as from 12 monoblock samples of the ITER-like PFU WECN001
- SEM/FIB/TEM analyses on the same samples after the TOF-ERDA measurements

Results

- ***Maximum He content found on SP (up at 10 at.%)*** on the standard tiles and ITER-like PFU
- ***Maximum He content on leading edge***
- Evidence of ***He bubbles*** found on the standard tiles and ITER-like PFU

→ Paper to be submitted before the end of the year





Deliverable: **PWIE-SP B.B3.T-T005-D009**
Status: ***completed***
Facilities: **accelerator 4 days**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B2.T-T005-D002**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE**

I. Bogdanovic Radovic et al.
C. Martin et al.

SP B.2: Analyses of (entire) WEST tiles (MPG)
SP B.3: Erosion/deposition profiles on samples from WEST (MPG)

Task and questions to be addressed

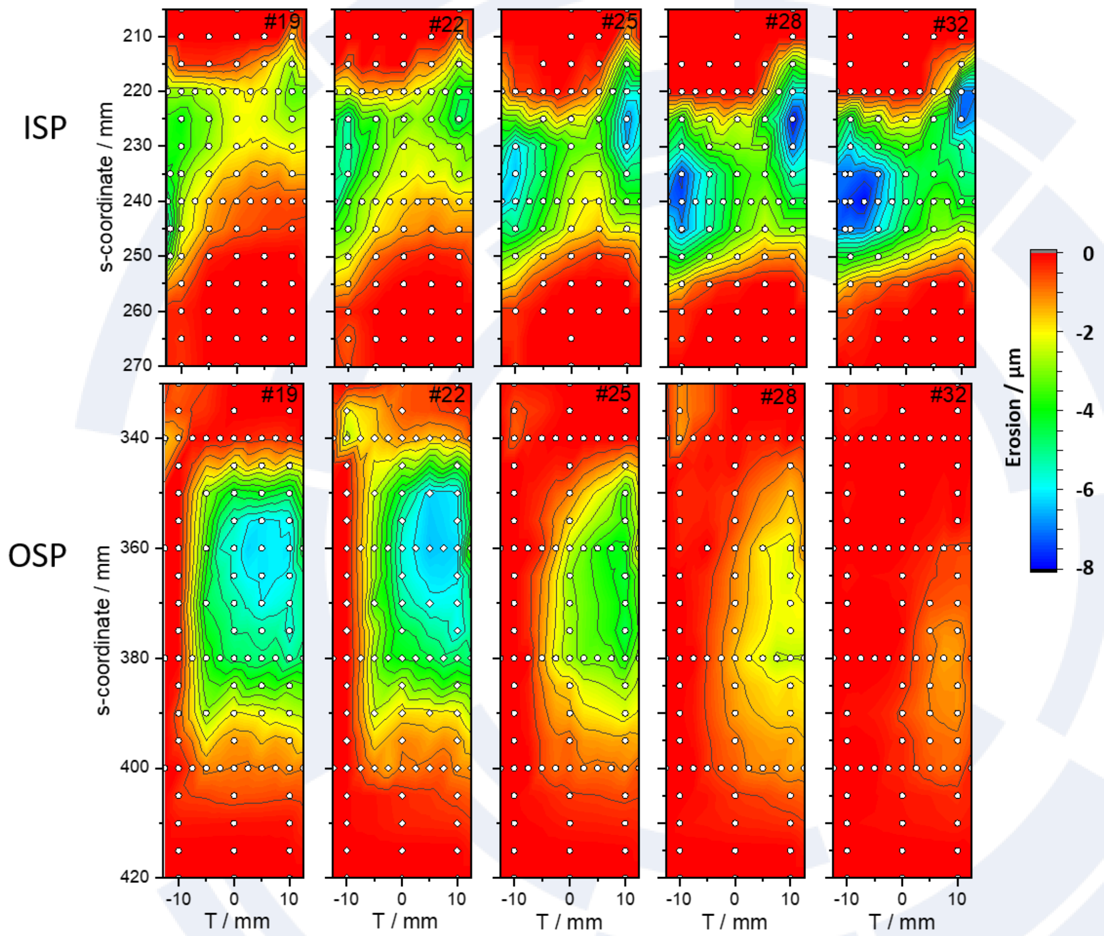
- Detailed investigation of selected PFUs from WEST, including side faces of marker tiles, at different locations with respect to magnetic ripple + IBA measurements of boronization samples

Approach

- SEM and IBA measurements performed on marker and standard tiles after C3, C4, C5 campaigns (Phase 1)
- First analysis of partial boronization (GDB) samples from WEST

Results

- Standard tiles dismounted after C5 from different positions in respect to the ripple in WEST - 2D erosion pattern determined (PFMC)
  - Some **~5-10 times different erosion rates between minima and maxima** of the ripple and with strong local variations
  - **Highest erosion on each tile is not at the toroidal central line** due to the beveling and shadowing of the tiles
- Gap sides of marker tiles analyzed (SEM, IBA): no conclusive results achieved



Deliverable: **PWIE-SP B.B2.T-T005-D003**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B.B3.T-T005-D007**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPTE**

M. Balden et al.

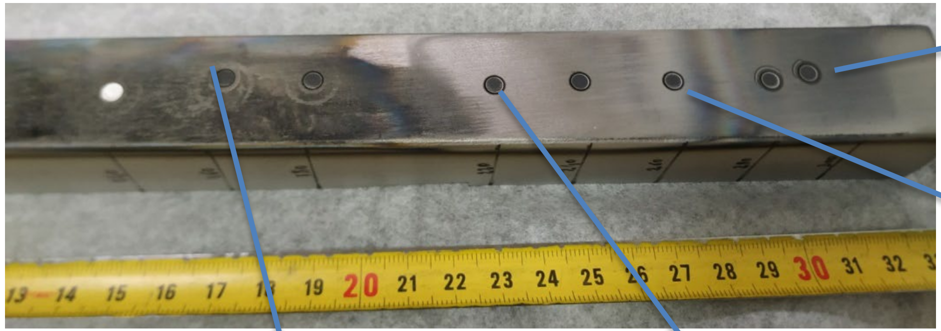
SP B.3: Composition of layers on WEST monoblock samples (IAP)

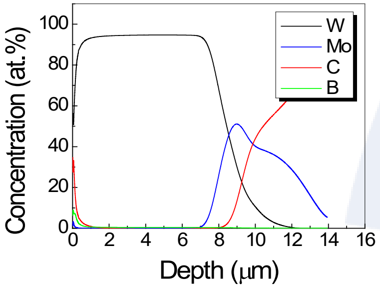
5 ISP and **5 OSP** W coated tiles from different toroidal locations analyzed by *GDOES*

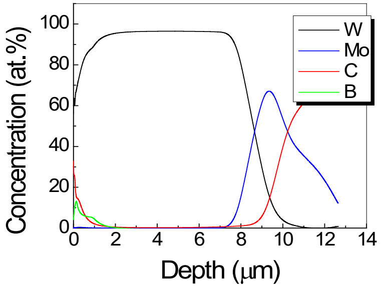
Task and questions to be addressed

- Elemental depth profiles and erosion/deposition patterns evaluated

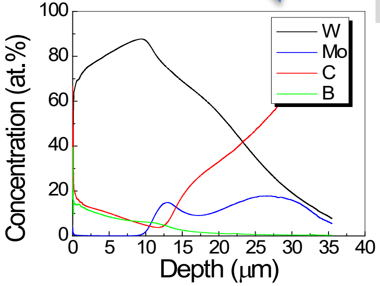
Results:

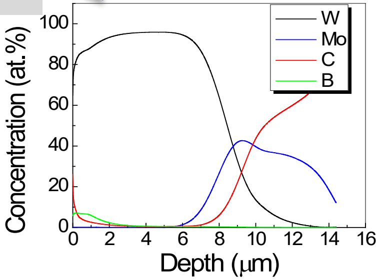






Inner tile #18

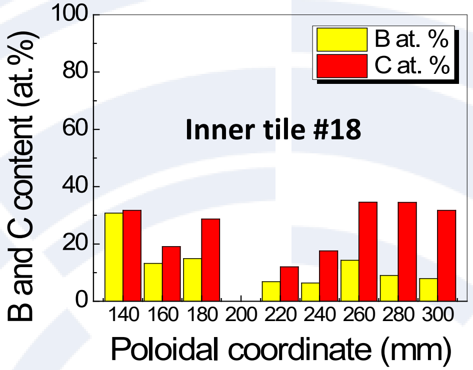


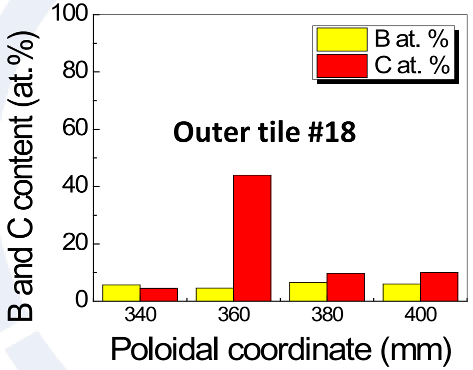


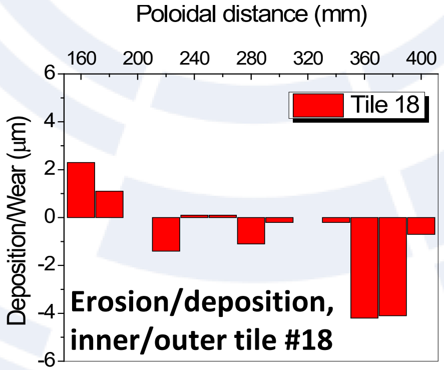
Deliverable: **PWIE-SP B.B3.T-T005-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

Conclusions:

- B detected on all tiles, peaks on the inner side
- Erosion/deposition patterns for W also available







E. Grigore, F. Baiasu, M. Gherendi

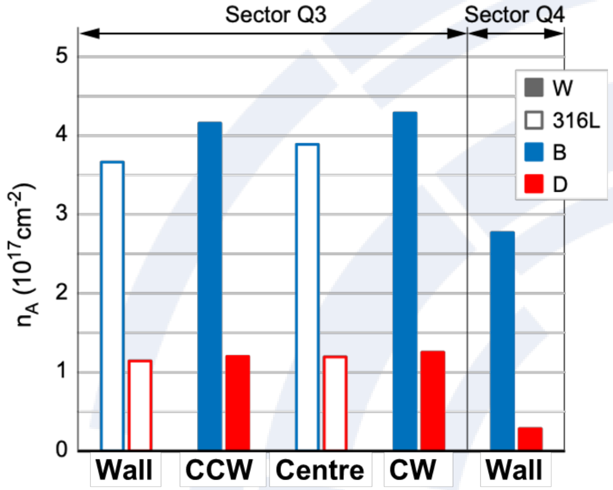
SP B.2: Analyses of (entire) WEST tiles (MPG)
SP B.3: Erosion/deposition profiles on samples from WEST (MPG)

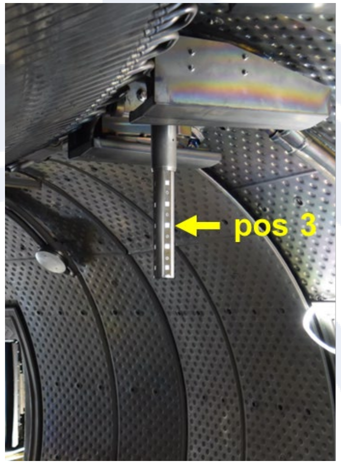
Task and questions to be addressed

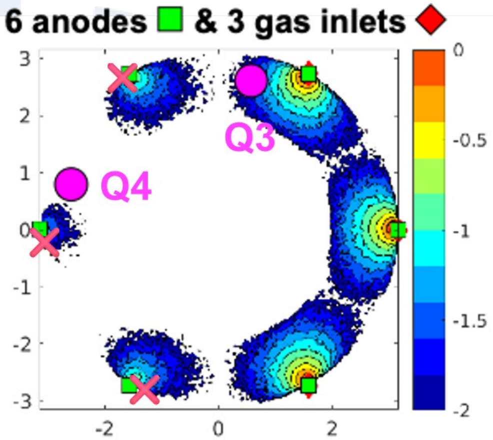
- Detailed investigation of selected PFUs from WEST, including side faces of marker tiles, at different locations with respect to magnetic ripple + IBA measurements of boronization samples

Approach

- SEM and IBA measurements performed on marker and standard tiles after C3, C4, C5 campaigns (Phase 1)
- First analysis of partial boronization (GDB) samples from WEST







Results

- Samples (W, 316L steel) exposed during partial GDB by two manipulators
- Deposition rate **lower in sector Q4 but much smaller effect** than predicted (×2.5 vs ×100)
- **No angular dependency** of deposition on samples inside glow discharge
- D/B fraction at Q4 factor 3 lower than at Q3 near active gas inlet

Deliverable: **PWIE-SP B.B2.T-T005-D003**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B.B3.T-T005-D007**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPTE**

K. Krieger et al.

SP B.3: Surface modifications and composition of layers on selected WEST, MAGNUM-PSI, PSI-2, and GyM samples (NCSRD)

Motivation: In the initial phase of ITER operations (SRO), the boronization will be toroidally non-symmetric

Non uniform boronization performed at WEST

(20 samples from 2 sample holders, 4 sides and 3 positions were analyzed after)

Task and questions to be addressed

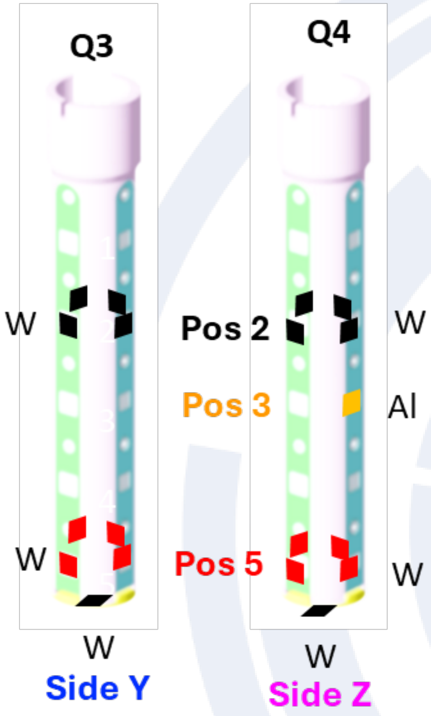
- How uniform is the B layer formation after non-uniform boronization?
- What is the modification of elemental composition after air exposure?

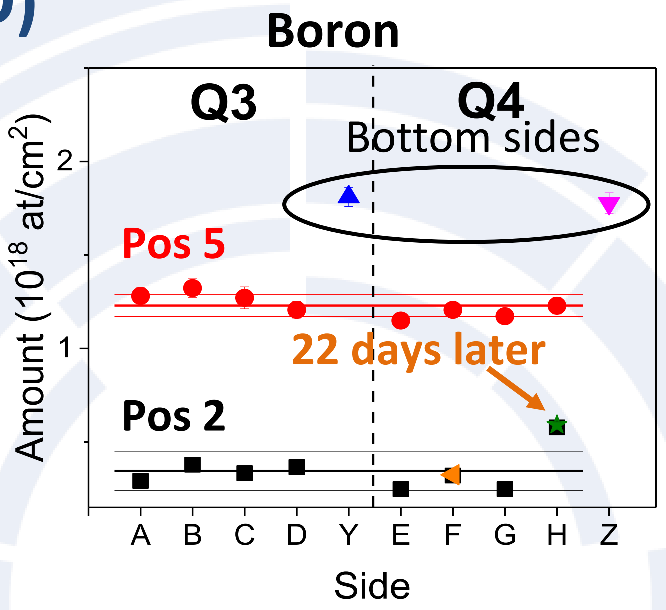
Methodology

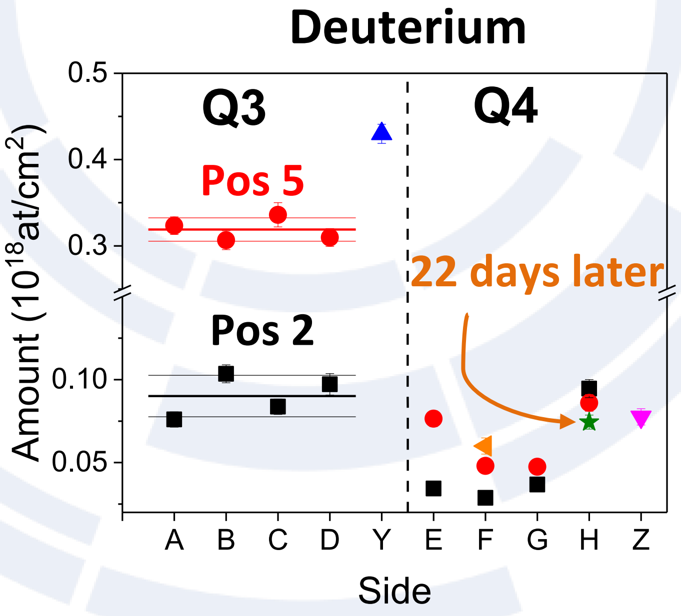
- RBS/NRA with d beam (1.4 MeV)

Results

- **Boron:** **No dependence on probe & side**; **dependence** on **vertical** position (~3.5 × **more B** in **pos 5** than in **pos 2); No change** after 22 days in air
- **Deuterium:** **Dependence** on **probe**; **dependence** on **vertical** position **only for Q3 (~3.5 × more D** in **pos 5** than in **pos 2); 22% decrease** after 22 days in air





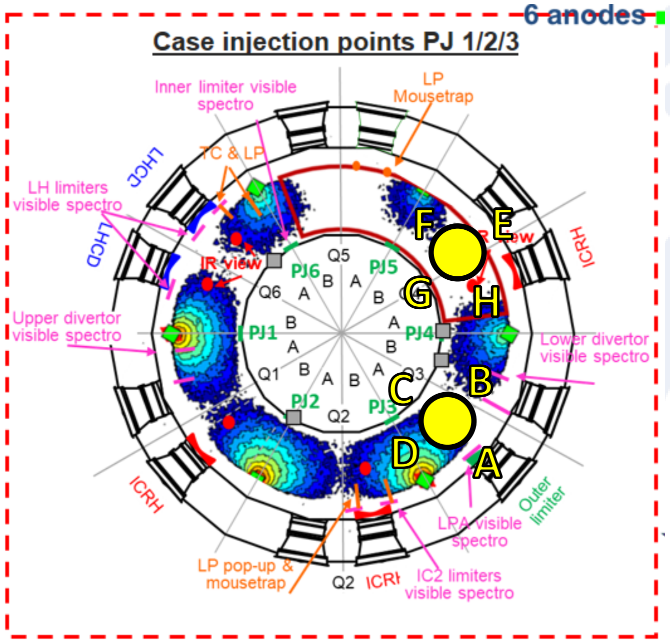


Deliverable: **PWIE-SP B.B3.T-T005-D008**
Status: ***completed***
Facilities: **Accelerator 4 days**
Linked WP or TSVV: **WPTE**

P. Tsavalas, K. Mergia, A. Lagoyannis, M. Axiotis

SP B.3: Ion Beam Analysis of boronization samples from WEST (VR)

Non-uniform boronization performed at WEST (PJ 1-3 out of 6).



Evaluate the uniformity of B layers in WEST:

- Homogeneity in toroidal position and vertical direction.
- Homogeneity in 4 toroidal directions.
- Amount of oxygen trapped in the boron layers.
- Presence of He in layers? Stability of layers in air?

Approach

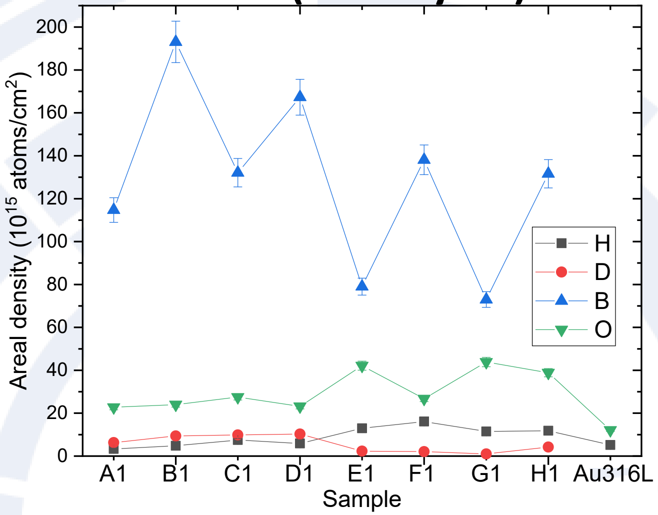
- **Samples received:** Au/boron layer/316L.
- Combination of different ion beam techniques (performed on different days, study ageing effect)

Results

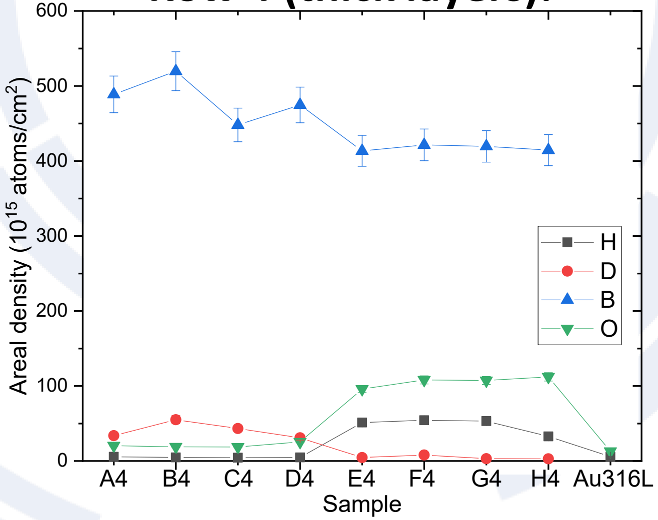
- **Vertical direction:** Boron layer in row 4 (A4-H4) significantly thicker than row 1 (A1-H1).
- **Toroidal Position:** Higher oxygen + hydrogen and lower deuterium in E-H samples, further from PJ 1-3.
- **Oxygen trapped:** Inverse correlation between boron and oxygen.
- **Future step:** Compare with uniform boronization (PJ 1-6).

