Project Meeting
Plasma-Wall Interactions and Exhaust

2025 Final Summary / 2026 Plans
Subproject: SP B Experiments on erosion, deposition, and material migration

Antti Hakola

VTT

S. Brezinsek (PL), J.W. Coenen, A. Hakola, K. Schmid, A. Kirschner,
J. Likonen, I. Classen, A. Goriaev, and D. Douai (DPL)

JÜLICH
Forschungszentrum

2025 Final Summary of SP B

PWIE-SP B.1.T-T005-D001 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)

PWIE-SP B.1.T-T005-D002 Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in GyM with flux and fluence (ENEA)

PWIE-SP B.1.T-T005-D003 Erosion rates of W/B model systems and re-deposited W with different morphologies and compositions in PSI-2 with flux and fluence (FZJ)

PWIE-SP B.1.T-T005-D004 Erosion rates of co-deposited W- and B-based model systems following exposure to controlled ion beams (OEAW)

PWIE-SPB.1.T-T005-D005 Erosion rates following high-energy dust impacts on W model systems and comparison to data from tokamaks (ENEA)

> All corresponding deliverables achieved and reported

PWIE-SP B.3.T-T005-D001 Depth profiles and surface morphology of selected B or W layers (CIEMAT)

PWIE-SP B.3.T-T005-D002 Surface modifications and fuel content of selected AUG, WEST, W7-X, and PSI-2 samples (FZJ)

PWIE-SP B.3.T-T005-D003 Composition of layers on selected WEST monoblock samples (IAP)

PWIE-SP