Deliverable: **PWIE-SP B.B3.T-T005-D010**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

Row 1 (thin layers):



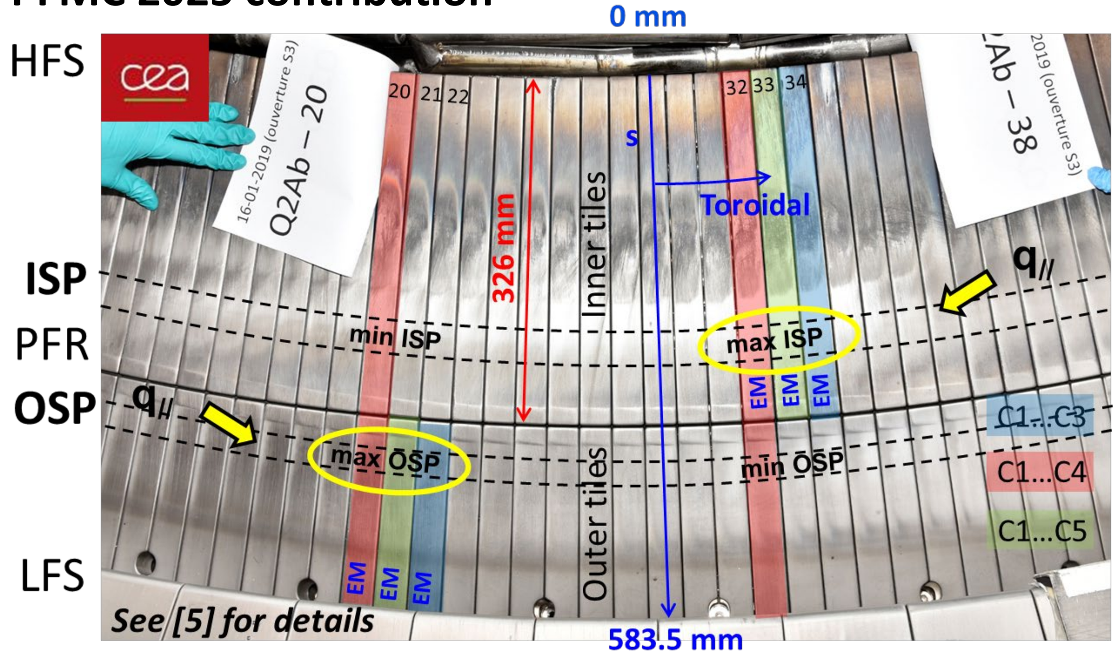
Row 4 (thick layers):

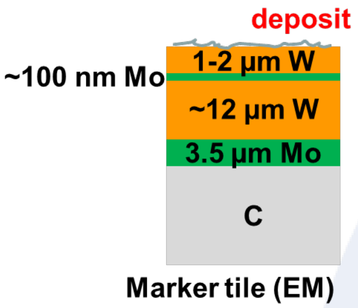


E. Pitthan, P. Petersson, M. Dhar, D. Gautam, M. Rubel, D. Primetzhofer

SP B.3: Composition of deposited layers on WEST during Phase 1 (VTT)

PFMC 2025 contribution





- Altogether **8 marker tiles** installed on the WEST divertor before Phase 1 and **sequentially removed after C3, C4, and C5**
- This work: data reported from 6 tiles (HFS and LFS regions) around the **maxima of the toroidal ripple**

- **5 campaigns carried out in Phase 1** – more than 7 h of plasma exposure
- **Boronizations** started during C3 and most of them (13) carried out in C4

	Plasma disch.	Cumulative time (s)	Disruptions	W_{LH} total (MJ)	W_{IC} total (MJ)	# Boro
C2 Nov17-Feb18	**716**	**1553**	**282**	**95.5**	**0**	**0**
C3 July-Dec18	**1076**	**7329**	**796**	**4947**	**105**	**3**
C4 July-Nov19	**1442**	**12669**	**1042**	**12123**	**1142**	**13**
C5 Nov20-Jan21	**655**	**4630**	**460**	**2625**	**182**	**2**

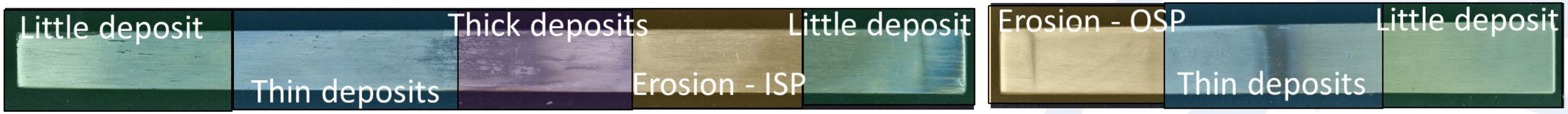
Deliverable: **PWIE-SP B.B3.T-T005-D011**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

A. Hakola et al.

SP B.3: Composition of deposited layers on WEST during Phase 1 (VTT)

PFMC 2025 contribution

S = 0 mm **S = 326 mm** **S = 583.5 mm**



THIN DEPOSITS (see figures)

- Thickness considerably **increases from C3 to C4** and a bit more to C5; surface layers strongly oxidized
- **Sublayers identified**: (i) B-rich layer <0.5 μm, (ii) metallic impurities ~0.5-1 μm, (iii) Mo marker at ~1.5 μm

EROSION AREAS

- **Mixture of different elements**, no clear deposition peaks
- Erosion amplified from C3 to C5

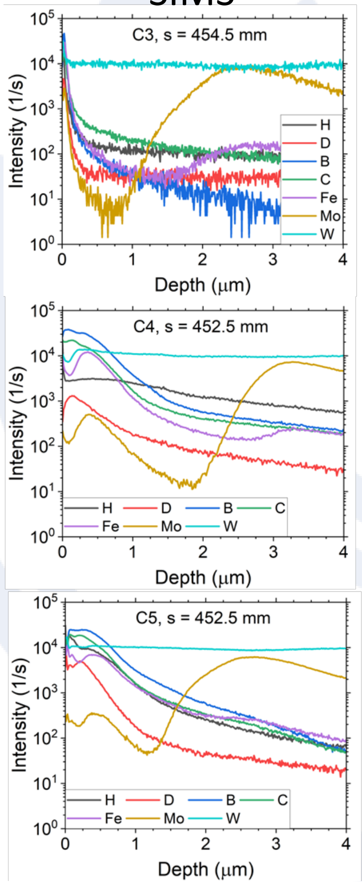
THICK DEPOSITS

- Thickness increases from ~3 μm to >10 μm from C3 to C5 – all elements show **relatively flat profiles**
- B at the top, metallic impurities deeper down (~1.5-3 μm), and **D levels lower** than on thin deposits

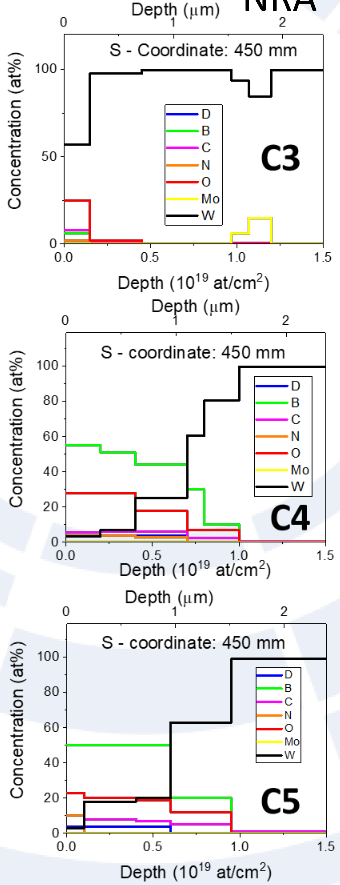
> - Layers mainly consist of B, O, and C as well as W
> - Especially "thin deposits" show clear sublayers rich in B+C+O and/or metallic elements while stratified structures identified in the "thick deposits"

Deliverable: **PWIE-SP B.B3.T-T005-D011**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

SIMS

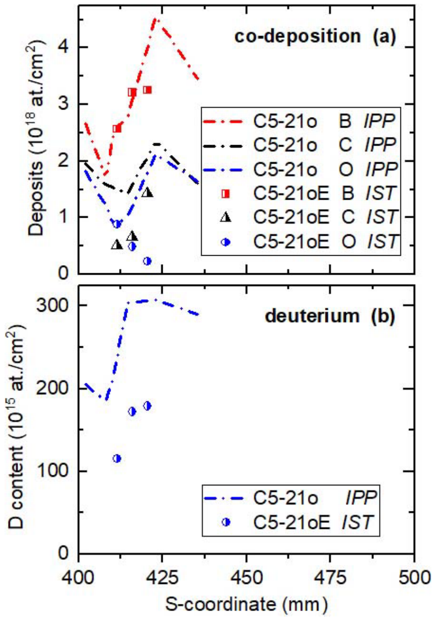


NRA



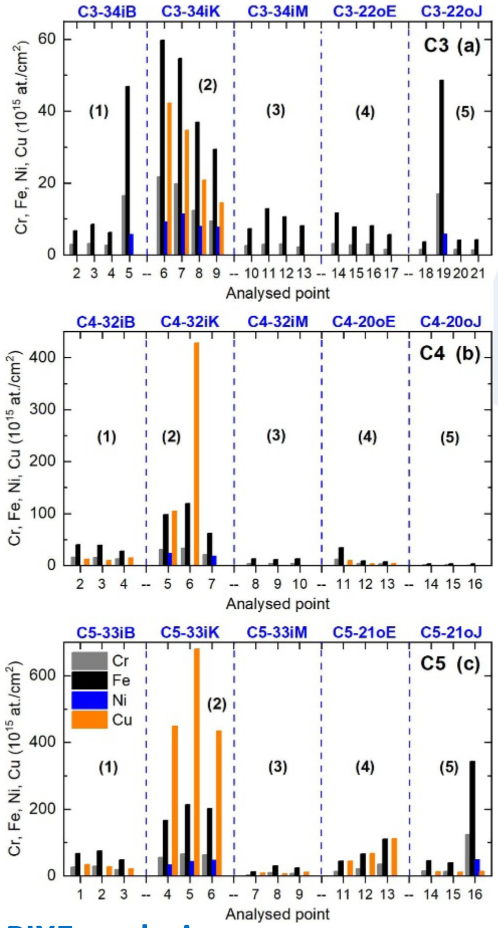
A. Hakola et al.

SP B.3: Composition and fuel content of layers on WEST samples (IST)



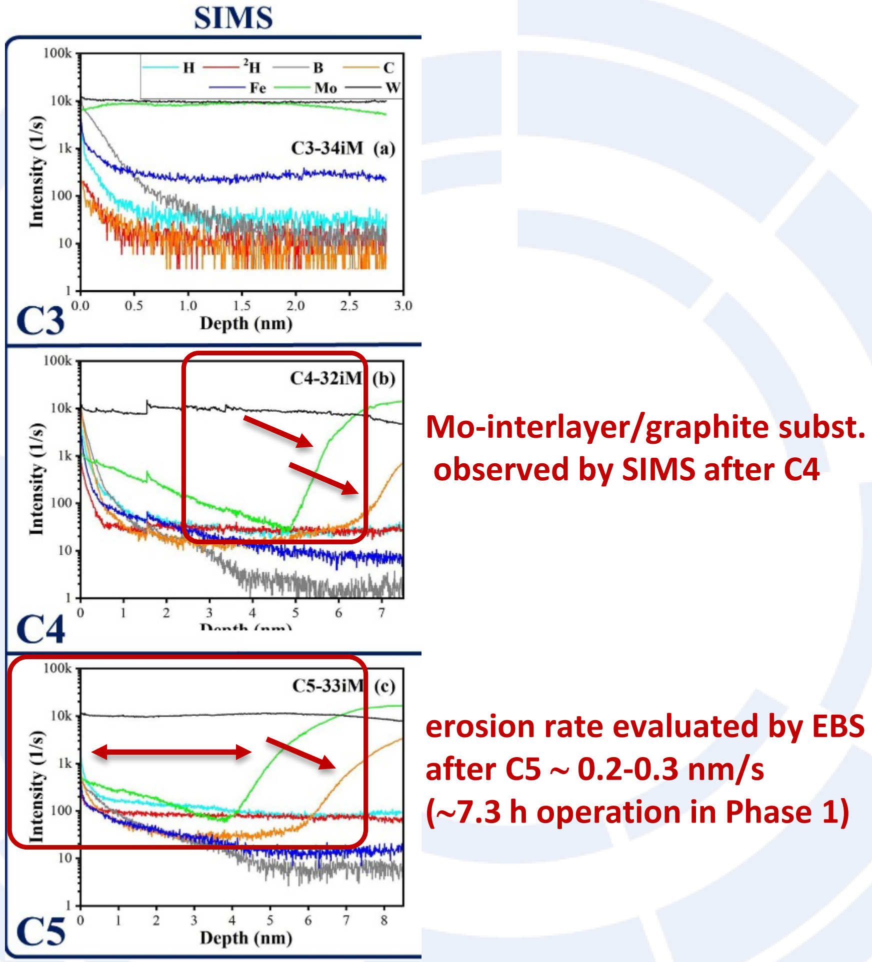
D, B, C, O content after the C5 campaign at s ~ 415 mm (OSP region):

- significant deposition behaviour (confirm the results from entire C5-21o tile (at IPP)



PIXE analysis:

- Fe:Cr:Ni ratios → stainless steel
- PIXE and IBA agree with each other



Detailed SIMS + EBS analysis at s ~ 238 mm (ISP)

Main conclusions

- Erosion rate of 0.2-0.3 nm/s at ISP in Phase 1
- Thick deposits after C4-C5 difficult to find in the disks by IBA (stability of B-rich layers ?)

Deliverable: **PWIE-SP B.B3.T-T005-D005**
Status: ***completed***
Facilities: **Accelerator 5 days**
Linked WP or TSVV: **-**

R. Mateus, N. Catarino, E. Alves

SP B.3: Depth profiles for layers on selected WEST samples (UT)

Task and questions to be addressed

- Perform surface analyses (including LIBS) for selected WEST samples

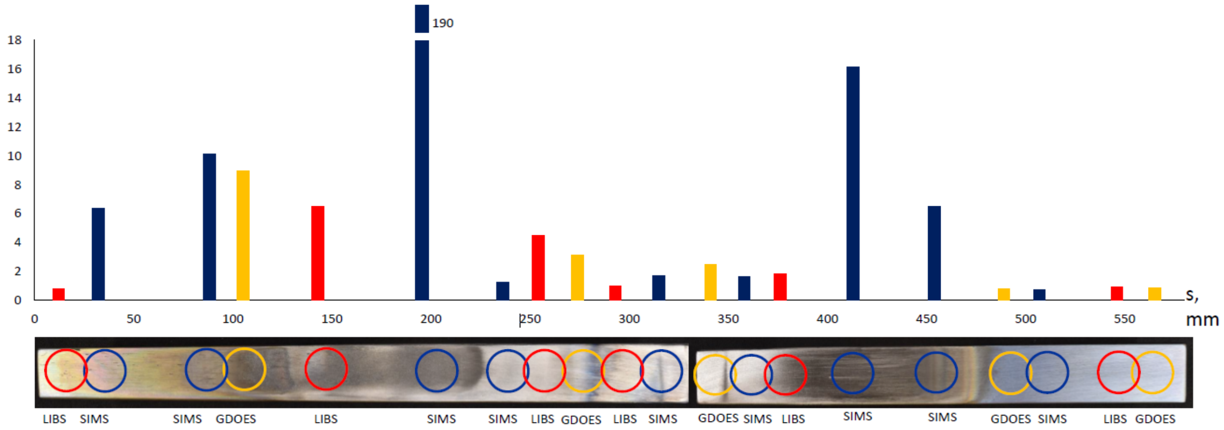
Approach

- Use ns-LIBS method for the composition analysis of the samples of interest, unfortunately the applied ns laser is now broken beyond repair
- The scope of the task was therefore changed to more detailed analysis of the existing data and reporting the results in PFMC 2025

Results

- LIBS allows determining the main elements of (W, Mo, C) + impurities (B) on C4 erosion marker tiles
- Strongest B I lines near 250 nm overlap with W II lines but their influence can be accounted for by using the intensities of adjacent W II lines
- LIBS depth profiles reproduced the layered structure on the erosion marker tiles similarly to SIMS, GDOES and other methods
- **Different methods give generally consistent B depth profiles and integral amounts with some outstanding cases on the thick deposits** → most likely due to high ablation rate for porous co-deposits

Deliverable: **PWIE-SP B.B3.T-T005-D012**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**



Combination of data by LIBS, SIMS, and GDOES for integrated B content on the analyzed C4 marker tiles

I. Jõgi, P. Paris

SP B.3: Surface modifications of selected WEST samples (IPPLM)

General Information

Examined samples: (i) WEST monoblock MB28, and (ii) 16 boronization samples from WEST

Task and questions to be addressed

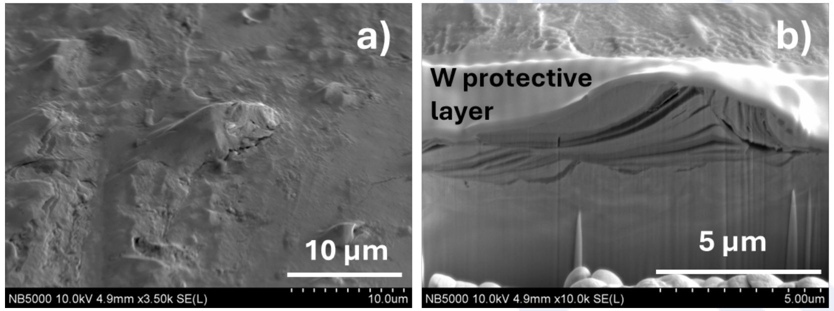
(i) assess surface modifications of the samples and (ii) co-deposits formed, including boron layers

Approach

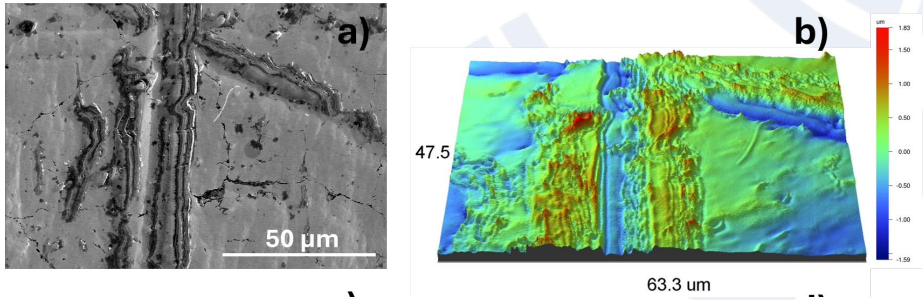
- Microscopic surface observations, EDX analysis, as well as FIB cross-sections and observations using optical profilometer studies
- On each boronization sample, FIB cross-sections made to assess the thickness of the boron layers

Results – MB28

- Only a **small part of the surface covered with deposits** (**outer divertor region**), mostly in shadowed areas. Deposits contain oxygen, boron, nitrogen, iron and copper
- Numerous **elongated objects/outgrowths** with well-defined/specified directions and layered structure observed



SEM image of the outgrowth (a) and its FIB cross-section (b).



SEM image of the morphology of deposits (a) and its 3D map (b).

Deliverable: **PWIE-SP B.B3.T-T005-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

E. Fortuna-Zaleśna

SP B.3: Surface modifications of selected WEST samples (IPPLM)

General Information

Examined samples: (i) WEST monoblock MB28, and (ii) 16 boronization samples from WEST

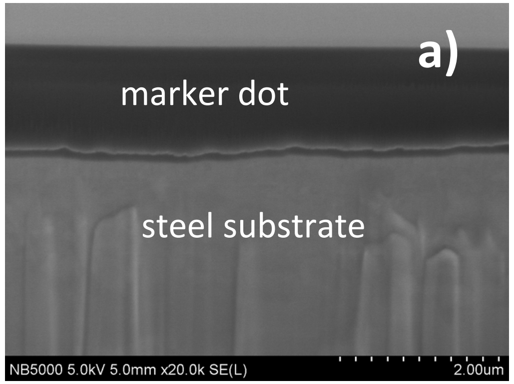
Task and questions to be addressed

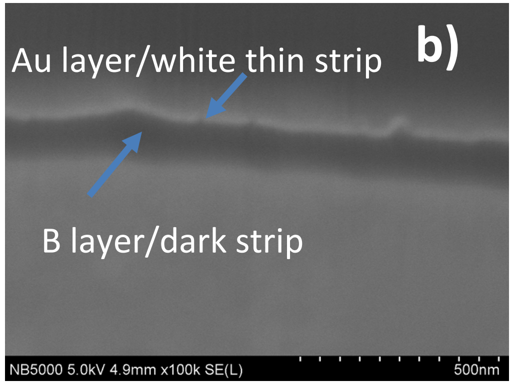
(i) assess surface modifications of the samples and (ii) co-deposits formed, including boron layers

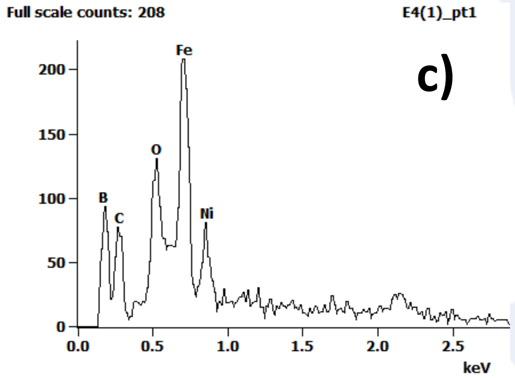
Approach

- Microscopic surface observations, EDX analysis, as well as FIB cross-sections and observations using optical profilometer studies
- On each boronization sample, FIB cross-sections made to assess the thickness of the boron layers

Results – boronization samples







SEM cross-section across the layer, sample E4 (a, b), and the corresponding EDX spectrum (c)

- *Protective Au layer on top*
- *Presence of B in a thin layer between the steel substrate and the Au layer*
- *Considerably thicker B layer on the A→H4 samples than on the A → H1 samples*

Deliverable: **PWIE-SP B.B3.T-T005-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

E. Fortuna-Zaleśna

SP B.2: Analyses of samples from AUG (MPG)

General Information

- Samples with **Pt marker layers** (as proxy for W) and **FIB-created depth markers** on bulk W exposed to dedicated AUG discharges with Ne seeding
- Boron layers created during boronisations (GDB) studied by exposing **witness samples during and immediately following GDBs**

Task and questions to be addressed

- Erosion and prompt redeposition of tungsten (and proxies to it)
- Spatial distribution, properties, deposition rates and D-retention of boron layers created by GDB

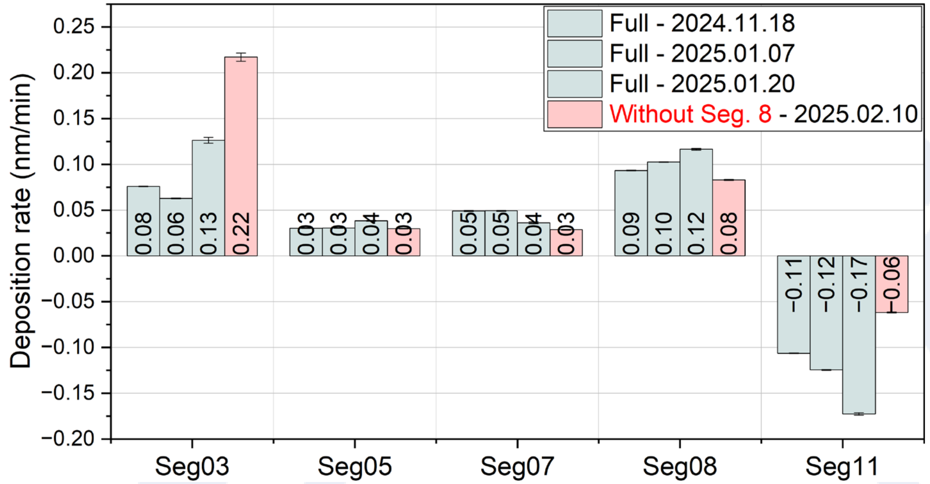
Approach

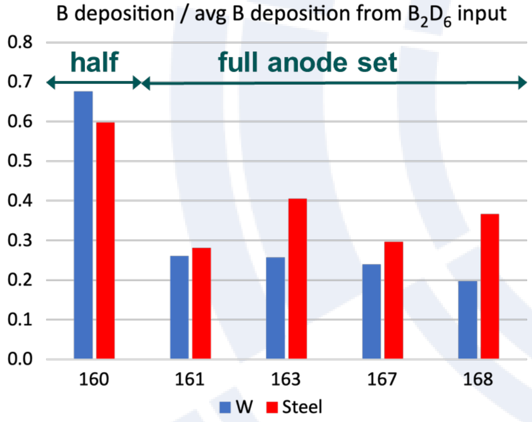
- Samples characterised by ion beam methods (RBS, NRA, PIXE) and SEM analysis before and after exposure

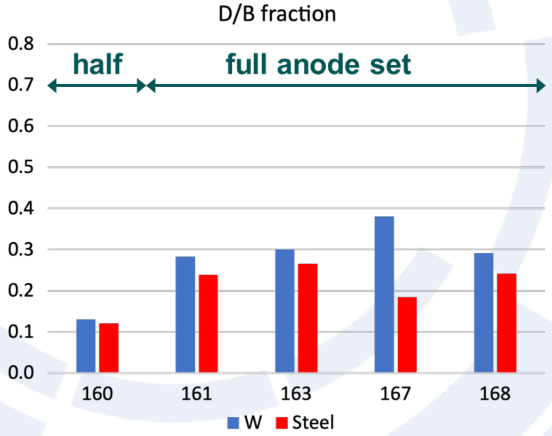
Results

- Deposition efficiency of AUG boronisations using **partial and full set of glow anodes assessed** and compared to *in situ* QMBs
- **Erosion-deposition patterns** of W in the divertor studied following the L- and H-mode experiments

Deliverable: **PWIE-SP B.B2.T-T005-D004**
Status: ***completed***
Facilities: **Accelerator 5 days**
Linked WP or TSVV: **WPTE**







Top: Deposition on QMBs shows significant toroidal variations and indicates that GDB not only deposits but also erodes material
Bottom: In contrast to QMB, higher B deposition on samples with half-GDB and lower D/B ratio

NB! B&D depletion by exposure to air with lower rate compared to the WEST GDB layers → attributed to higher T_{wall}

M. Balden, K. Krieger et al.

SP B.2: Analyses of samples from AUG (VTT)
SP B.2: Deposition profiles on samples from AUG (RBI)

General Information

- Samples with **Pt marker layers** (as proxy for W) and **FIB-created depth markers** on bulk W exposed to dedicated AUG discharges with Ne seeding

Task and questions to be addressed

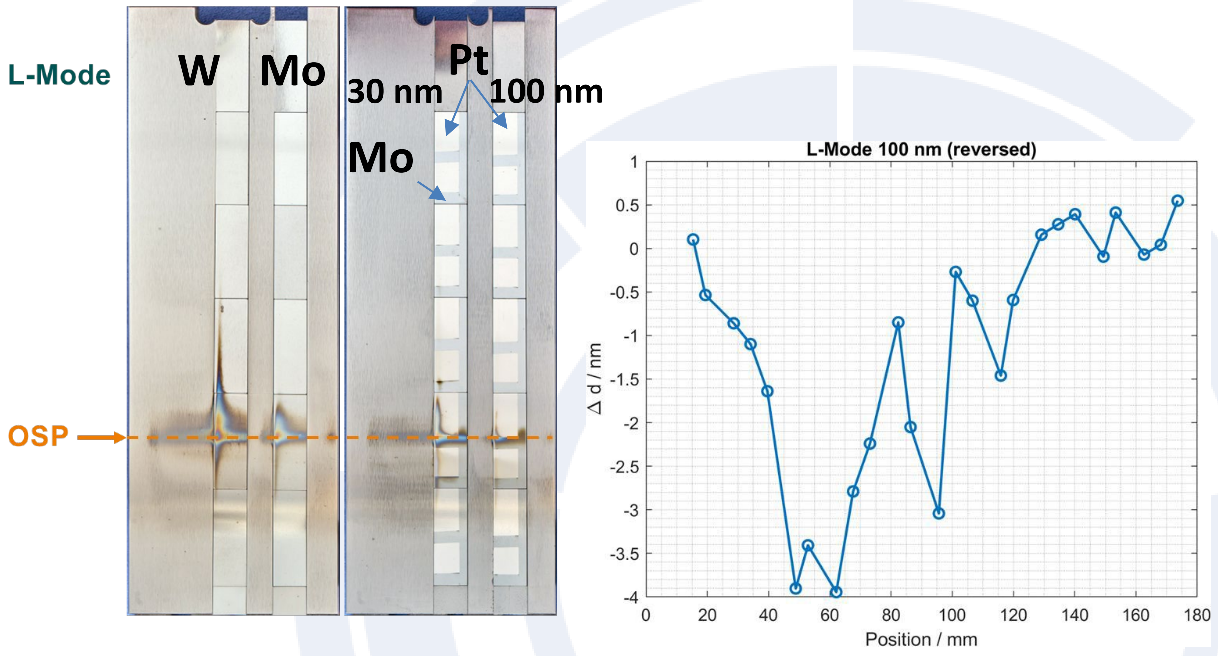
- Erosion and prompt redeposition of Pt as well as other elements on the samples, both macroscopically and in the µm scale

Approach

- Samples characterised by ion beam methods (RBS, NRA, PIXE, TOF-ERDA) following their exposure to L- and H-mode discharges

Results

- Large **difference in the erosion characteristics** of Pt markers after the L- and H-mode experiment
- **Deposition observed for the first time also between the markers**, elemental composition still to be clarified



Photograph of divertor tiles exposed to AUG L-mode plasma discharges and poloidal erosion/deposition profile for the 100-nm thick Pt markers.

Deliverable: **PWIE-SP B.B2.T-T005-D005**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B.B2.T-T005-D006**
Status: ***ongoing (to be completed in the end of 2025)***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

A. Hakola, S. Saari

SP B.2: Analyses of samples from AUG (VTT)
SP B.2: Deposition profiles on samples from AUG (RBI)

General Information

- Samples with **Pt marker layers** (as proxy for W) and **FIB-created depth markers** on bulk W exposed to dedicated AUG discharges with Ne seeding

Task and questions to be addressed

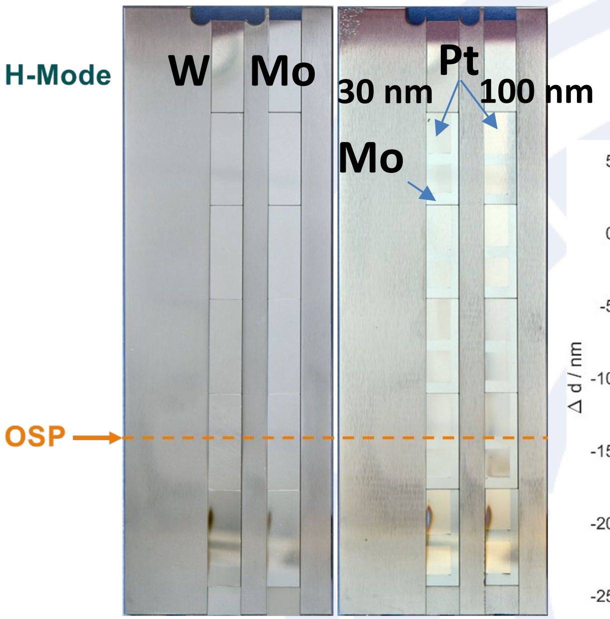
- Erosion and prompt redeposition of Pt as well as other elements on the samples, both macroscopically and in the μm scale

Approach

- Samples characterised by ion beam methods (RBS, NRA, PIXE, TOF-ERDA) following their exposure to L- and H-mode discharges

Results

- Large **difference in the erosion characteristics** of Pt markers after the L- and H-mode experiment
- **Deposition observed for the first time also between the markers**, elemental composition still to be clarified



Photograph of divertor tiles exposed to AUG H-mode plasma discharges and poloidal erosion/deposition profile for the 100-nm thick Pt markers.

Deliverable: **PWIE-SP B.B2.T-T005-D005**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B.B2.T-T005-D006**
Status: ***ongoing (to be completed in the end of 2025)***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPTE**

A. Hakola, S. Saari

SP B.2: Changes in the surface properties of samples exposed on AUG (FZJ)

Task and questions to be addressed

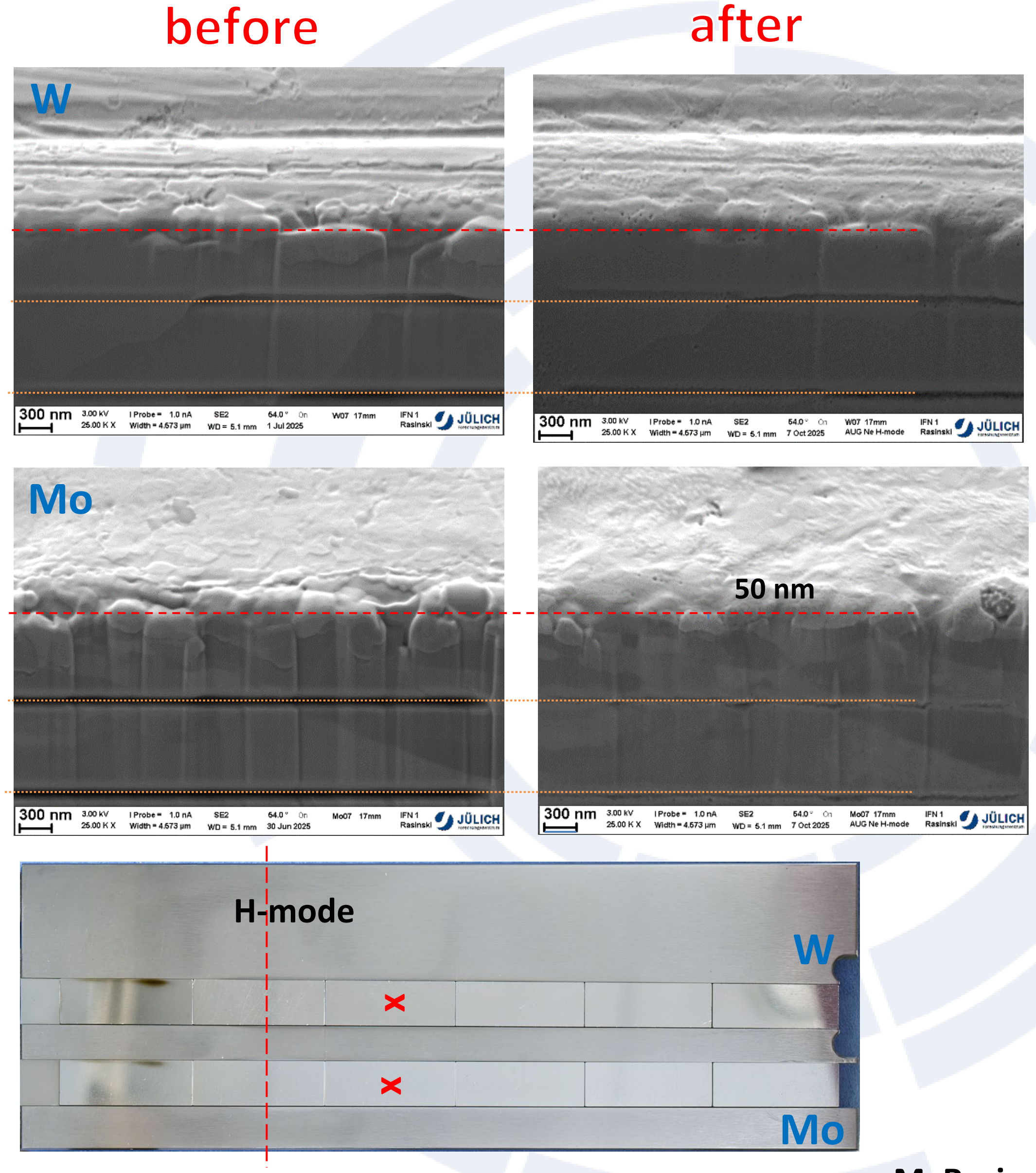
- Analysis of W and Mo samples exposed in AUG to L-mode and H-mode plasmas with Ne seeding

Approach

- Set of samples were pre-characterized and prepared for the AUG exposure (FIB cross-sections for erosion/deposition studies)
- After AUG exposures samples were characterized by means of electron microscopy techniques

Results

- **Low erosion spotted** for Mo samples exposed to H-mode AUG plasma (at most 50 nm).
- Erosion below 50 nm of W samples exposed to H-mode AUG plasmas
- No visible erosion of both Mo and W exposed to L-mode AUG plasmas



M. Rasinski

Deliverable: **PWIE-SP B.B2.T-T005-D007**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE**

SP B.3: Analyses of wall tiles originating from AUG (MPG)

General Information

- Determine erosion and deposition patterns on various plasma-exposed tiles

Task and questions to be addressed

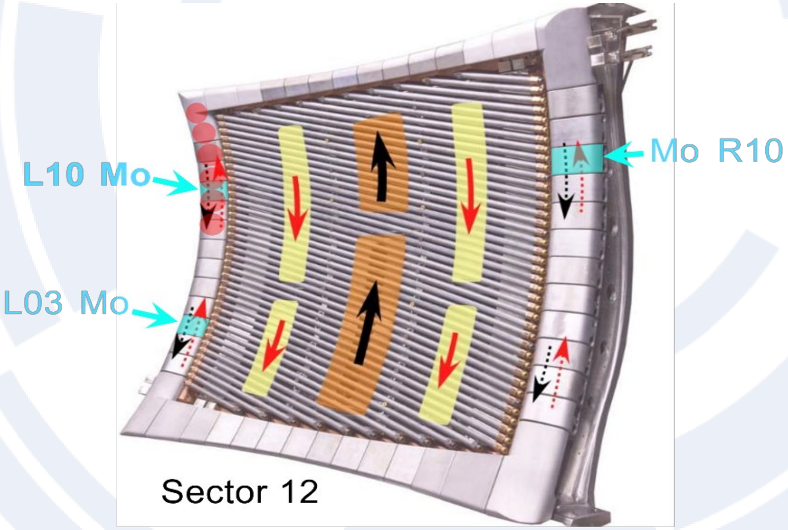
- Perform surface analyses for erosion, deposition and surface-modification patterns on wall components retrieved from AUG

Approach

- SEM and IBA measurements performed at many analysed spots on several exposed tiles

Results

- Erosion patterns on AUG ICRH limiter marker tiles determined: **maximum erosion of Mo-coated graphite tiles below 1 µm** → provides feedback to the dedicated ICRH experiment under WPTE
- Thickness of deposits with respect to boron deposition determined on many **long-term samples as well as on 8 pre-characterised tiles**, exposed only during one campaign



Deliverable: **PWIE-SP B.B3.T-T005-D007**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPTE**

M. Balden

SP B.2: Analyses of W7-X samples (MPG)
SP B.3: Erosion/deposition profiles of samples from W7-X (MPG)

Task and questions to be addressed

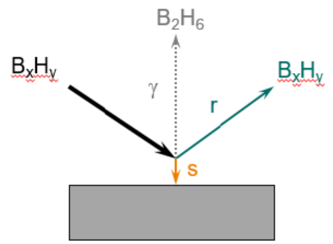
- Determine erosion and deposition patterns on manipulator samples from OP2 experiments and boronizations on W7-X with the focus on the amount of B on selected locations

Approach

- IBA measurements for all the available W7-X samples
    - Cavity samples to assess sticking of B (radicals)
    - B erosion and deposition rates during/after boronizations

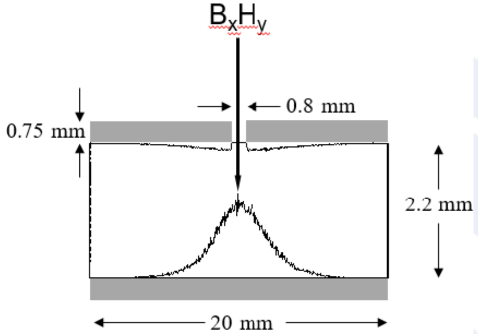
Results

- Surface loss probability β measured for boron radicals during boronizations on W7-X and AUG
    - **Ions: $\beta \approx 0.2$ Neutrals: $\beta \approx 1.0$**
- **Open question**: Which ion/radical species: B^+, BH^+, BH_2^+, … $B_2H_6^+$?

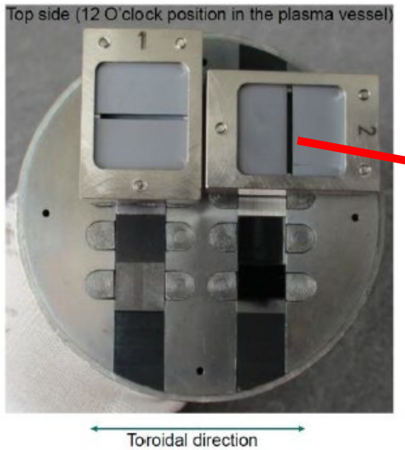


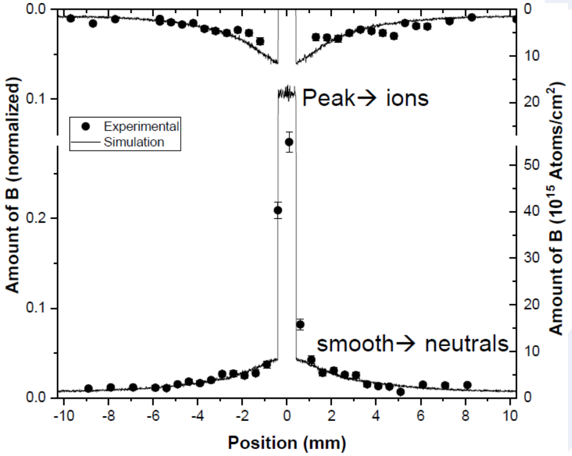
s: sticking coefficient
r: reflection coefficient
γ: reaction probability

$\beta = s + \gamma = 1 - r$: surface loss probability



Cavity technique: $r \Rightarrow \beta$





Deliverable: **PWIE-SP B.B2.T-T005-D009**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPW7X**

Deliverable: **PWIE-SP B.B3.T-T005-D007**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPW7X**

M. Mayer, C.P. Dhard

SP B.2: Analyses of W7-X samples (MPG)
SP B.3: Erosion/deposition profiles of samples from W7-X (MPG)

Task and questions to be addressed

- Determine erosion and deposition patterns on manipulator samples from OP2 experiments and boronizations on W7-X with the focus on the amount of B on selected locations

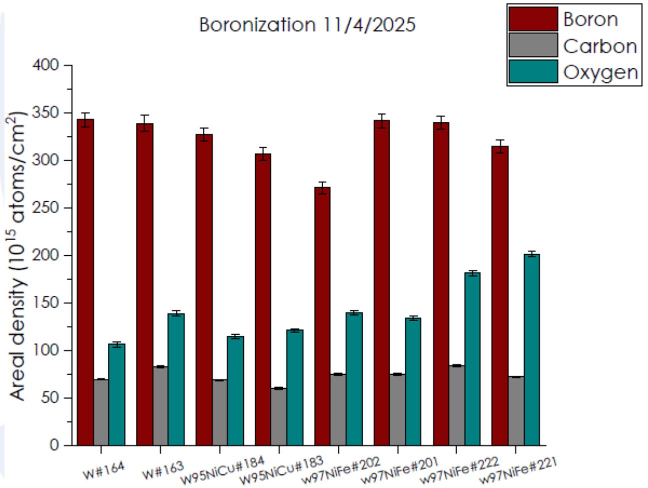
Approach

- IBA measurements for all the available W7-X samples
    - Cavity samples to assess sticking of B (radicals)
    - B erosion and deposition rates during/after boronizations

Results

- **No correlation** between the substrate material or surface roughness and the boron layer thickness
- **Thicker boron layers present lower C/B and O/B ratios**
- Higher carbon concentrations in OP2.3 than in OP2.2

Sample Name	Boron layer thickness		Carbon layer thickness			Oxygen layer thickness		
	average 10^{15} atoms/cm², nm	std. dev (%)	average 10^{15} atoms/cm²	std. dev (%)	C/B	average 10^{15} atoms/cm²	std. dev (%)	O/B
OP2.2								
13.09.2024	93.2, 7.1	12.2	46.0	15.1	**0.49**	77.9	4.4	**0.8**
21.10.2024	80.2, 6.1	4.0	36.5	43.1	**0.35**	68.1	6.1	**0.8**
OP2.3								
14.02.2025	152.6, 11.7	4.9	48.8	14.3	**0.32**	109.6	16.9	**0.72**
11.04.2025	323.0, 24.7	7.2	73.5	9.9	**0.23**	142.2	21.7	**0.44**



Deliverable: **PWIE-SP B.B2.T-T005-D009**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPW7X**

Deliverable: **PWIE-SP B.B3.T-T005-D007**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPW7X**

M. Mayer, C.P. Dhard

SP B.2: Analyses of samples from W7-X manipulator experiments (FZJ)
SP B.3: Surface modifications and fuel content of selected W7-X samples (FZJ)

Task and questions to be addressed

- Investigate erosion and surface modification of various samples exposed to W7-X plasmas
- Perform surface analyses for erosion, deposition, fuel-retention, and surface-modification patterns on wall components and samples (including LIBS) retrieved from W7-X

Approach

- Preparation and pre-characterization of W and Mo samples before W7-X OP2.3 exposures and post-exposure analyses using SEM, EDX, FIB, NRA, and LIBS after OP2.3

Results

- All samples were **pre-characterized, prepared and successfully exposed** in W7-X using the MPM manipulator
- Post characterization ongoing, to be continued in 2026

Deliverable: **PWIE-SP B.B2.T-T005-D008**
Status: ***completed***
Facilities: **Accelerator 2 days**
Linked WP or TSVV: **WPW7X**

Deliverable: **PWIE-SP B.B3.T-T005-D002**
Status: ***completed***
Facilities: **Accelerator 1 day**
Linked WP or TSVV: **WPW7X**

M. Rasinski, T. Dittmar

SP B.4 - Reference coatings for ITER and DEMO

SP B.4 deliverables 2025

Activity	Deliverable ID(s)	Title
SP B.4	D001 3 PM	W- and B-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (ENEA)
SP B.4	D002 4 PM	W-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (IAP)
SP B.4	D003 6 PM	B reference layers with pre-defined composition and morphology for comparison with data from tokamaks (IAP)
SP B.4	D004 2 PM	Raman analyses of selected B reference samples (CEA)
SP B.4	D005 1 PM	SEM and SIMS analyses of selected B and W reference samples (CIEMAT)
SP B.4	D006 2 PM	LIBS and SEM analyses of selected B reference samples (FZJ)
SP B.4	D007 2 PM + 1 PM (AR)	Microscopy investigations of selected B and W reference samples (IPPLM)
SP B.4	D008 5 PM	Ion-beam analyses of selected B and W reference samples (IST)
SP B.4	D009 4 PM	XPS and TDS analyses of selected B reference samples (JSI)
SP B.4	D010 5 PM	Ion-beam and structural analyses of selected B and W reference samples (NCSRD)
SP B.4	D011 1 PM	TOF-ERDA analyses of selected B and W reference samples (RBI)
SP B.4	D012 1.5 PM	Ion-beam analyses of selected B reference samples (VR)
SP B.4	D013 1 PM	SIMS measurements and ion-beam analyses of selected B and W reference samples (VTT)

SP B.4: W-based reference coatings for linear-machine experiments (IAP)

Production of W coatings (5µm) on Mo substrate for experiments in linear plasma facilities

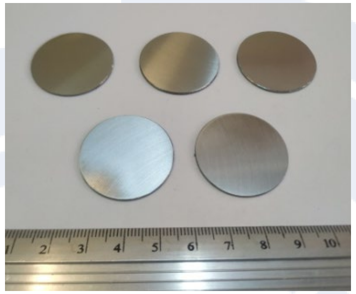
- *6 Samples deposited on 30 mm diameter Mo substrates (#1mm)*
- *4 Samples deposited on 12x15 mm Mo substrates (#1mm)*

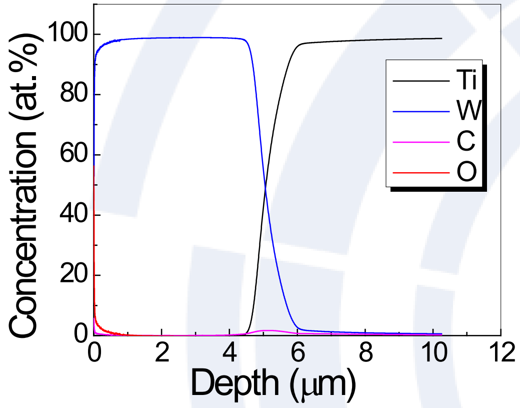
Results:

- *GDOES* data (for chemical composition and thickness) indicates:
  thickness 5 µm; no contaminants within the coating
- *XRD* analyses (for phase investigations) suggest:
  W monophasic structure with no preferential orientation

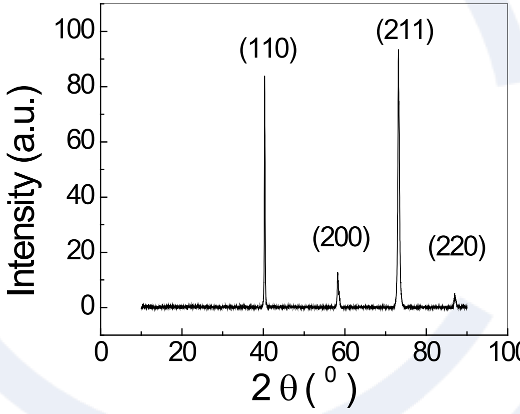
Conclusions:

- W coatings with a thickness of 5 µm deposited and sent to different RUs for further experiments in linear plasma devices
- W-N, W-O and W-N-O coatings already delivered to different RUs





Example of GDOES depth profiles for a W coating



Example of an XRD pattern for a W coating

Deliverable: **PWIE-SP B.B4.T-T005-D002**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **SP B.1**

E. Grigore, F. Baiasu, M. Gherendi

SP B.4: Microscopy investigations of selected B and W reference samples (IPPLM)

General Information

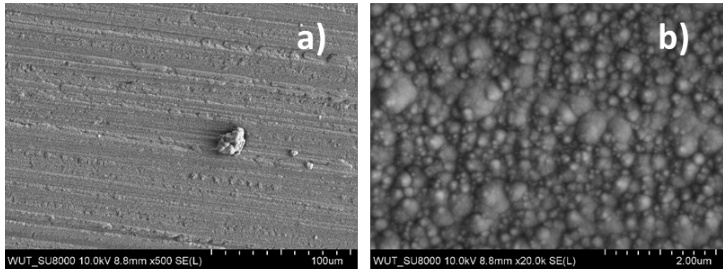
Examined samples:

- Reference W coatings (IAP): (i) W-N-O deposit on Mo, (ii) W-O deposit on Mo, and (iii) W-N deposit on Mo
- Reference B layers 100 nm (IAP)

Approach

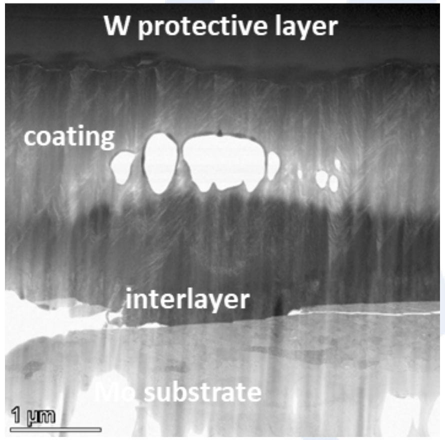
- On each sample, microscopic surface observations, EDX analysis, and profilometry were carried out.
- STEM/TEM studies were applied to examine their internal structure.

Results – W-N-O coatings (similar results for other coatings)



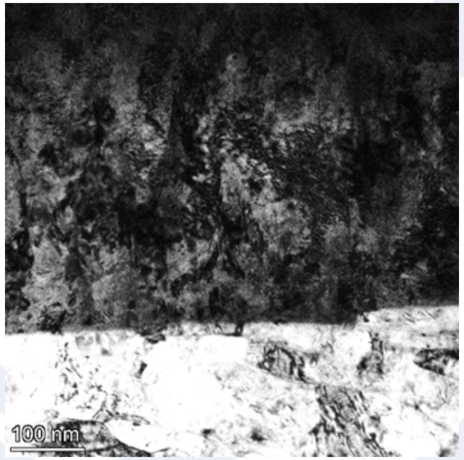
SEM images of the surface (a-b)

- *Surface roughness R_a~ 0.4 µm, granular morphology*



STEM HAADF-BF image of a thin foil from the sample

- *Thickness of the interlayer ~ 400 nm, coating ~ 2.1 µm.*



TEM images of the interlayer

- *Interlayer nanocrystalline with a columnar structure*
- *Coating itself amorphous*

Deliverable: **PWIE-SP B.B4.T-T005-D007**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

E. Fortuna-Zaleśna

SP B.4: Ion-beam analyses of selected B and W reference samples (IST)

Task and questions to be addressed

- Carry out IBA and XRD for selected W reference samples to determine their surface composition and structure

Approach

- simultaneous ERDA + RBS / 2.0 MeV $^4He^+$ incident beams / for H , D analysis
- simultaneous RBS + NRA / 1.75 MeV $^3He^+$ incident beams / for D analysis
- EBS / 1.75 MeV / 2.15 MeV $^1H^+$ incident beams / W, N, O, Mo analysis

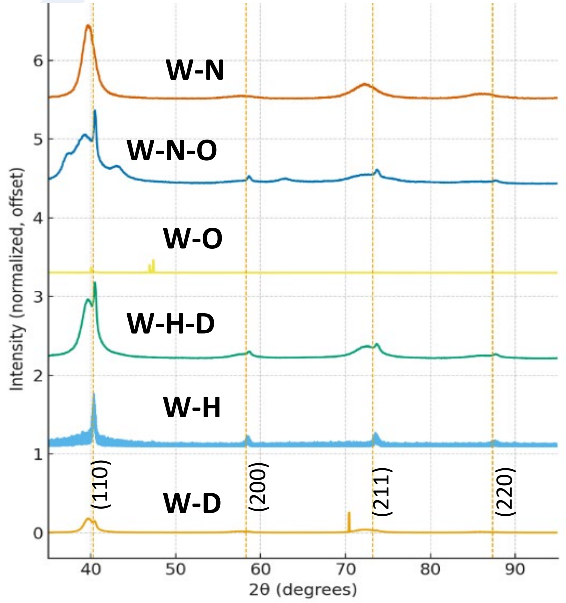
Results

- Main elemental depth composition achieved by IBA
- The dominant phase across all the coatings is bcc W
- Complementary diffraction patterns: (W-H vs. W-D) and (W-N vs. W-O)
- H and D acts as **interstitial species, leading to minor lattice distortions**
- O promotes the **formation of oxide phases** (mainly $W_{18}O_{19}$)
- No crystalline W-nitride formation

Deliverable: **PWIE-SP B.B4.T-T005-D008**
Status: ***completed***
Facilities: **Accelerator 5 days**
Linked WP or TSVV: **-**

Table 2. W coatings deposited on Mo produced at INFLPR for IBA and XRD.

#	Reference	Nominal comp.	Nominal thick.	Substrate	Producer
1	EU2-208-4	W+D	~5 µm	Mo	INFLPR
2	EU2-204-4	W+H+D	~4 µm	Mo	INFLPR
3	EU2-203-7	W+H	~4.5 µm	Mo	INFLPR
4	EU2-180-2	W+O	~2 µm	Mo	INFLPR
5	EU2-942-5	W+N	~2 µm	Mo	INFLPR
6	EU2-210-5	W+N+O	~3 µm	Mo	INFLPR



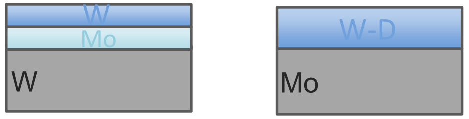
Overlay of W-based diffractograms (normalized; vertical offset)

R. Mateus, S. Magalhães

SP B.4: XPS and TDS analyses of B and W reference samples (JSI)

Task and questions to be addressed

- XPS analysis of W+Mo film on W and W-D film on Mo, film thickness ~5 µm

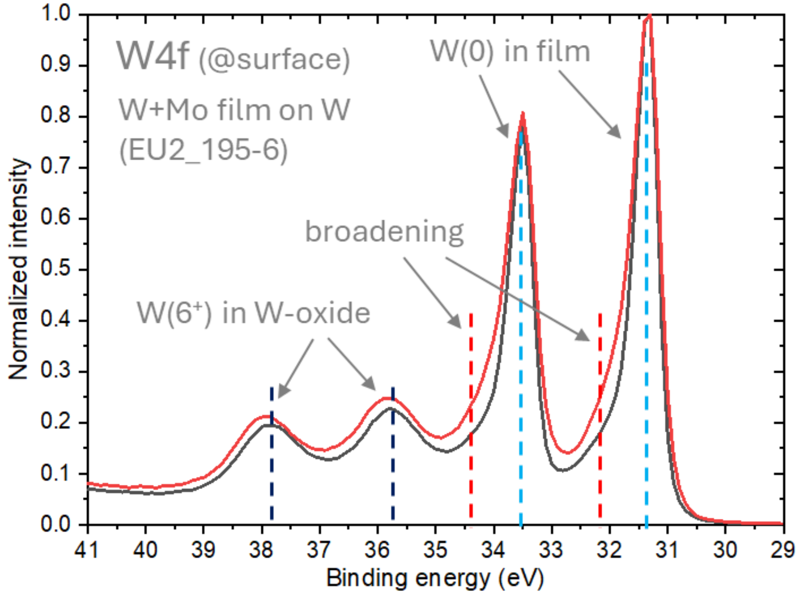


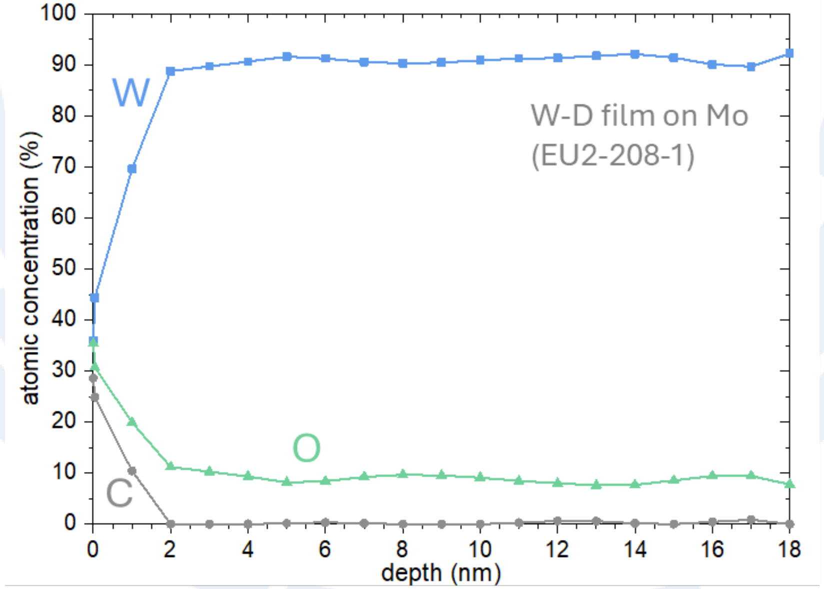
Approach

- XPS spectrometer (Genesis, Physical Electronics). Surface analysis 0.1 mm in diameter and depth of ~4 nm. A depth profile was performed by sputtering with Ar-ion beam of 3 keV over 3×3 mm^2 (~2.0 nm/min)

Results

- ***Surface analysis***:
  - Similar surface composition for both samples: 33 at.% of W, 33 at.% of O, 30 at.% of C (contamination) and 4 at.% of N.
  - **Small degree of oxidation** of W-atoms on the surface (25% oxidized of W-oxide phase and 75% of W-metallic phase on the surface).
  - Broadening of the W 4f surface spectra at energy 32 eV and 34.5 eV indicates the **disorder/defects induced by D** in the subsurface region
- ***Depth profiles***: Depth profiles (down to 20 nm) show concentrations of W and O: 90% and 10% for W-D, 85% and 15% for W+Mo





Deliverable: **PWIE-SP B.B4.T-T005-D009**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

J. Kovač, M. Panjan

SP B.4: Production of W and B reference coatings (ENEA-PoliMi)

Task and questions to be addressed

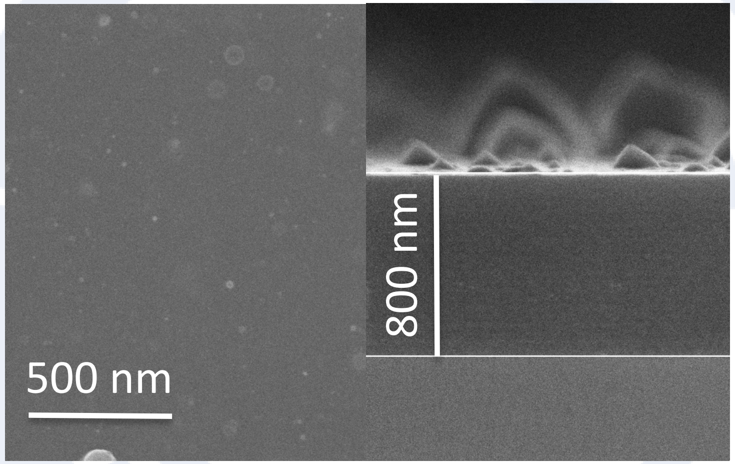
- Production of W and B reference coatings, multilayer structures, and proxies for re-deposited layers with varying composition, morphology, and grain structure for laboratory experiments and exposures in linear plasma devices

Approach

- B coatings produced via Pulsed Laser Deposition (PLD), from 100 nm to 1 µm
- Nanocolumnar W and compact W produced via HiPIMS
- Porous W-O deposited via PLD
- Polishing of PSI-2 geometry W substrates at PoliMi

Results

- B coatings (14 on W PSI-2 geometry and 8 on Si 10x10 mm^2) – **done**
- 5 nanocolumnar W on Mo disks – **done**
- 16 nanocolumnar W on W PSI-2 geometry – 12 **done**, 4 **planned by the end of November**
- 6 nanocolumnar W on Mo flat 10x10 mm^2 - **done**
- 11 porous W-O on Mo disks – 5 **done**, 6 **planned by the end of November**
- 14 compact W on Mo disks – **done**
- 4 amorphous W – **done**



Example of a boron coating

Deliverable: **PWIE-SP B.B4.T-T005-D001**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **SP B.1, SP D**

D. Dellasega, L. Bana, G. Alberti, D. Vavassori, D. Vassallo, M. Pedroni, A. Uccello, M. Passoni

SP B.4: TOF-ERDA analyses of selected B reference samples (RBI)

Boron sample (100 nm on W), obtained from ENEA

Task and questions to be addressed

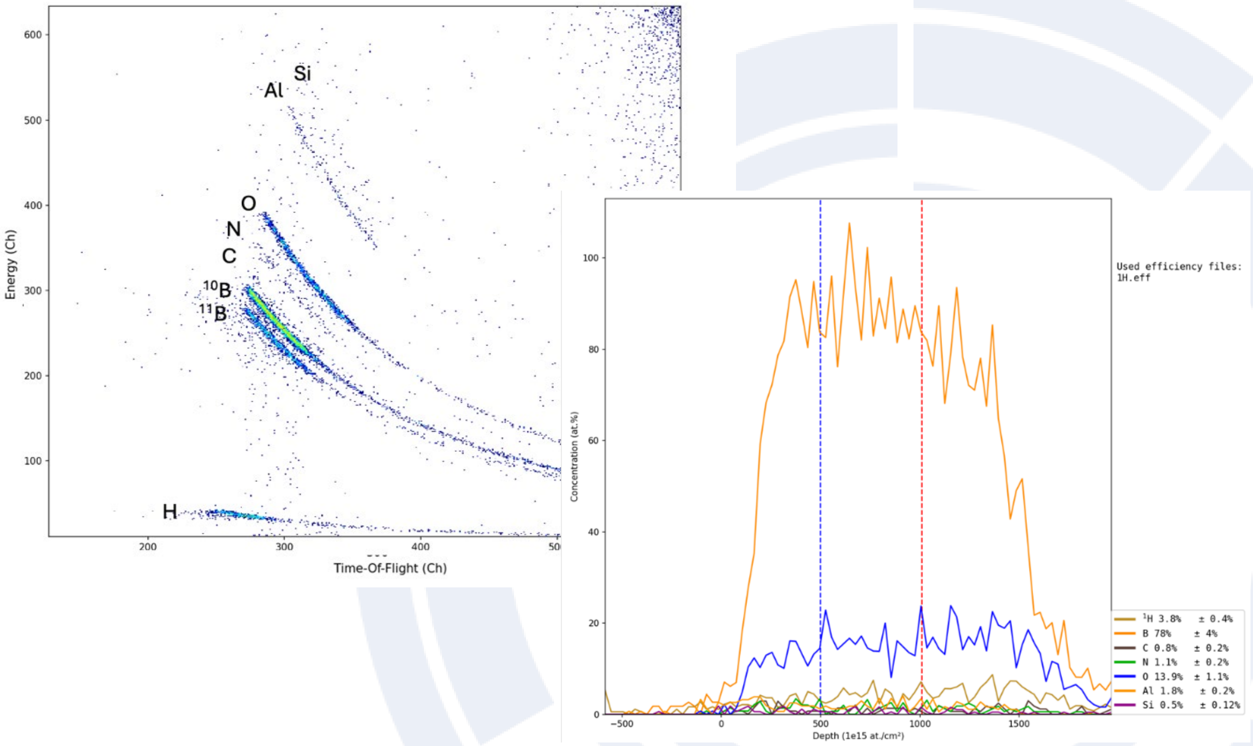
- Determine composition and depth profiles of elements in the sample as well as layer thickness

Approach

- TOF-ERDA with 23 MeV $^{127}I^{7+}$ beam

Results

- <u>Sample composition</u>: H 3.8 at.%, B 78 at.%, C 0.8 at.%, N 1.0 at.%, O 13.8 at.%, Al 1.8 at.%, Si 0.5 at.%
- <u>Sample thickness</u>: 1600×10^{15} cm^2



2D E-TOF map and depth profiles of all elements found on the studied sample

Deliverable: **PWIE-SP B.B4.T-T005-D011**
Status: ***completed***
Facilities: **Accelerator 4 days**
Linked WP or TSVV: **-**

Z. Siketić, I. Bogdanović Radović

SP B.4: Ion-beam analyses of selected B reference samples (VR)

Boron films deposited on tungsten by PoliMi exposed to the deuterium plasma of the linear device GyM (E_{ion} = 76 eV, Fluence = 4×10^{23} m^{-2}), received from Andrea Uccello (CNR)

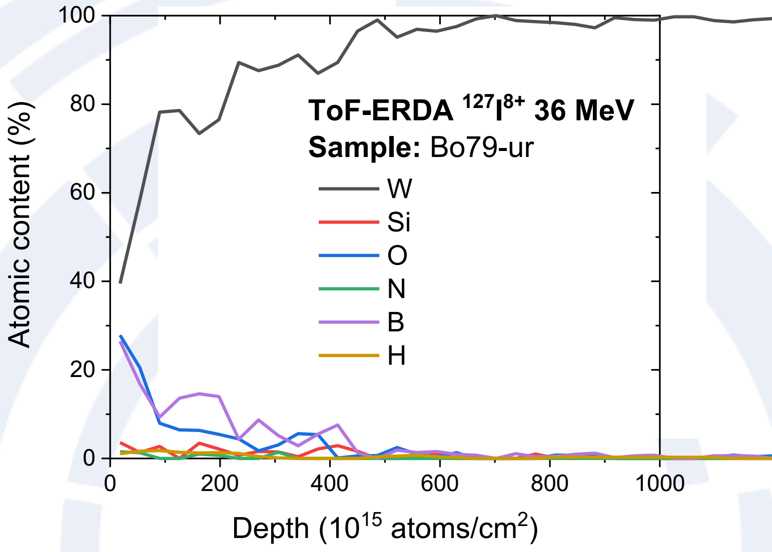
Aim: Investigation of chemical composition and atomic distribution on the sample surface

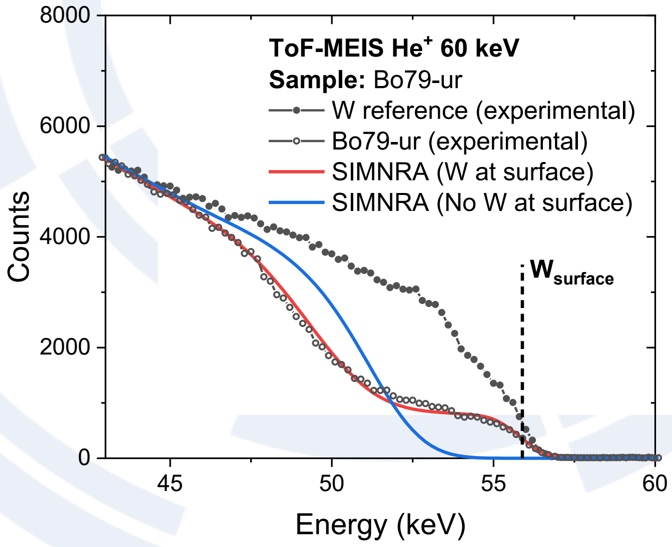
Approach

- ToF-ERDA: identification and depth profile of all isotopes
- EBS+NRA+PIXE using H^+ 2.6 MeV: higher sensitivity to B
- ToF-MEIS (medium-energy ion scattering): High-resolution W surface distribution:
  - **ToF-MEIS depth resolution corresponds to 1.4 nm for W at the surface**

Results

- The presence of B, O, N, and H was identified at the surface. No deuterium observed
- **Boron areal density corresponds to 3.7 nm**, assuming the density of pure boron (2.351 g/cm^3)
- Presence of W at the surface confirmed by ToF-MEIS analysis:
  - **Results indicate incorporation of W within the B–O layer at the surface and/or incomplete coverage of surface layer.**





Deliverable: **PWIE-SP B.B4.T-T005-D012**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **SP B.1**

E. Pitthan, R. Holenak, D. Primetzhofer

SP B.4: Production of B-based reference coatings (IAP)

Task and questions to be addressed

- Production of B reference coatings, multilayer structures, and proxies for re-deposited layers with varying composition, morphology, and grain structure for laboratory experiments and exposures in linear plasma devices

Approach

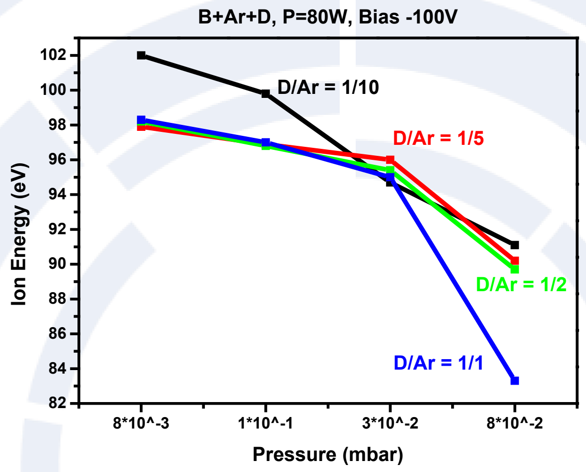
- Development of production recipes in dedicated setups to understand the formation of B layers under different conditions

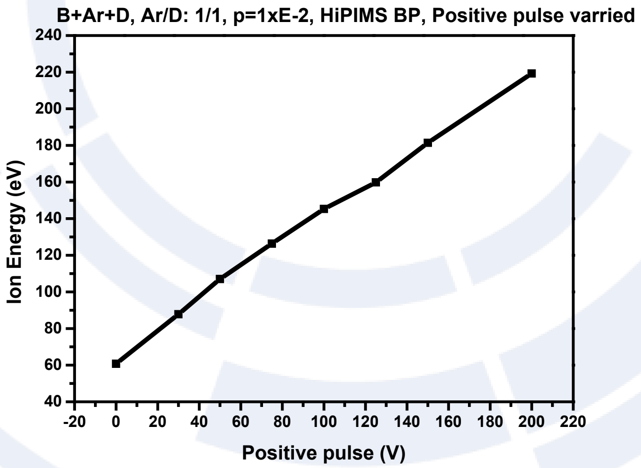
Results

For each condition we now know – useful for fine-tuning the recipes

- ion energy
- deposition rate (Particle flux)
- D/B ratio by TDS

Ion energy dependence versus various plasma parameters



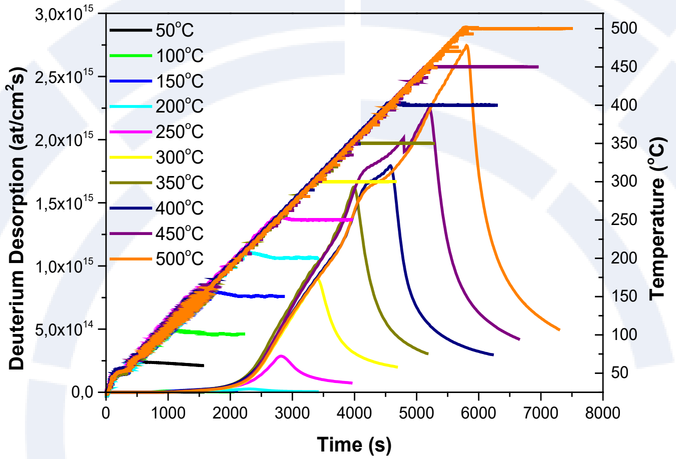


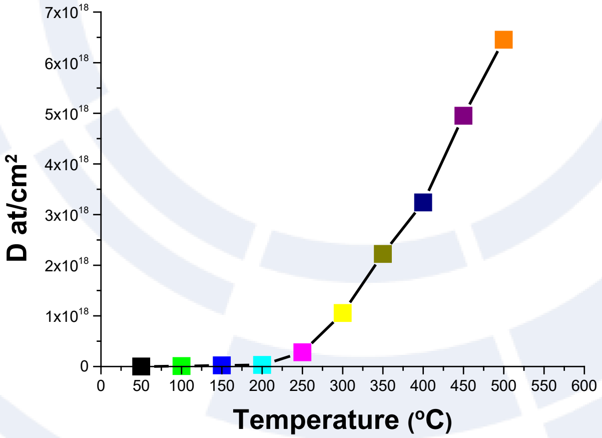
Deliverable: **PWIE-SP B.B4.T-T005-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

C. Porosnicu, P. Dinca, B. Butoi, O. G. Pompilian, C. Staicu, B. Solomonea, C. P. Lungu

SP B.4: Production of B-based reference coatings (IAP)

Preparation of 5×5 mm² W samples coated with $B+D_2$(10%) , thermal treatment up to 500°C





Task and questions to be addressed

- Production of B reference coatings, multilayer structures, and proxies for re-deposited layers with varying composition, morphology, and grain structure for laboratory experiments and exposures in linear plasma devices

Approach

- Development of production recipes in dedicated setups to understand the formation of B layers under different conditions

Status report of layers produced in 2025

- B layers with controlled D inclusions (10 at%) - Completed – Febr/Mar 2025
- B layers with a nominal thickness of 100 nm and 5 μm - Completed – Feb/Mar 2025
- B and $B+D_2$ (10 at%) layers with a nominal thickness of 100 nm and 5 μm on special substrates (W, 12 × 15 mm²) – ongoing
- Deposition of B (5 μm) on Mo (⌀30 mm) with different roughnesses – target Dec 2025
- $B+D_2$ (10 at%) layers with annealing at temperatures of 50 – 500°C – target Dec 2025

Deliverable: **PWIE-SP B.B4.T-T005-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

C. Porosnicu, P. Dinca, B. Butoi, O. G. Pompilian, C. Staicu, B. Solomonea, C. P. Lungu

SP B.4: TOF-ERDA analyses of selected B reference samples (RBI)

Boron samples with D from IAP (C. Porosnicu)

Task and questions to be addressed

B samples with D at different temperatures, from RT to 500°C

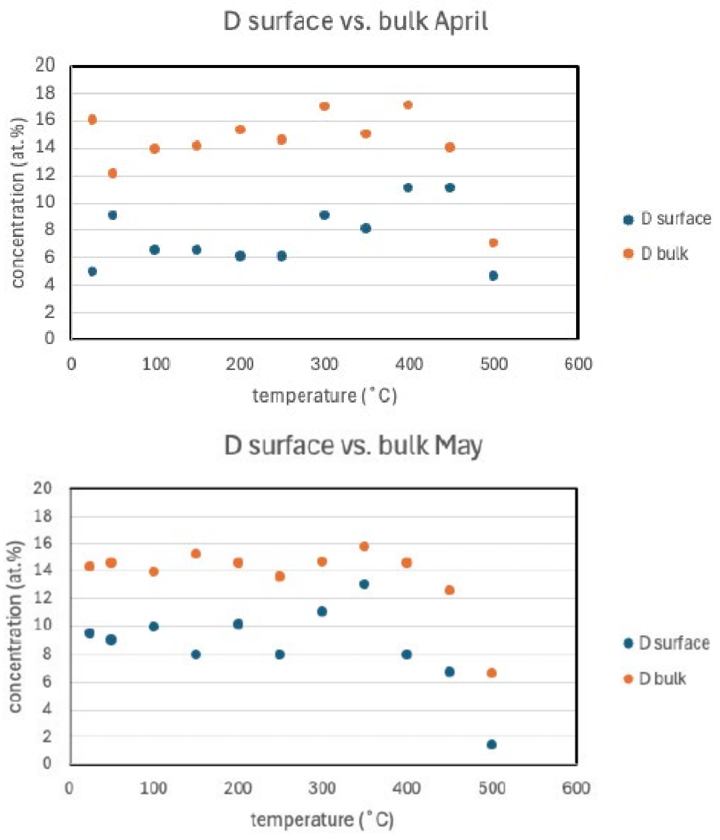
- to determine composition and depth profiles of thin B+D films as a function of temperature
- to study changes in the sample composition in the near surface region by measuring samples left on ambient conditions after one month

Approach

- TOF-ERDA with 23 MeV $^{127}I^{7+}$ beam
- Samples first analyzed on April 22, 2025 following storage in vacuum and Ar, second analysis following aging in ambient conditions on May 19, 2025; concentration calculated for near surface and bulk

Results

- In general, thickness of the surface oxide layer slightly increased in samples measured in May
- In some samples D concentration near the surface increased



Concentration of D (at.%) near the sample surface (blue) and in the bulk (yellow) as a function of temperature in April and May

Deliverable: **PWIE-SP B.B4.T-T005-D011**
Status: ***completed***
Facilities: **Accelerator 4 days**
Linked WP or TSVV: **-**

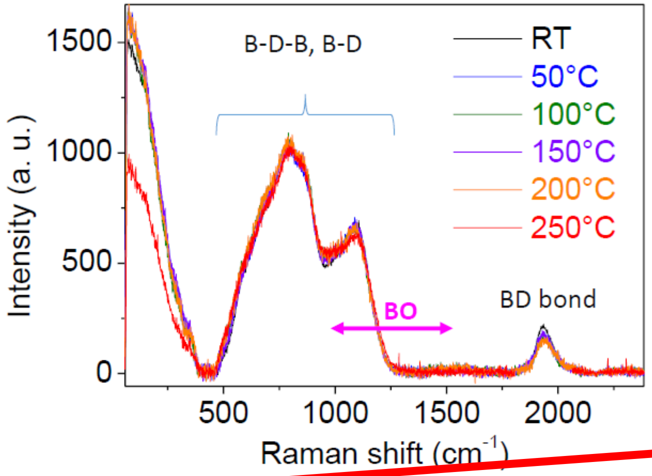
Z. Siketić, I. Bogdanović Radović

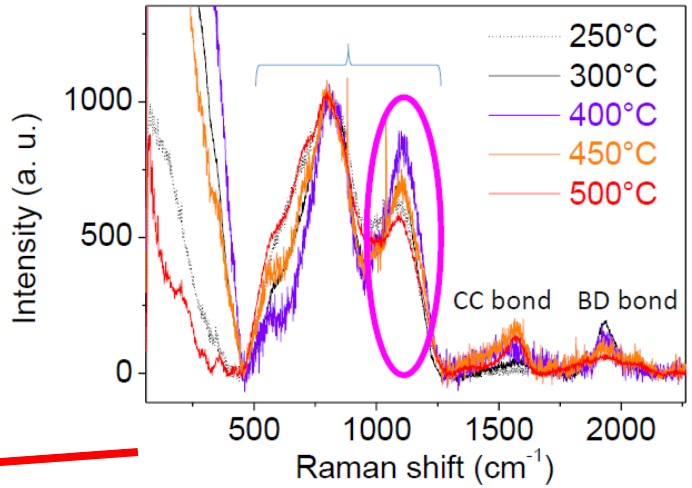
SP B.4: Raman analyses of different B reference layers (CEA)

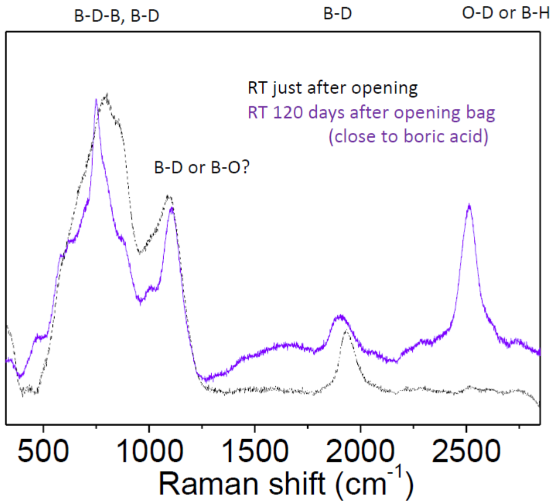
This task covers Raman measurements for B layers provided by IAP, ENEA, and VR (supplemented by optical microscopy)

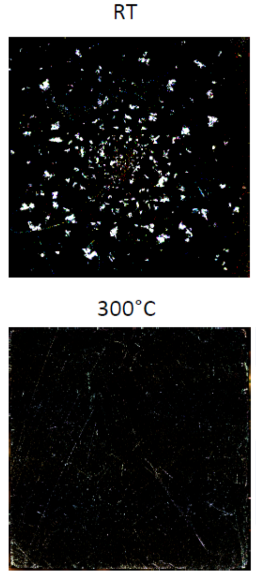
Results

- B layers annealed at different temperatures (IAP)
  - **White crystals found** when T_{ann} < 200°C upon exposure to air → appear to be $B(OH)_3$
  - Outside of the crystals: boron structure remains stable when T_{ann} < 250°C but evolves above 250°C → **due to contamination? Due to oxidization?**
  - Outside of the crystals: strong changes in spectrum after exposure to air → **formation of BO or BH compounds?**
- Thin B layers (100 nm) (ENEA and VR) **show a-B-like spectra** but are generally thin and require further investigations









Examples of white crystals (RT) and more homogeneous surface (300°C) of the B+D_2(10%) , samples from IAP

Deliverable: **PWIE-SP B.B4.T-T005-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

C. Pardanaud, C. Martin, G. Giacommetti

SP B.4: Ion-beam and structural analyses of B reference samples (NCSRD)

Analysis of $B+D_2$ (10%) 5 μm thick layers on W annealed in the temperature range 50–500 °C

Task and questions to be addressed

- Determination of deuterium release
- Determination of structural and surface modifications

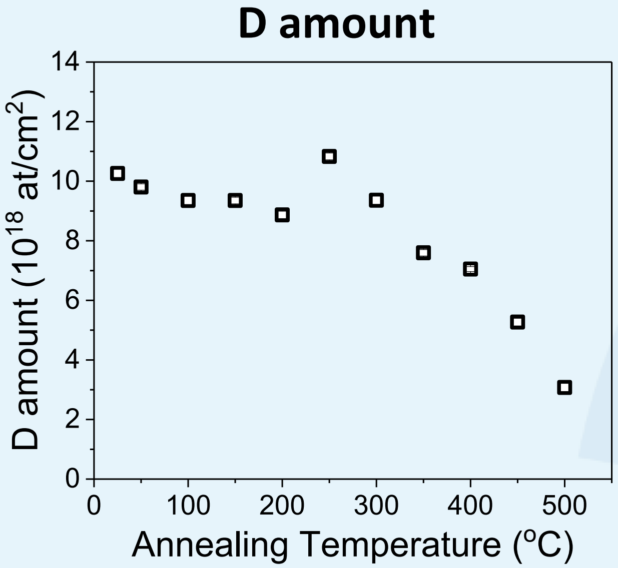
Methodology

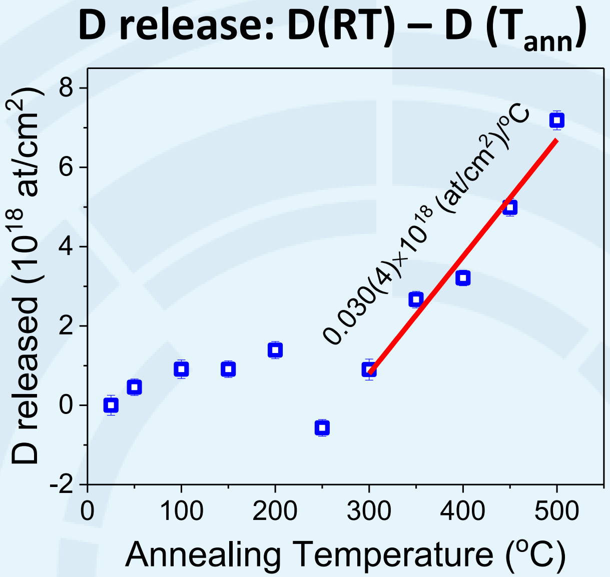
- d beam RBS/NRA; XRD at grazing incidence; SEM/EDX analyses

Results

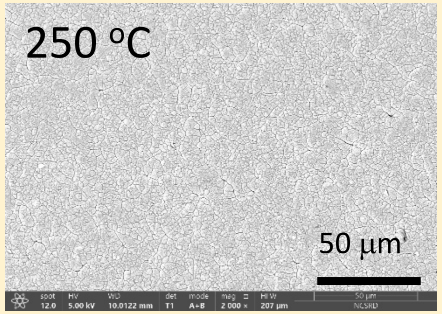
- D release **increases almost linearly with T_{ann}** for $T_{ann} \geq 300$°C
- **Crack formation** for $T_{ann} \geq 300$°C; crack width increases almost linearly with T_{ann}

Deliverable: **PWIE-SP B.B4.T-T005-D010**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **-**

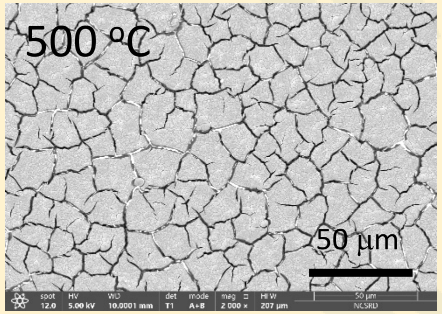


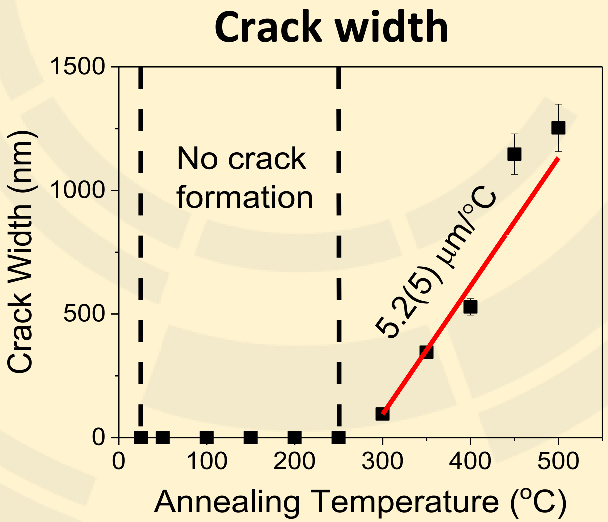


No cracks



Crack formation





P. Tsavalas, K. Mergia, A. Lagoyannis, M. Axiotis, D. Papadakis

SP B.4: Ion-beam and structural analyses of B reference samples (NCSRD)

Task and questions to be addressed

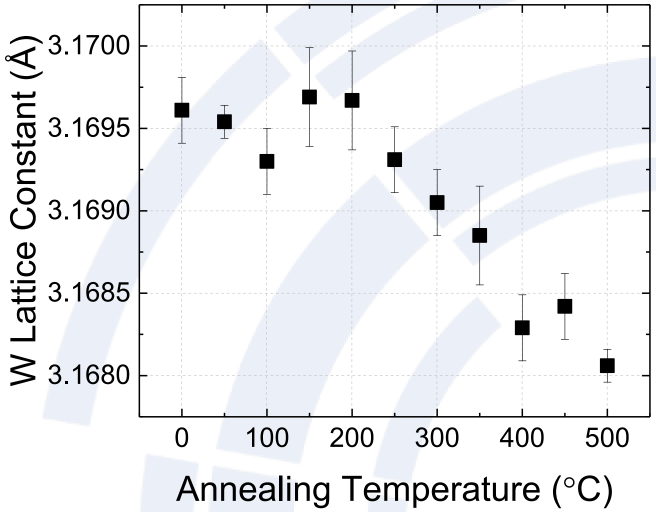
- The cause for crack formation (see previous slide)
- Correlation between D release and crack formation

Results

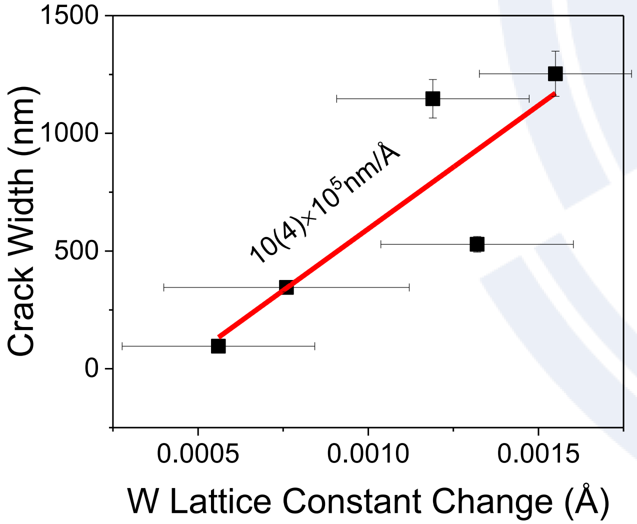
- W **lattice constant decreases** almost linearly with T_{ann} for $T_{ann} \geq 250°C$
- Almost linear correlation between crack width and W lattice constant change
- Almost **linear correlation between D release and crack width**
- The W substrate is strained during B deposition (unstrained W lattice constant 3.1648 Å) → changes the strain at the interface with the B layer leading to crack formation?
- Crack formation **may contribute to D release**

Deliverable: **PWIE-SP B.B4.T-T005-D010**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **-**

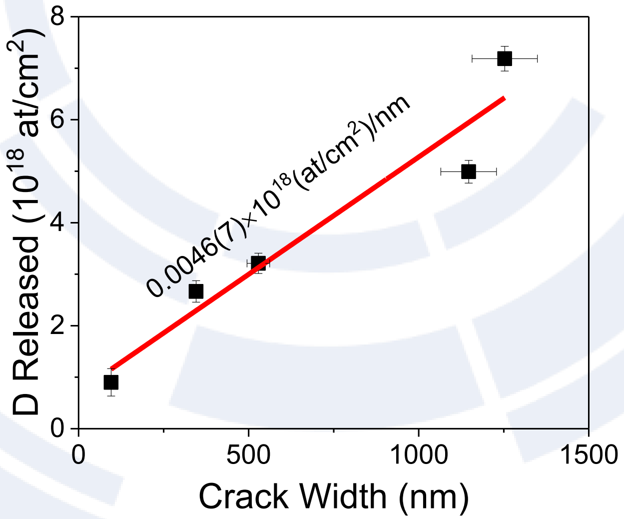
W lattice constant (probed depth ~2 μm)



Crack width vs W lattice constant change



D release vs crack width

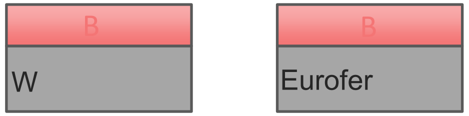


P. Tsavalas, K. Mergia, A. Lagoyannis, M. Axiotis, D. Papadakis

SP B.4: XPS and TDS analyses of B and W reference samples (JSI)

Task and questions to be addressed

- XPS analysis of B films on W and Eurofer, film thickness ~5 µm

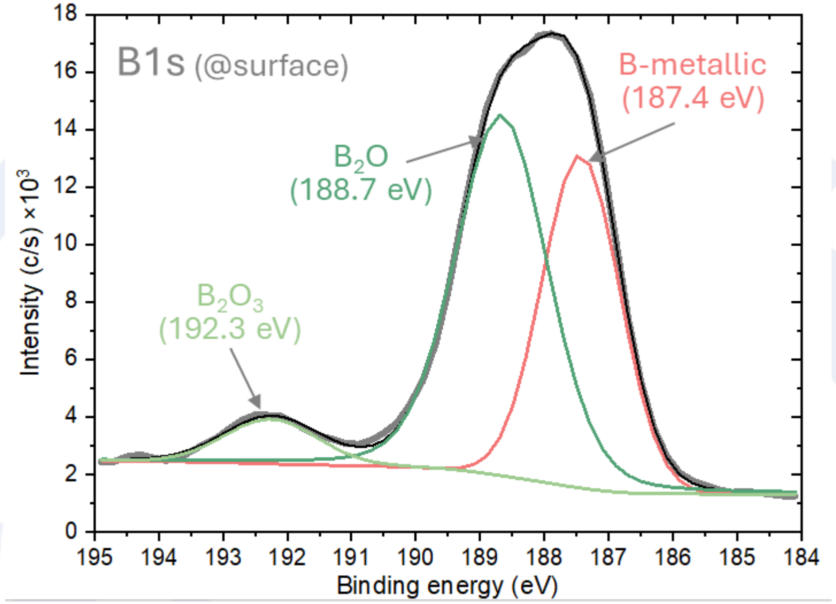


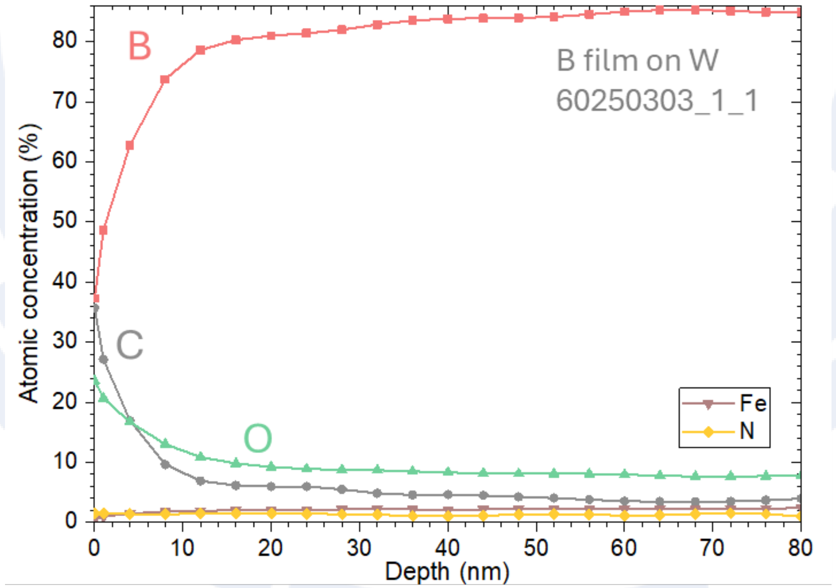
Approach

- XPS spectrometer (Genesis, Physical Electronics). Surface analysis 0.1 mm in diameter and depth of ~4 nm. Depth profiles performed by sputtering with Ar-ion beam of 3 keV over 3×3 mm² (~2.0 nm/min)

Results

- Both samples show similar composition and depth profiles
- ***Surface analysis***:
  - 37.7 at.% of B, 35.5 at.% of C and 22.5 at.% of O, 1.9 at.% of N and 1.0 at.% of Fe. Traces of Na, Si, In were detected
  - B 1s spectrum shows three chemical states - metallic phase (187.4 eV), B_2O (188.7 eV) and B_2O_3 (192.3 eV)
- ***Depth profiles***: Uniform distribution of elements – B (85 at.%), O (8 at.%), C (5 at.%), Fe (2 at.% metallic), Cr (1 at.%, metallic) and N (1 at.%). B 1s peak shows dominance of metallic state (187.9 eV), there is only small presence of B_2O_3 phase in the film (2% of total B).





Deliverable: **PWIE-SP B.B4.T-T005-D009**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

J. Kovač, M. Panjan

SP B.4: XPS and TDS analyses of B and W reference samples (JSI)

Task and questions to be addressed

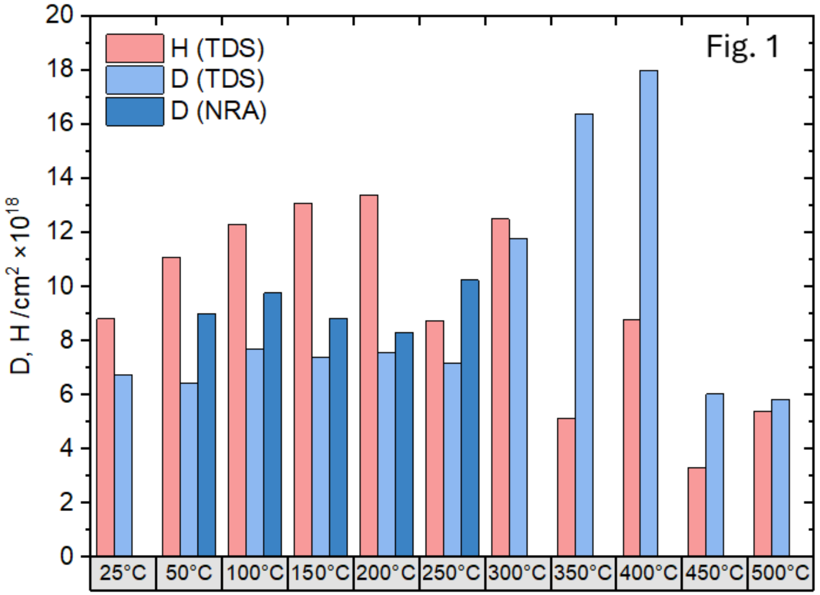
- TDS should provide complementary data on bonding of D in 5 µm thick B films

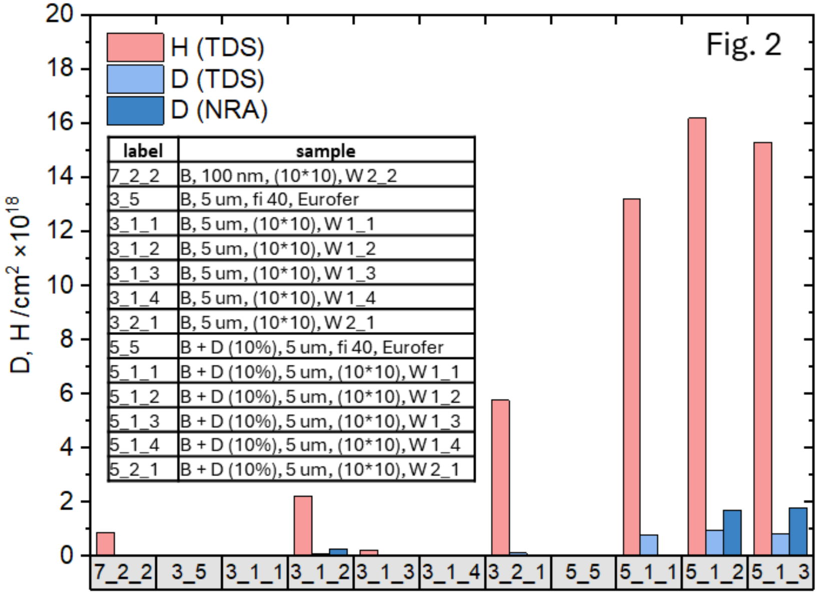
Approach

- Samples with various amount of D in B films (altogether 24 samples) analysed by TDS and 9 of them by NRA (i.e. before TDS measurement)

Results

- Key findings are temperature of max D_2/HD release (not presented here)
- Total released amount expressed as D/cm^2 and H/cm^2 for comparison
  - **Fig. 1**: amount of H, D for 11 differently preheated samples
  - **Fig. 2**: amount of H, D of 13 samples with B deposited at various deposition parameters (see inner table)
- The **amount of D by TDS matches well to NRA results**. Sensitivity of quadruple mass spectrometer is lower at weak signals which is not applied in the evaluation
- The amount of H is rather high but its origin is not well traced to deposition parameters





label	sample
7_2_2	B, 100 nm, (10*10), W 2_2
3_5	B, 5 um, fi 40, Eurofer
3_1_1	B, 5 um, (10*10), W 1_1
3_1_2	B, 5 um, (10*10), W 1_2
3_1_3	B, 5 um, (10*10), W 1_3
3_1_4	B, 5 um, (10*10), W 1_4
3_2_1	B, 5 um, (10*10), W 2_1
5_5	B + D (10%), 5 um, fi 40, Eurofer
5_1_1	B + D (10%), 5 um, (10*10), W 1_1
5_1_2	B + D (10%), 5 um, (10*10), W 1_2
5_1_3	B + D (10%), 5 um, (10*10), W 1_3
5_1_4	B + D (10%), 5 um, (10*10), W 1_4
5_2_1	B + D (10%), 5 um, (10*10), W 2_1

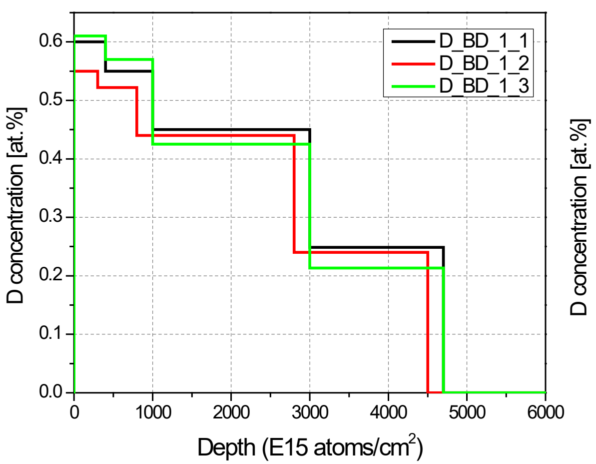
Deliverable: **PWIE-SP B.B4.T-T005-D009**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

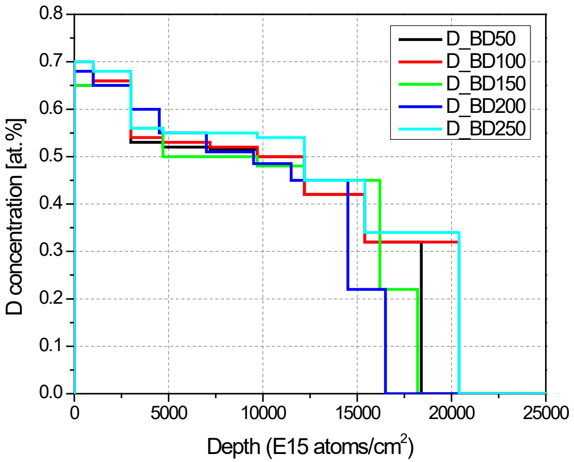
V. Nemanič, M. Žumer, A. Kurtishaj-Hamzaj

SP B.3: Micro- and macroscale composition of layers on selected samples (JSI)

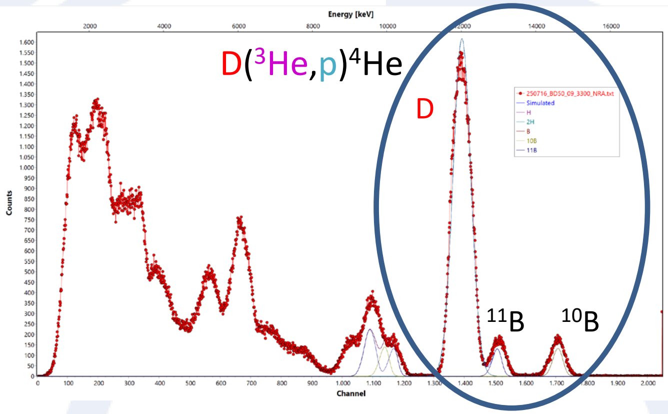
Task scope re-directed to deal with the analysis of B reference samples

- Deuterated boron samples* from Romania measured in the INSIBA chamber
- A **$^{3}He^{2+}$ beam** with an energy of **3.3 MeV** was used. Two detectors were employed to simultaneously collect the **RBS (150°) and NRA (135°)** signals. The accumulated dose for each measurement was **3.4 µC.**
- **Deuterium depth profiles:**





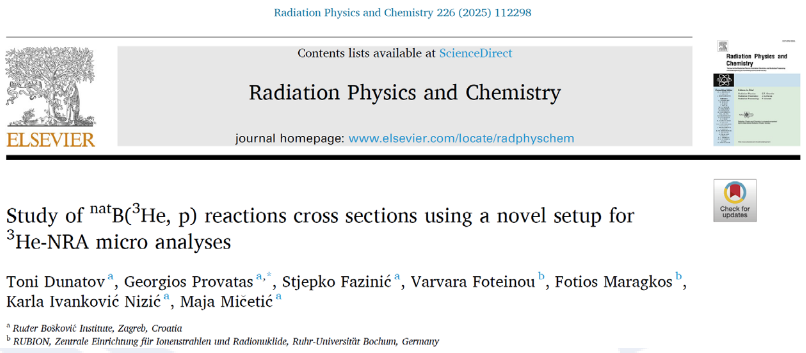
Sample holder with 5 of 9 samples analysed



$^{10}B(^{3}He, p_{1,3})^{12}C$

$^{11}B(^{3}He, p_{0,1,2,3})^{13}C$

$^{11}B(^{3}He, d_{0})^{12}C$


Radiation Physics and Chemistry 226 (2025) 112298

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

ELSEVIER

Study of $^{nat}B(^{3}He, p)$ reactions cross sections using a novel setup for ^{3}He-NRA micro analyses

Toni Dunatov [a], Georgios Provatas [a,*], Stjepko Fazinić [a], Varvara Foteinou [b], Fotios Maragkos [b], Karla Ivanković Nizić [a], Maja Mičetić [a]

[a] Ruđer Bošković Institute, Zagreb, Croatia

[b] RUBION, Zentrale Einrichtung für Ionenstrahlen und Radionuklide, Ruhr-Universität Bochum, Germany

Deliverable: **PWIE-SP B.B3.T-T005-D006**
Status: ***completed***
Facilities: **Accelerator 7 days**
Linked WP or TSVV: **-**

**samples were also analysed by TDS by Vincenc Nemanič*

S. Markelj, E. Punzón Quijorna

SP B.4: Ion-beam analyses of selected B and W reference samples (IST)

Task and questions to be addressed

- Carry out ion-beam analyses for selected B reference samples to determine their surface composition

Table 1. B coatings deposited on W produced at INFLPR and at ENEA for IBA.

#	Reference	Nominal comp.	Nominal thick.	Substrate	Producer
1	60250303_2_3	B	5 μm	W	INFLPR
2	60250305_2_3	B+D	5 μm	W	INFLPR
3	60250227_2_1	B	100 nm	W	INFLPR
4	Bo76B	B	100 nm	W	ENEA

Approach

- Elemental composition of thin B samples films (~100 nm):
  - RBS analysis / 1000 keV $^4He^+$ ion beams – to enhance energy loss
  - NRA analysis / $^{11}B(p,\alpha_1)2\alpha$, $E_r \approx$ 650 keV - 700 keV $^1H^+$ ion beams
- Elemental composition of thick B samples: EBS + NRA analysis

Results

- Easy measurement of composition and thickness of B layers
- **Evidence of fast oxidation** of B layers over time at room temperature

Deliverable: **PWIE-SP B.B4.T-T005-D008**
Status: ***completed***
Facilities: **Accelerator 5 days**
Linked WP or TSVV: **-**

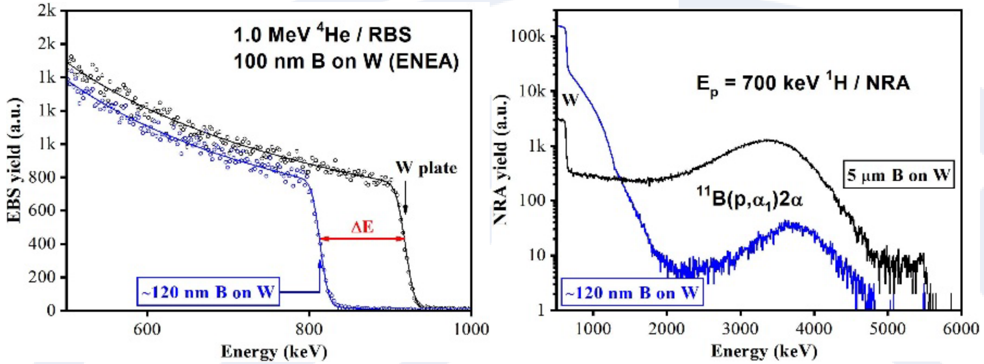


Fig. 1 - Analysis of thickness and composition of thin B films

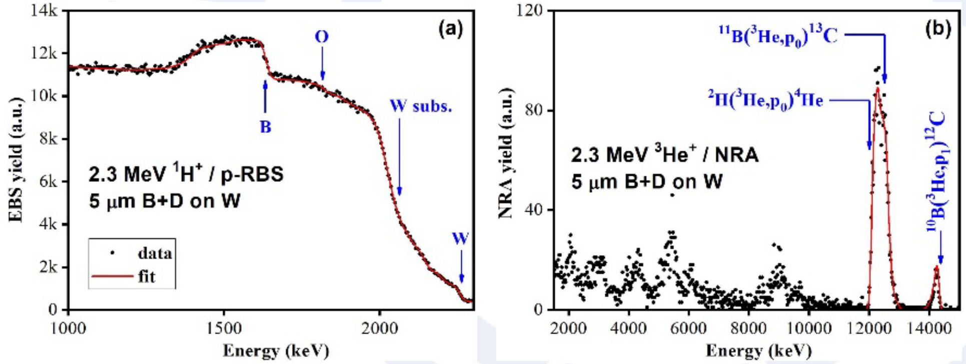


Fig. 2 - Analysis of thickness and composition of thicker B films

Future work / collaboration between IST and IAP

Title of a PhD work plan:
Oxidation behaviour of boron coatings for nuclear fusion applications (collaboration with INFLPR)

R. Mateus, N. Catarino, R. Silva

SP B.3: Depth profiles and surface morphology of selected B or W layers (CIEMAT)
SP B.4: SEM and SIMS analyses of selected B and W reference samples (CIEMAT)

Boron samples analyzed as received as well as 1 and 3 months after storage in air

Task and questions to be addressed

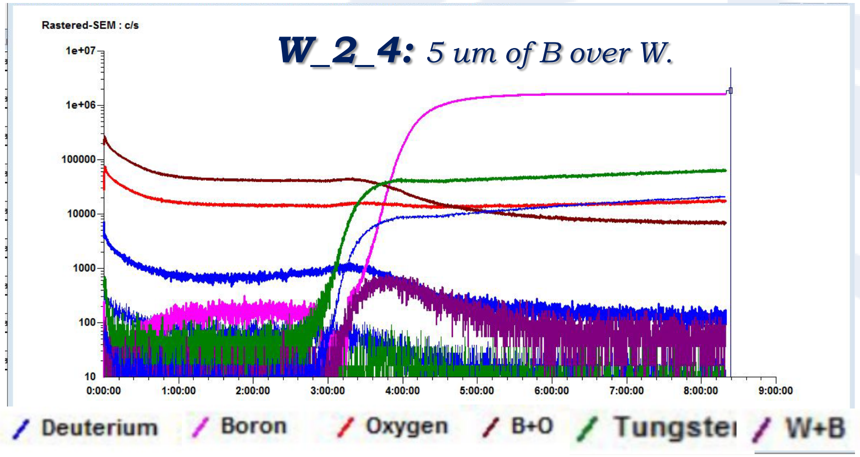
- Determine the composition and properties of the difference B layers from other labs (ENEA, IAP,…)

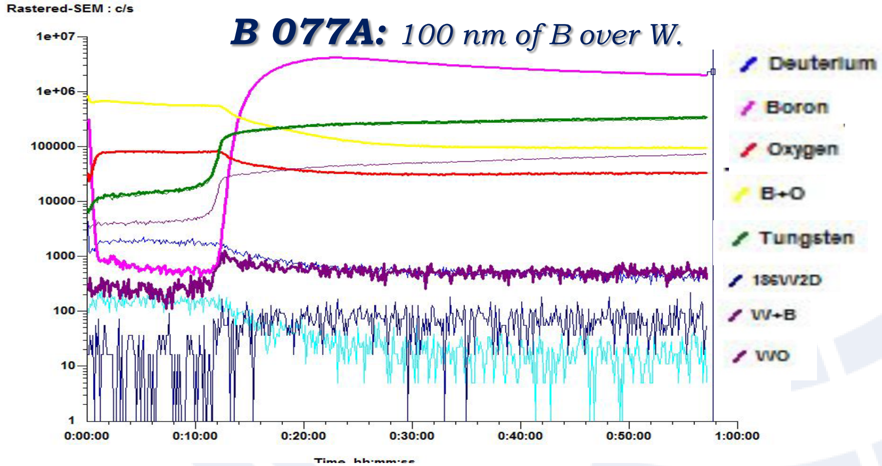
Approach

- SIMS and SEM if required

Results

- Analysis completed, data interpretation ongoing
- Strange B signal behavior: on some samples, pure B only appears when the W substrate is reached while **the layer shows B+O & W+B signals**
- All samples have **similar O levels** - oxidized during shipping?
    - ✓ Pure B sheets purchased as standards to disentangle





Deliverable: **PWIE-SP B.B3.T-T005-D001**
Status: *ongoing (to be completed in the end of 2025)*
Facilities: **-**
Linked WP or TSVV: **-**

Deliverable: **PWIE-SP B.B4.T-T005-D005**
Status: *ongoing (to be completed in the end of 2025)*
Facilities: **-**
Linked WP or TSVV: **-**

D.Alegre, G. Delgado, M. González-Viada

SP B.4: Microscopy investigations of selected B and W reference samples (IPPLM)

General Information

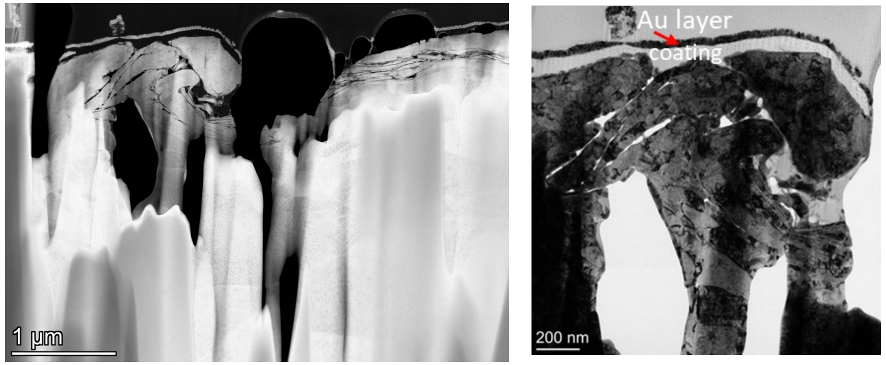
Examined samples:

- Reference W coatings (IAP): (i) W-N-O deposit on Mo, (ii) W-O deposit on Mo, and (iii) W-N deposit on Mo
- Reference B layers 100 nm (IAP)

Approach

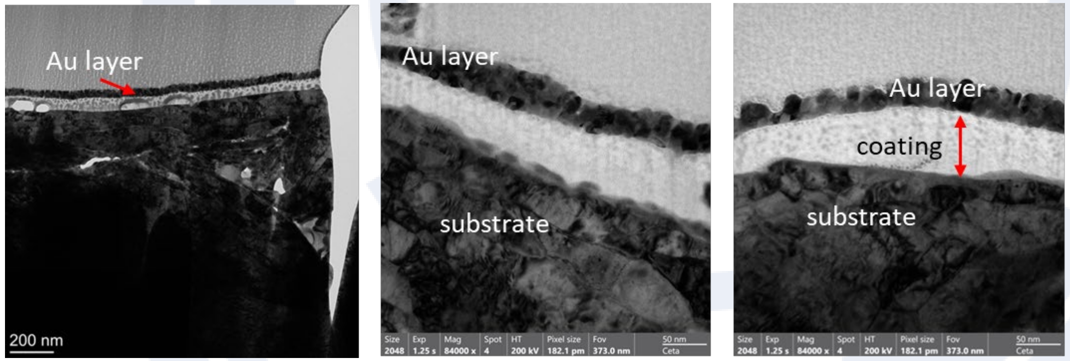
- On each sample, microscopic surface observations, EDX analysis, and profilometry carried out
- STEM/TEM studies were applied to examine their internal structure

Results – reference B layer



STEM HAADF images of a thin foil cut from the sample

- *Heavily damaged area near the surface, cracks and spalling visible*



TEM images of the coating.

- *The coating is amorphous and has a thickness of ~70 nm*

Deliverable: **PWIE-SP B.B4.T-T005-D007**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **-**

E. Fortuna-Zaleśna

SP B.4: Ion-beam analyses of selected B reference samples (VR)

Investigation of boron layers prepared by different groups (round robin exercise).

Comparative analysis/characterization of boron layer preparation by different groups

- Preparation (sputter deposition), characterization (IBA), and distribution of boron layers for further characterization.
- IBA characterization of other layers received (POLIMI and IAP).

Approach

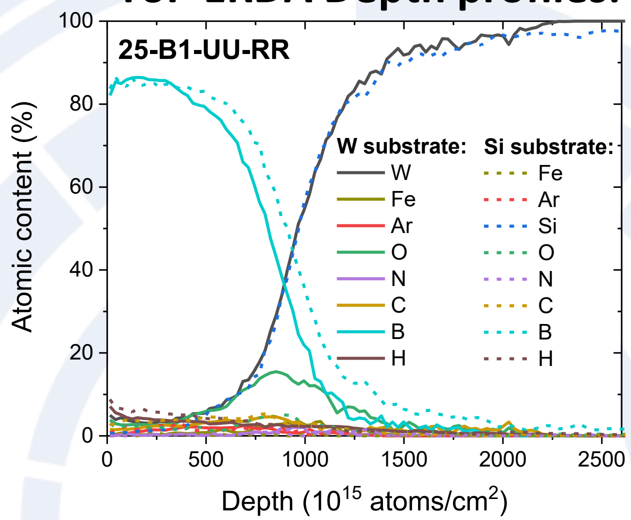
- Boron on W (polished disks) and Si(100) substrates (substrate effect).
- 1000°C annealing before deposition.
- Sputter deposition in Ar of boron layers for 4 hours (100 nm from internal QCM).

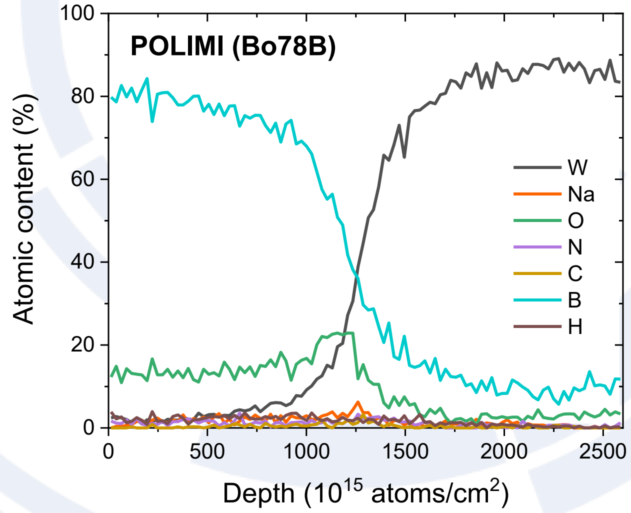
Results

- Presence of H, O, Ar, C, N (< 7 at.%), and Cr+Fe (<0.5at.%) observed in agreement with SIMS (VTT).
- **Higher concentration of oxygen in the B/W interfacial** region (both UU-VR and POLIMI).
- **No significant change in composition** from longer periods of air exposure.

Deliverable: **PWIE-SP B.B4.T-T005-D012**
Status: ***completed***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **ENR-MAT.02.VR**

ToF-ERDA Depth profiles:

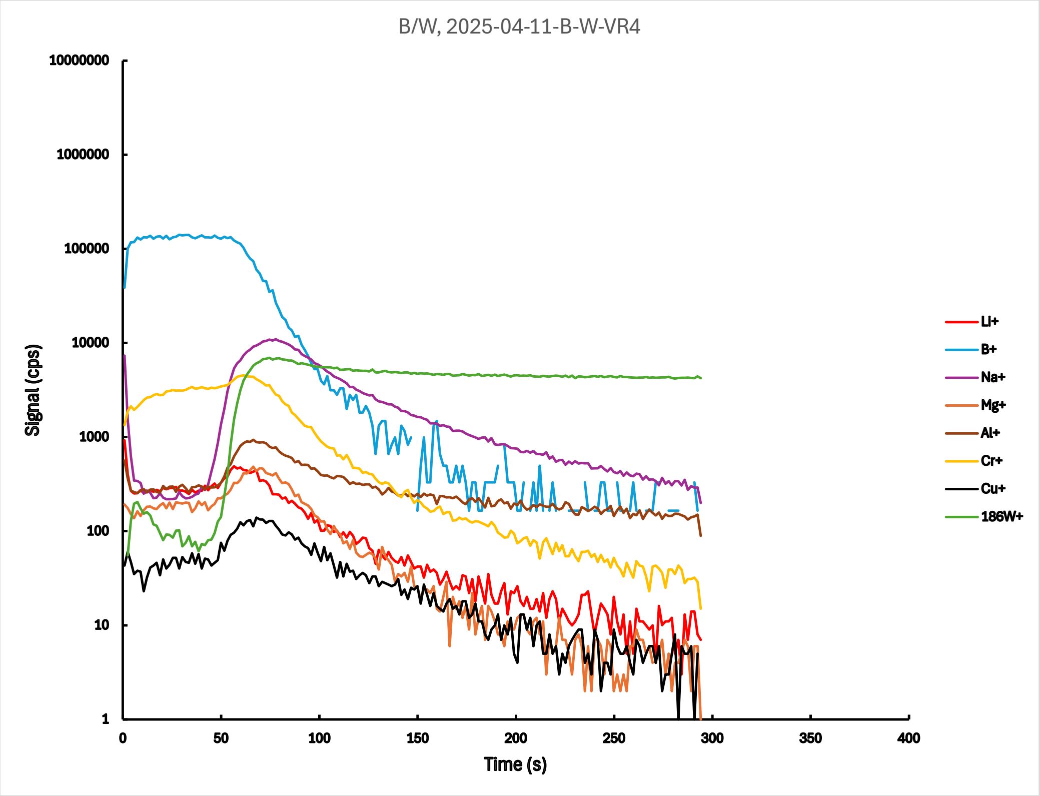


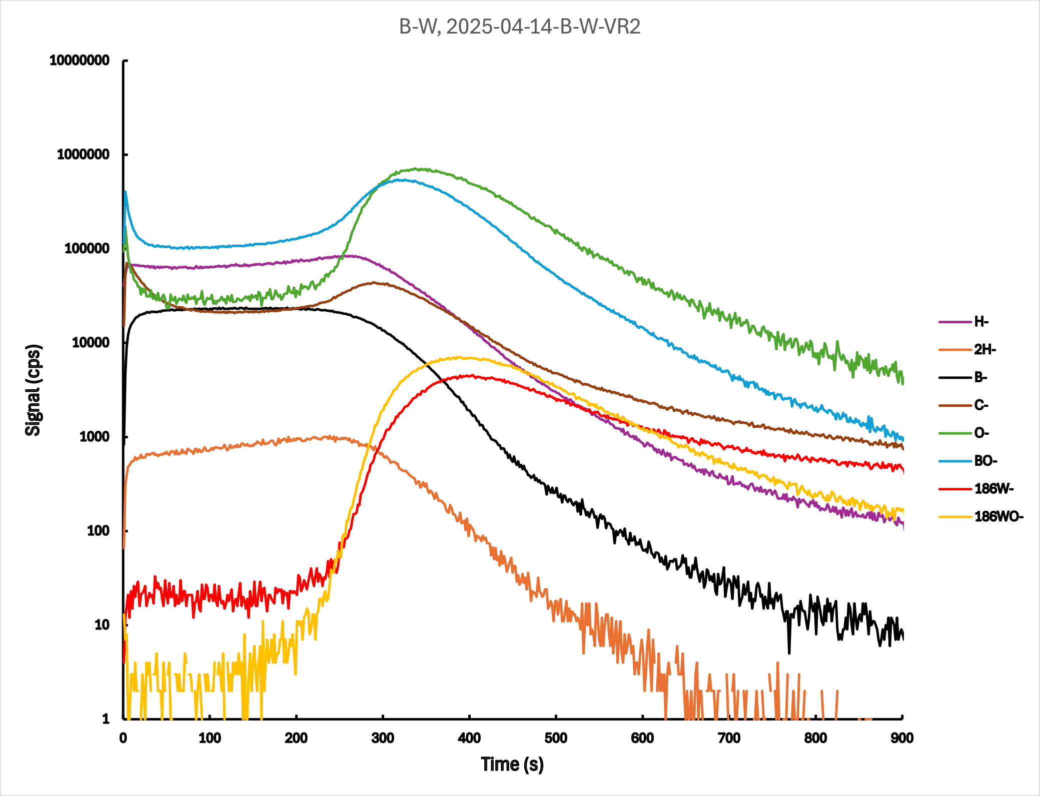


E. Pitthan, P. Petersson, D. Gautam, M. Rubel, D. Primetzhofer

SP B.4: SIMS analyses of selected B reference samples (VTT)

First application of the new VTT TOF-SIMS device for extracting depth profiles of B reference layers – studying ageing of the samples





- TOF-SIMS measurements using **positive and negative secondary ions for VT samples**
- Layers contain several impurities
- **Notable O concentrations on the samples** – and the interface peak becomes flat and strong when repeating the measurements after 2 months → **oxidization of the samples with time**

Deliverable: **PWIE-SP B.B4.T-T005-D013**
Status: ***completed***
Facilities: **Accelerator 1 day**
Linked WP or TSVV: **-**

A. Hakola, J. Likonen

SP B.4: LIBS and SEM analyses of selected B reference samples (FZJ)

Task and questions to be addressed

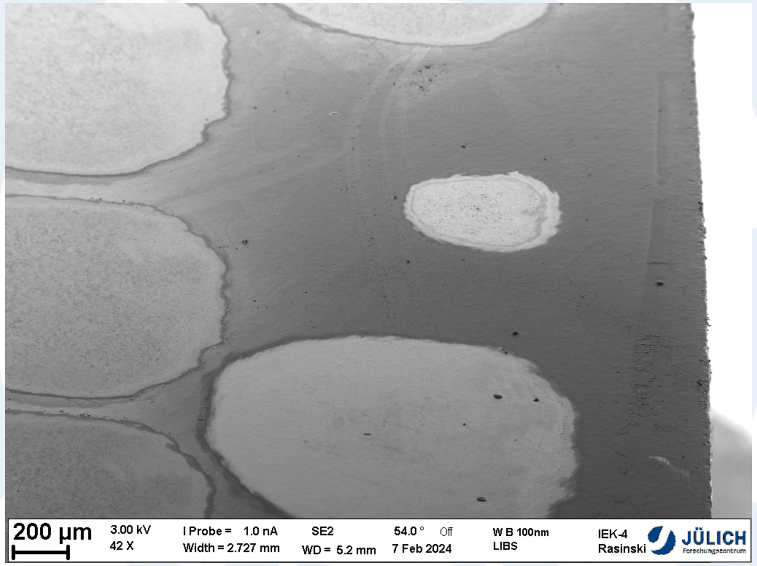
- Characterization of B layers after manufacturing and after PSI-2 exposures

Approach

- Each sample used in PSI-2 experiment within SP B.1 D003 was characterized by SEM and FIB. Selected samples will be investigated by LIBS by the end of the year.
- Considering continuation of B layer exposures in PSI-2 – the surface analysis will be also continued

Results

- First LIBS measurements for B layers on W substrates:
  - Laser parameter study, good signals
  - ~ 60...80 nm depth resolution
  - Further optimize the setup to improve the detection limit and try to get absolute B quantification
- FIB analysis enabled to assess the erosion rate of B layers in PSI-2 D_2 plasma exposures



LIBS measurement spots on a B-W sample

Deliverable: **PWIE-SP B.B4.T-T005-D006**
Status: ***ongoing (to be finished by the end of 2025)***
Facilities: **-**
Linked WP or TSVV: **SP B.1**

R. Yi, M. Rasinski

SP B.5 - Production of metallic dust in toroidal devices

SP B.5 deliverables 2025

Activity	Deliverable ID(s)	Title
SP B.5	D001 1.5 PM	Database of the characteristics of produced W dust particles in the presence of different gas mixtures and comparison with data from tokamaks (IAP)
SP B.5	D002 1.5 PM	Database of the characteristics of produced B dust particles in the presence of different gas mixtures and comparison with data from tokamaks (IAP)
SP B.5	D003 2 PM	Surface analyses of dust generated on AUG, WEST, and W7-X and comparison to the data originating from laboratory experiments (MPG)
SP B.5	D004 2 PM	Report on surface properties of boron dust on plasma-facing components and assessment for heat balance for boron powder injected into AUG plasmas (VR)
SP B.5	D005 4 PM	Ion-beam analyses of dust samples originating from AUG, WEST, and W7-X (RBI)
SP B.5	D006 2 PM	Microscopy and LIBS analyses of dust samples originating from AUG, WEST, and W7-X (FZJ)
SP B.5	D007 4 PM	Ion-beam analyses of B dust originating from AUG, WEST, and W7-X (VR)
SP B.5	D008 4 PM	Microscopy analyses of B dust originating from WEST and W7-X (IPPLM)
SP B.5	D009 1 PM	Report on the properties, composition, and amounts of dust produced on WEST during the Phase 1 operations (CEA)
SP B.5	D010 2 PM	Fracture and strentgh properties of B and W reference layers on W (UKAEA)

SP B.5: Production of W dust in toroidal devices (IAP)

- **Assessing the amount of dust that will be produced in toroidal devices.**
- **TASK:** W dust generation by MSGA in the presence of gases relevant for radiative cooling:

  i) Kr, Ne (dust synthesis rate, morphology, chemical composition, and D_2 retention); **DONE**

  ii) Exploratory parametric study regarding the synthesis of dust in H_2/N_2 discharges.

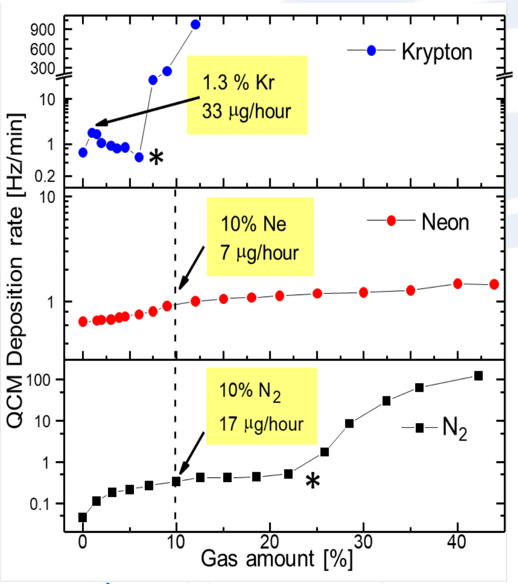
  - **Question:** Is dust produced in N_2/H_2? **YES.**
  - Evaluation of the dust production rate and properties (morphology, chemical composition) upon the N_2 content in the discharge. **DONE**

Approach

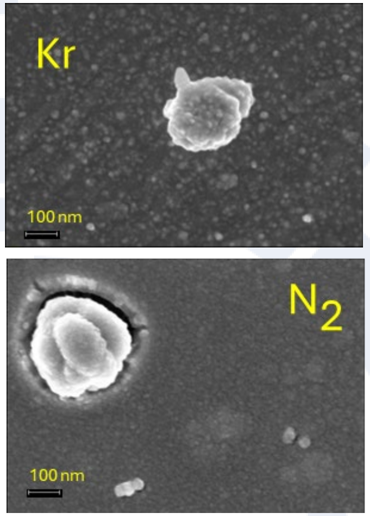
- Deposition rates were measured by QCM, increasing the amount of gas up to 40%;
- A transition to high rates appears for N_2 (25 %) and Kr (5%); not for Ne up to 40%;
- For sample deposition were selected 10 % of N_2 and Ne, and 1.3 % of Kr;
- The collected dust was investigated by SEM, XPS, and TDS.

Results:

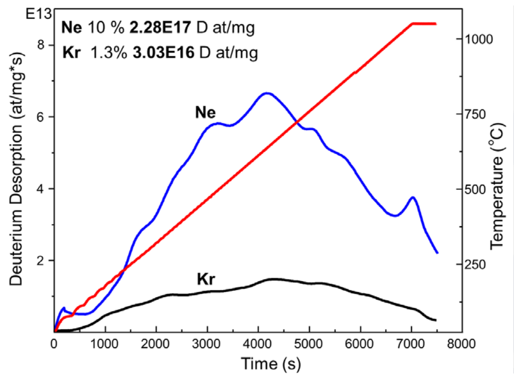
- Kr is most efficient in producing W dust;
- The collected dust contains NPs (up to 20 nm) and larger agglomerated particles;
- It appears that Ne deposited dust retains more D_2 compared to the Kr case;
- XPS results prove the presence of WN in the dust samples deposited with N_2.



Dust deposition rates using Kr, Ne, and N_2 in the discharges.



SEM images of samples deposited in Kr/D_2 and N_2/D_2.



D_2 retention in Ne and Kr deposited dust samples (TDS)

Deliverable: **PWIE-SP B.5.T-T003-D001**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **TSVV 7**

T. Acsente, G. Dinescu

SP B.5: Production of B dust in toroidal devices (IAP)

- **Database of the characteristics of produced B dust particles in the presence of different gas mixtures and comparison with data from tokamaks**

Task and questions to be addressed

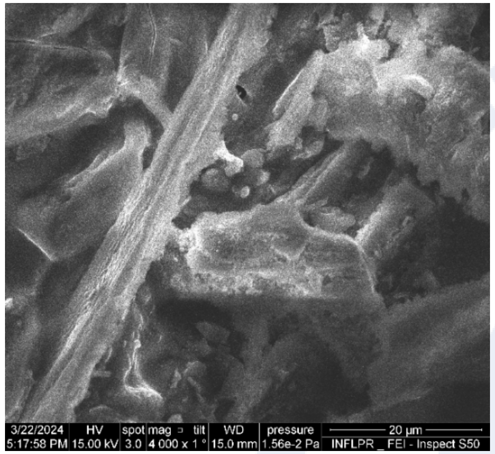
- Production and analysis of B dust/ particles

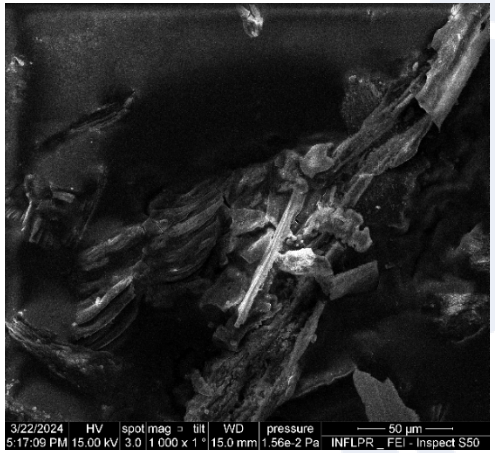
Approach

- Vacuum chamber, working pressure: 1×10^{-2} mbar
- B target (1 inch)
- W tip (1 mm)
- DC source
- Ar/D_2 atmosphere

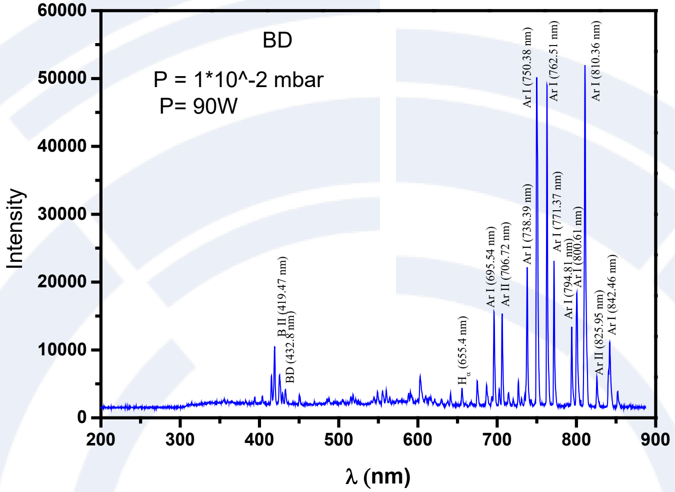
Results

- SEM measurements: particle diameters
- OES measurements: peak identification
- TDS measurements: desorption temperature and D amount

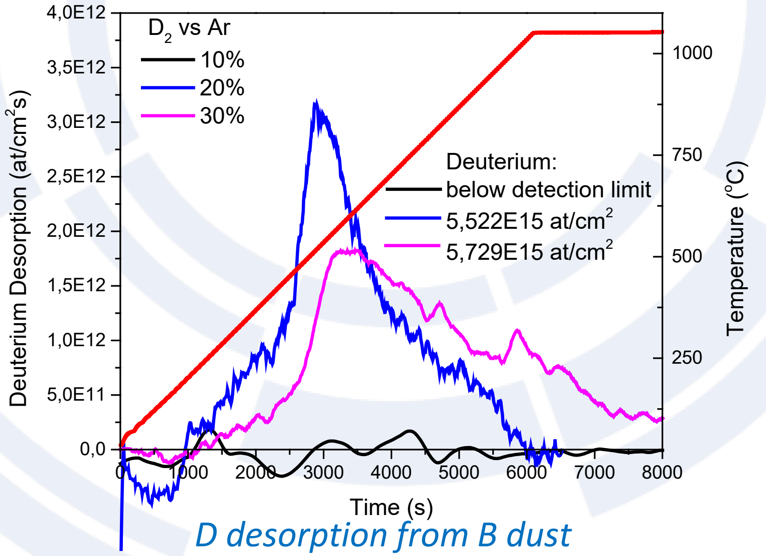




SEM images of the produced B dust



OES imaging of B dust using W disharges



D desorption from B dust

C. P. Lungu, C. Staicu, P. Dinca, B. Solomonea

Deliverable: **PWIE-SP B.5.T-T003-D002**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **TSVV 7**

SP B.5: Boron-dust interactions in fusion plasmas (VR)

Routine boronization in an all-W ITER → important to understand the survivability of boron dust (*in situ* from layer delamination or artificially injected as powder) → strong dependence on plasma-surface interactions and intrinsic boron properties that are external input to dust dynamic codes

Boron properties central for dust survivability studies

- Electron-boron interactions, ion-boron interactions, intrinsic thermal properties, intrinsic optical properties

Electron-boron interactions (0-5 keV electron energies)

- **Secondary electron emission.** Analytical description of the SEE yield (incident energy / angular dependence) and mean electron exit energy based on reliable ***experimental results*** from Bronshtein & Fraiman.
- **Electron backscattering.** Analytical description of the EBS yield (incident energy / angular dependence) and mean electron exit energy based on the results of dedicated ***Geant4 Monte Carlo simulations***.

Ion-boron interactions (0-5 keV H,D,T,^{3}He,^{4}He,B,Ne,W atom energies)

- **Physical sputtering.** Analytical description of the sputtering yield (incident energy / angular dependence) based on the results of ***SDTrimSP6 Monte Carlo simulations*** by the ERO team.
- **Ion backscattering.** Analytical description of the particle and energy reflection coefficients (incident energy / angular dependence) based on the results of ***SDTrimSP6 Monte Carlo simulations*** by the ERO team.
- **Potential electron emission.** Analytical description of the PEE yield (incident energy and angle independent) and mean electron exit energy based on ***established semi-empirical formulas*** in absence of dedicated experiments.
- **Kinetic electron emission.** Generally negligible.

Deliverable: **PWIE-SP B.5.T-T003-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE**

P. Tolias, S. Ratynskaia, L. Boccaccia, T. Rizzi

Many thanks to Dmitry Matveev and the ERO team for sharing their SDTrimSP6 boron data!

SP B.5: Boron-dust interactions in fusion plasmas (VR)

Intrinsic thermal properties

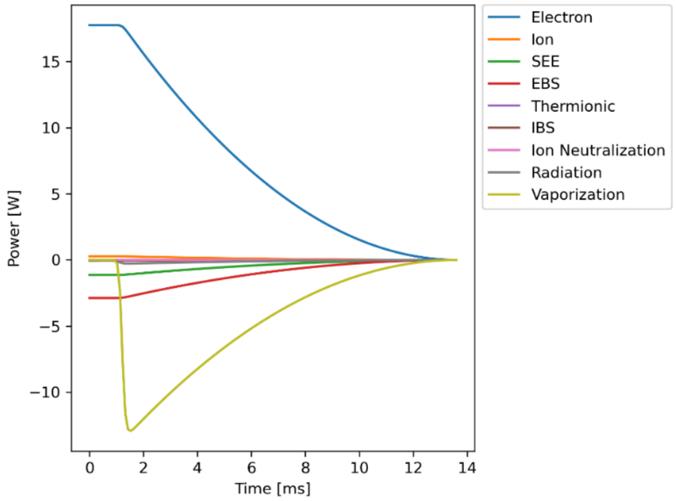
- **Evaporative cooling.** Analytical description of the vapor pressure based on ***experimental results***.
- **Thermionic cooling.** Analytical description based on the ***Richardson-Dushman formula***.
- **Heat capacity and latent heats**. Analytical description based on ***experimental results***.

Intrinsic optical properties

- **Extinction coefficient**. Construction of an ***extended dataset*** within 0.01 eV - 30 keV for amorphous boron based on ellipsometry measurements, transmittance measurements and theoretical calculations.
- **Refractive index**. Calculation on the basis of the ***Kramers-Kronig relations*** and compliance with the f-sum rule and inertial-sum rule.
- **Adhesive force.** Utilization of the complex refractive index for calculation of the Hamaker coefficient on the basis of the ***Lifshitz theory*** of van der Waals forces.
- **Radiative cooling.** Utilization of the complex refractive index for calculation of the total hemispherical emissivity on the basis of the ***Mie scattering theory*** for spherical dust.

Extension of material library of the MIGRAINe dust transport code to boron

- MIGRAINe calculations of the different microphysics contributions to boron dust heating and cooling for a uniform $100\ \mathrm{eV}, 10^{19}\ \mathrm{m}^{-3}$ deuterium plasma.
- Boron dust heating is dominated by electron collection, as expected.
- Boron dust cooling is dominated by vaporization with respectable contributions from secondary electron emission and electron backscattering.
- Difference from tungsten dust cooling that would have been dominated by vaporization and thermionic cooling.



Deliverable: **PWIE-SP B.5.T-T003-D004**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE**

P. Tolias, S. Ratynskaia, L. Boccaccia, T. Rizzi

Many thanks to Dmitry Matveev and the ERO team for sharing their SDTrimSP6 boron data!

SP B.5: Fracture and strength properties of B and W reference layers on W (UKAEA)

The aim is to use micromechanical testing techniques (bending of FIB-produced microcantilevers in a nanoindenter) to determine interfacial and bulk mechanical properties (strength and toughness) of reference B/W layers on W substrates.

Task and questions to be addressed

- Information about mechanical properties of reference layers and layer-substrate interface is to be used to improve the fundamental understanding of the propensity of deposit layers relevant for full-W device (i.e., B, W and mixed) for dust generation, and provide materials data for modeling of dust formation due to deposits fracture and exfoliation.
- Focus on a dependence of mechanical properties on thickness, consistency and composition of layers, and surface state of substrates.

Approach

- Task uses instruments and facilities in Materials Research Facility (UKAEA):
    - TESCAN AMBER X dual-column SEM-plasma FIB (Xe) for sample preparation
    - FEI Helios NanoLab 600i dual-column SEM-FIB (Ga) for manufacturing of microcantilevers using FIB micromachining
    - Agilent G200 nanoindenter for bending/fracture testing of microcantilevers
- Batch of samples produced by IAP, received at UKAEA, $10 \times 10 \times 1$ mm^3 W substrates with 5 µm thick B layer

Deliverable: **PWIE-SP B.5.T-T003-D010**
Status: ***ongoing (to be completed in the end of 2025)***
Facilities: **MRF (UKAEA)**
Linked WP or TSVV: **-**

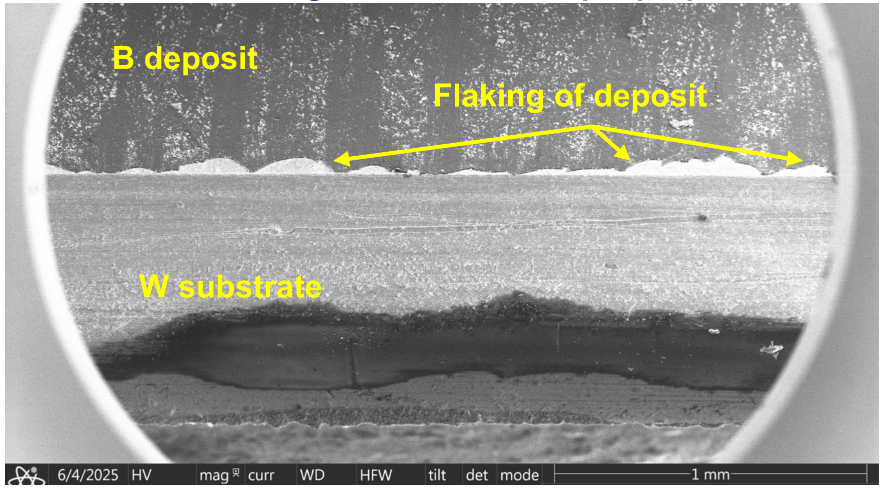
Y. Zayachuk

SP B.5: Fracture and strength properties of B and W reference layers on W (UKAEA)

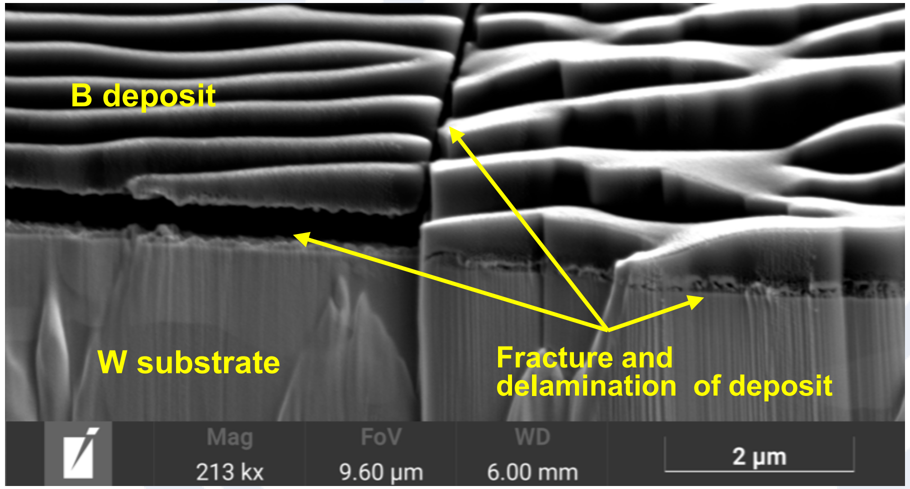
Results

- The overall methodology seems to be **unworkable when applied to available B-W samples** due to the difficulty in sample preparation.
    - Mechanical sample prep (cutting and grinding) leads to delamination of the B deposit.
    - Plasma FIB cutting of the sample's edge (whereby large area of material can be removed and surface polished, up to ~mm in width, without any mechanical action) was attempted as a replacement for mechanical preparation.
    - Even in the case of pFIB sample preparation the cracks running along the interface between B layer and W substrate were found, making cantilever testing impossible.
- These observations indicate **fragility of thick B deposits** → their fracture and subsequent dust generation appear likely.

Following mechanical sample prep:



Following plasma FIB sample prep:



Deliverable: **PWIE-SP B.5.T-T003-D010**
Status: ***ongoing (to be completed in the end of 2025)***
Facilities: **MRF (UKAEA)**
Linked WP or TSVV: **-**

Y. Zayachuk

SP B.5: Surface analysis of dust generated on AUG (MPG)

General Information

- Obtain statistical data of dust particles collected in AUG

Task and questions to be addressed

- Investigate (including ion-beam analyses, SEM, EDX) the properties of dust samples observed on AUG, WEST, and W7-X and validate proposed dust production mechanisms against laboratory experiments

Approach

- Collecting dust on Si collector plates mounted in special collector boxes (AUG)
- SEM measurements assisted by EDX: automated images collected, particle detection in the images, and recording EDX spectra for chemical anlyses of the individual articles

Results

- Automated recording system set back into operation
- Data taken from collector plates of the last campaigns

Deliverable: **PWIE-SP B.5.T-T003-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE, SP D**

M. Balden et al.

SP B.5: Dust collection using sticky probes on W7-X (MPG)

General Information

- Several dust samples collected from W7-X divertor units after OP2.3 using sticky probes and sent for further analyses

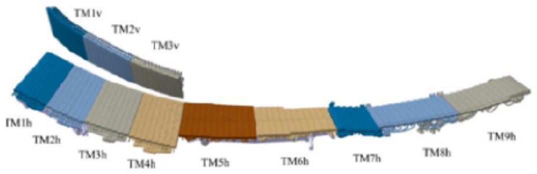
Divertor unit is denoted with

DU[number of module][upper or lower]

8 = upper

9 = lower

e.g. DU18 = divertor unit, module 1, upper module



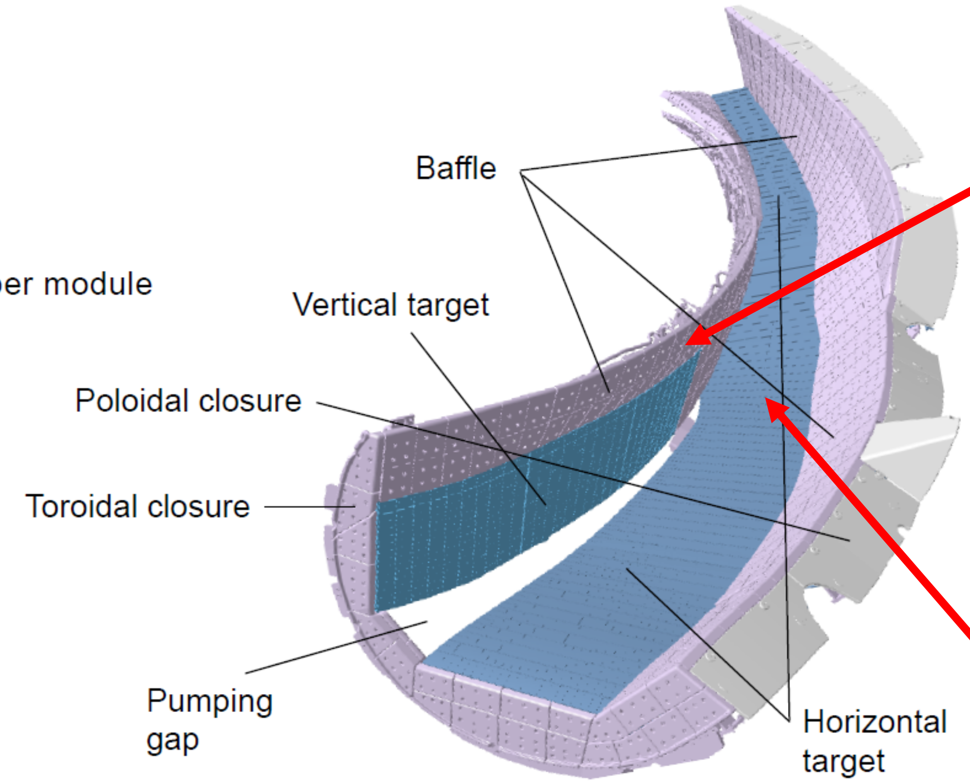


Photo credit: M. Endler Inspection after OP2.3

Photo credit: M. Endler Inspection after OP2.3

Deliverable: **PWIE-SP B.5.T-T003-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPW7X**

C. P. Dhard, L. Dittrich, M. Endler, M. Krause

SP B.5: Ion-beam analyses of B dust originating from W7-X (VR)

IBA of dust samples from W7-X

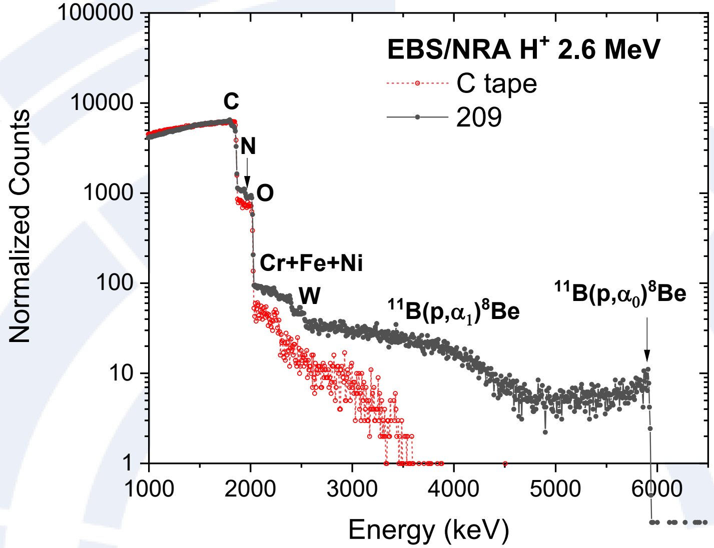
Identify chemical composition forming the dust and tracing their source on the plasma-facing components

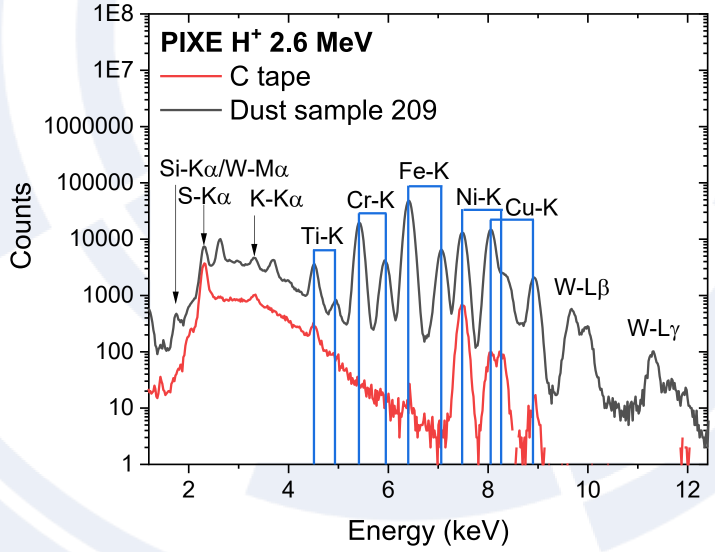
Approach

- 39 samples received collected from divertor units from all modules.
- Ion beam analysis performed: EBS+NRA+PIXE and ToF-ERDA.

Results

- **Example of data for EBS/NRA + PIXE 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**
  - Detailed analysis of data is in progress
  - µ-beam 2D elemental maps of selected isolated flakes are planned





Deliverable: **PWIE-SP B.5.T-T003-D007**
Status: ***ongoing (to be finished in the end of 2025)***
Facilities: **Accelerator 3 days**
Linked WP or TSVV: **WPW7X**

E. Pitthan, P. Petersson, M. Rubel, D. Primetzhofer

SP B.5: Ion-beam analyses of dust samples originating from W7-X (RBI)

15 dust samples received from W7-X

Task and questions to be addressed

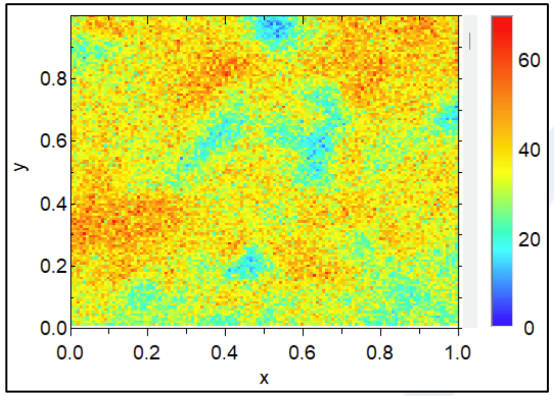
- Determine concentration of light elements and metals in dust samples using IBA techniques

Approach

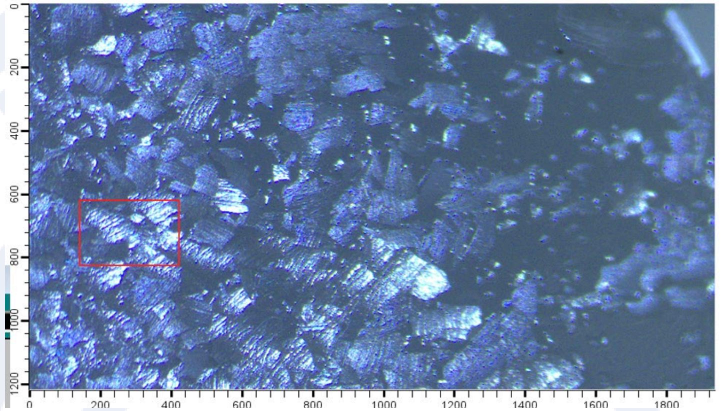
- NRA, PIXE and RBS measurements with focused ion beam of 3 MeV ^{3}He to measure light and heavier elements on the samples

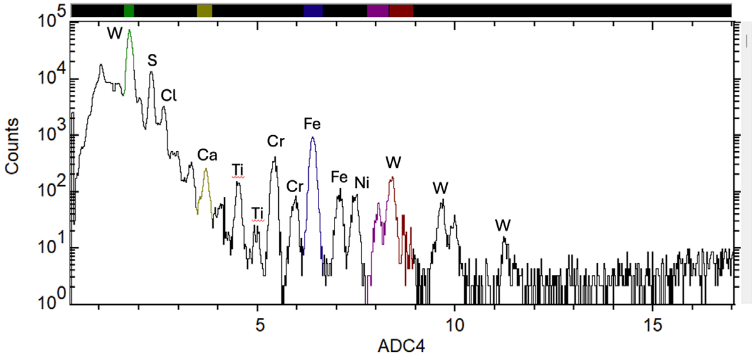
Results

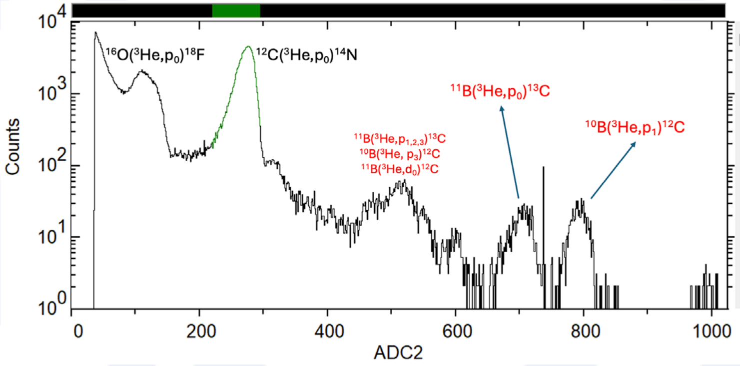
- All measurements completed
- Analysis of the PIXE, NRA and RBS spectra ongoing
- **Clusters of W, Fe, Cr, Ti found** along with boron
- Two samples contained copper droplets without boron



PIXE W_K map







PIXE and NRA spectra of sample #193 (Module 1)

Deliverable: **PWIE-SP B.5.T-T003-D005**
Status: ***ongoing (to be finished in the end of 2025)***
Facilities: **Accelerator 5 days**
Linked WP or TSVV: **WPW7X**

G. Provatas, S. Gouesmia, I. Bogdanović Radović

SP B.5: Microscopy and LIBS analyses of dust samples originating from W7-X (FZJ)

Task and questions to be addressed

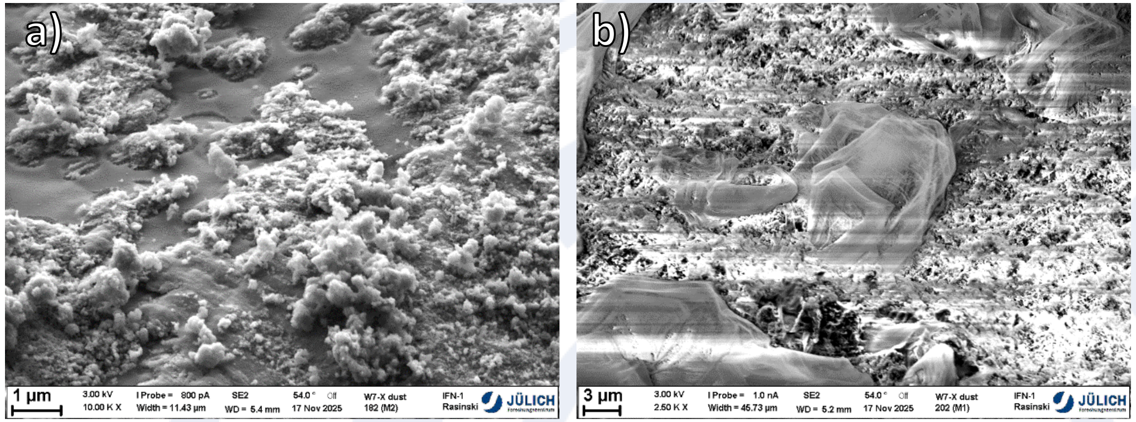
- Investigate the structure and composition of selected dust samples from W7X

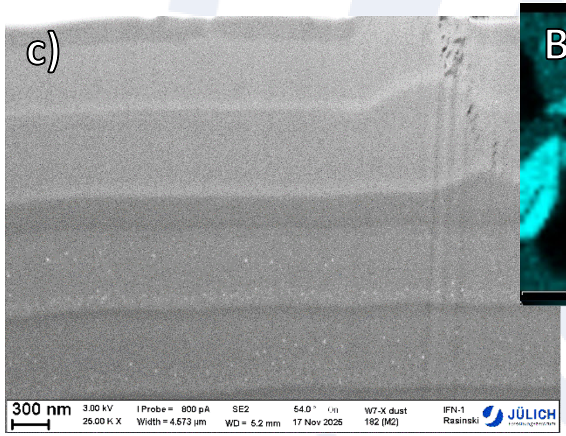
Approach

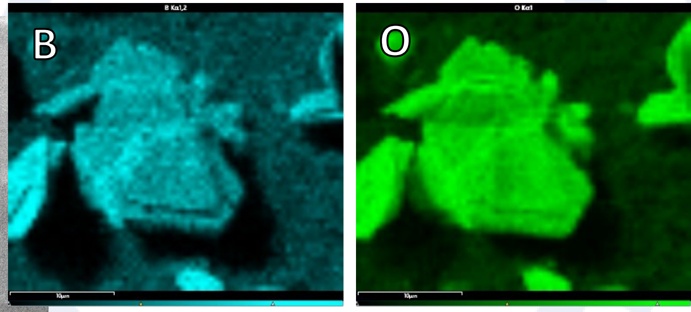
- SEM investigation combined with EDX chemical composition analysis on the surface and FIB prepared cross-sections
  - Delivered samples: 195, 200, 202 (M1); 172, 181, 182 (M2); 143, 153, 158 (M3); 112 (M4); 119, 132, 141 (M5)
  - Analysed samples 202 (M1), 182 (M2), 158 (M3), 119, 141 (M5)

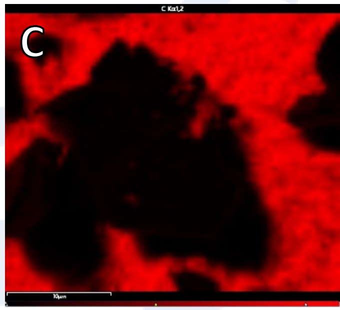
Results

- Each sample consist of a **thick deposit** (thickness 20-150 μm)
- Deposits consist of C, O and B with trace elements of Si, Fe, Cr, Cu, Ca, Cl (with concentrations below 0.1 at. %)
- Deposits have a **dense structure with visible layers** resulting from exposure and grow conditions during W7-X campaign.









SEM images of the surface of dust sample 182 (a, c) and 202 (b) together with EDX surface analysis of sample 202

Deliverable: **PWIE-SP B.5.T-T003-D006**
Status: ***ongoing (to be finished in the end of 2025)***
Facilities: **-**
Linked WP or TSVV: **WPW7X**

M. Rasinski, T. Dittmar

SP B.5: Microscopy analyses of dust samples originating from W7-X (IPPLM)

General Information

Examined samples:

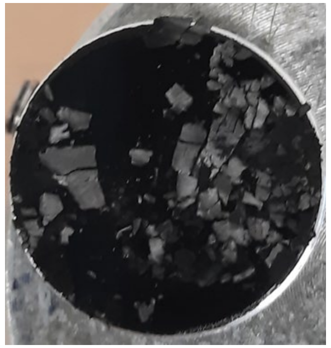
17 samples from W7-X shipped for analyses, up to now results reported from 2 samples (labelled 194 and 206) in the baffle region

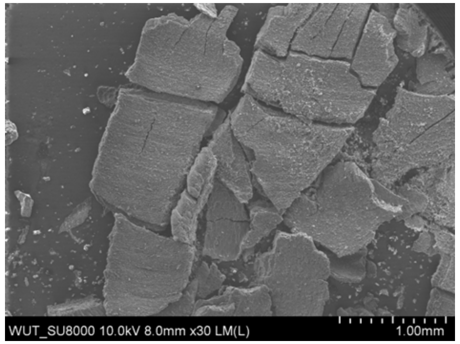
Task and questions to be addressed

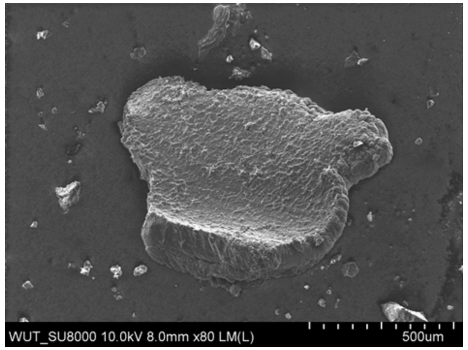
General objective: Determination of the composition, morphology, and, potentially, thickness of the collected co-deposited layers.

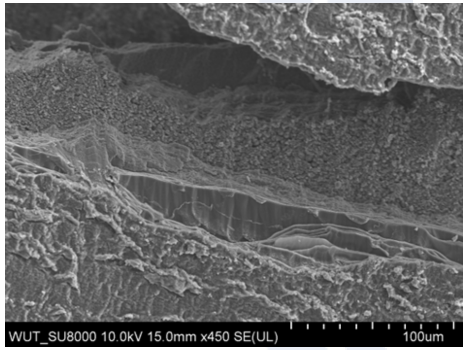
Approach

- On each sample, microscopic surface observations of co-deposited layers will be performed
- FIB cross-sections will be cut on selected samples to determine (i) structure and (ii) thickness of the examined flakes
- Optical profilometry to assess the thickness of the flakes









Sample 206 features relatively large (mm-sized) and thick flakes of deposits with varied morphology (granular, scaly, tile-like). Carbon is the dominant element.

Deliverable: **PWIE-SP B.5.T-T003-D008**
Status: ***ongoing (to be finished in the end of 2025)***
Facilities: **-**
Linked WP or TSVV: **WPW7X**

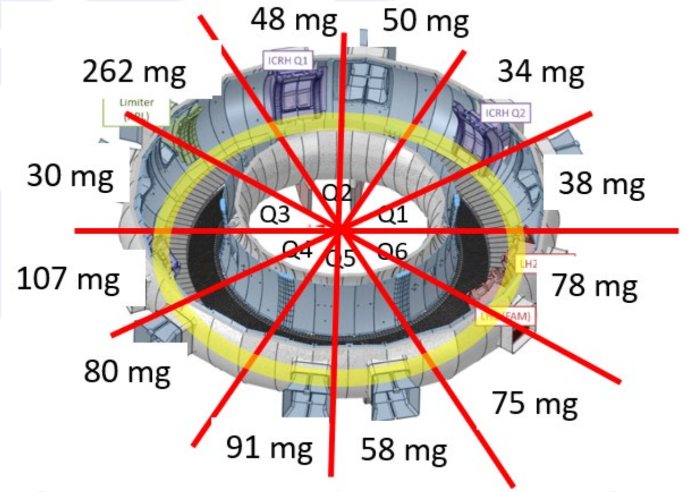
SEM images of flakes, sample 206 – images at different maginifications

- *Thickness of some flakes significantly exceeds 100 µm*
- ***Layered structure visible*** *on the edges of the flakes or at the cracks*
- ***Iron-rich particles/clusters*** *on the surface of the deposited flakes*

E. Fortuna-Zaleśna

SP B.5: Report on the properties, composition, and amounts of dust produced on WEST during the Phase 2 operations (CEA)

Work carried out within SAE and reported in PWIE



Task and questions to be addressed

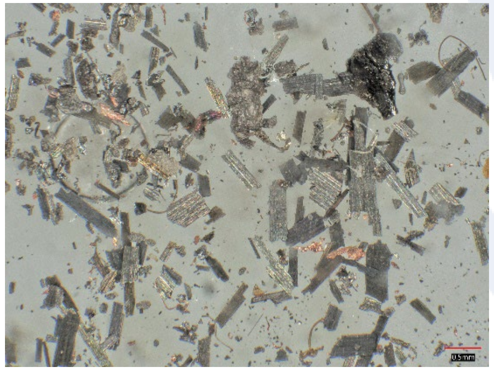
- Use WEST and its tungsten plasma facing materials to assess dust characteristics

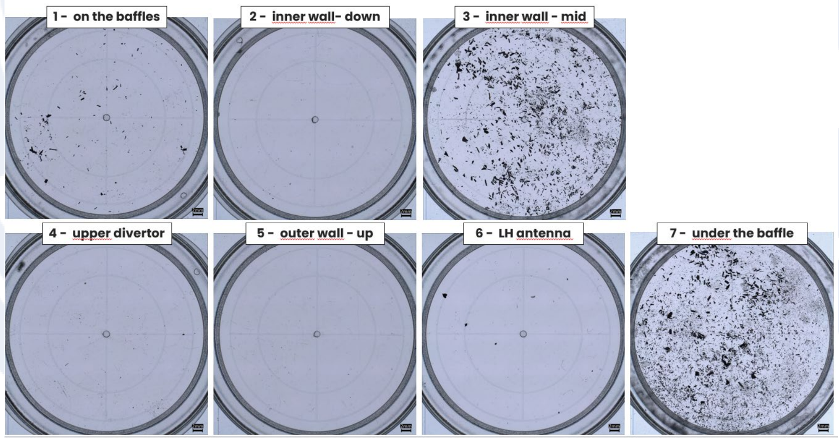
Approach

- In-situ dust collection at various poloidal locations (2024) and toroidal locations (2025) – **done**
- Weight measurements - **done**
- Statistical analysis of particles size using image treatment - **done**
- SEM/EDX analyses to identify chemical composition - **ongoing**

Results

- Most of the dust was found at the bottom of the VV
- **Dust evenly distributed across the 12 sectors**
- **Particles of W coating, Cu and glass**





Deliverable: **PWIE-SP B.5.T-T003-D009**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE, WPSAE**

M. Diez, A. Flament, C. Martin, et al.

SP B.6 – B deposition on diagnostic mirrors

SP B.6 deliverables 2025

Activity	Deliverable ID(s)	Title
SP B.6	D001 3 PM	Preparation and post characterization of exposed Mo mirrors (FZJ)
SP B.6	D002 1 PM	Handling and exposure of Mo mirrors using AUG LBO-manipulator during boronizations (MPG)
SP B.6	D003 1 PM	Handling and exposure of Mo mirrors using W7-X multipurpose manipulator during boronizations (MPG)
SP B.6	D004 3 PM	Changes in the optical properties of the exposed Mo mirrors (EPFL)

SP B.6: Preparation and post characterization of exposed Mo mirrors (FZJ)

Task and questions to be addressed

- Characterize diagnostics mirrors after exposure to boronizations on W7-X and AUG

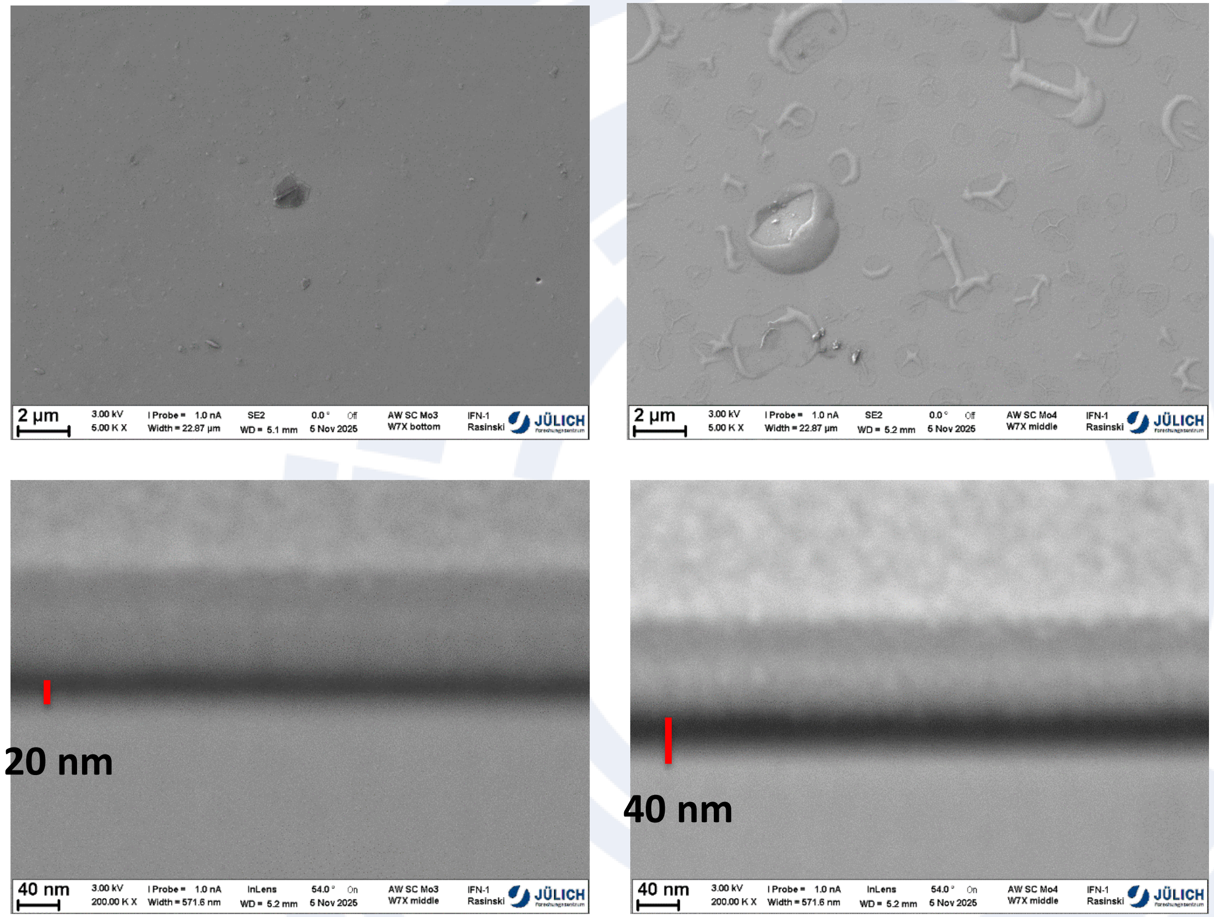
Approach

- 4 Mo mirror samples prepared, characterized and exposed during boronizations on W7-X (1) and AUG (3)
- Post-characterization including reflectivity, weight loss, surface roughness and photography - **finished**
- Post-characterization including SIMS and SEM/FIB - **finished**

Results

Different thickness measured for B layers depending on exposure conditions

- at LBO location
- boronization, electrode on (2)
- boronization + plasma (3)
- boronization, electrode off (4)



SEM surface image (top row) and FIB cross-section (bottom row) of Mo SC mirror exposed in AUG to conditions 3 (left) and 4 (right)

Deliverable: **PWIE-SP B.6.T-T002-D001**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE, WPW7X**

A. Litnovsky et al.

SP B.6: Exposure of Mo mirrors on AUG and W7-X (MPG)

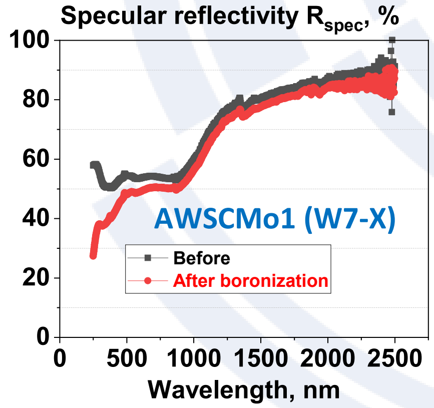
Task and questions to be addressed

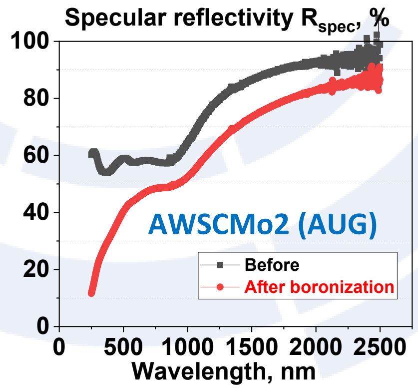
- Handling and exposure of Mo mirrors using AUG LBO-manipulator (D002) and the MPM of W7-X (D003) during boronizations

Results

- All Mo samples exposed successfully and sent for further analyses

Mirror	Facility/Location	Description	Principal results
AWSCMo1	W7-X MPM manipulator	At the first wall, boronization only	Reflectivity R_{tot} drop to 30% in the UV, mass increase 30 µg
AWSCMo2	AUG LBO manipulator	LBO location, boronization, electrode on	Reflectivity R_{tot} drop to 14% in the UV, mass increase 60 µg
AWSCMo3	AUG LBO manipulator	At LBO location, boronization + plasma	Reflectivity R_{tot} drop to 4% (!) in the UV, mass increase 203 µg
AWSCMo4	AUG LBO manipulator	At LBO location, boronization, electrode off	Reflectivity R_{tot} drop to 38% (but!) in the UV, mass increase 500 (!) µg, Roughness R_a ~ 17%





Deliverable: **PWIE-SP B.6.T-T002-D002**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPTE**

Deliverable: **PWIE-SP B.6.T-T002-D003**
Status: ***completed***
Facilities: **-**
Linked WP or TSVV: **WPW7X**

V. Rohde, M. Balden, C.P. Dhard

SP B.6: Changes in the optical properties of the exposed Mo mirrors (EPFL)

Samples received at Uni Basel (10.11.25). Removal of boron will start after the characterization results (FZJ) are sent to Uni Basel.

Deliverable: **PWIE-SP B.6.T-T002-D004**
Status: ***delayed***
Facilities: **-**
Linked WP or TSVV: **WPTE, WPW7X**

L. Marot

Concluding remarks

- Generally the **work has progressed steadily since the kick-off meeting**
  - ✓ Several smaller, thematic meetings organized after the Prague meeting in March (on dust, mirrors, and sample analyses) to agree on the details
  - ✓ Needs for W and B samples updated in July before the holidays and task descriptions adjusted accordingly to ensure completion of the activities as much as possible in 2025
- On SP B.1 **work on W samples could finally be pursued in addition to which several B samples have been exposed** on the contributing linear machines and in laboratory setups
  - ✓ Many exposures have, however, resulted in large damages and surface modifications → more experiments with gentler parameters and/or different sample specifications required
- **WEST analyses formed the main part of activities** under SP B.2 and SP B.3 – but now new samples also available from AUG
  - ✓ AUG (follow-up) analyses will be largely carried out in 2026
  - ✓ WEST analyses will still be an integral part of the work programme in 2026-2027, flavored by individual samples from W7-X
- **Reference coatings (SP B.4) largely focused on B layers** in 2025 and this trend expected to continue in 2026-2027
  - ✓ Several contributions considered for PSI, including an ”overview” of the programme by A. Hakola
- **Dust and mirror activities (SP B.5 and SP B.6) to be stopped**, any outstanding work relevant for contributing devices can be finished under the overall analysis activities
  - ✓ Situation may, however, change – stay tuned for any updates to follow

WPPWIE SP B in 2026-2027 – status of preparations

- **Selection made and resources in PM balanced** between different subprojects and tasks to be carried out
  - ✓ SP B continues to have a large share of the resources (and related time on linear devices and accelerators) even though reductions have made compared to 2025 budget
- **Detailed RU selection in line with** what has been communicated privately to the task holders
  - ✓ Now it is time to start working with the usual activity sheets
- **Everybody will be contacted within the next couple of weeks** to agree on the detailed work plan for 2026-2027
  - ✓ **NB1!** We have 2-year programme
  - ✓ **NB2!** Task descriptions to be elaborated based on feedback obtained in this meeting

Distribution of Human Resources at 50% funding rate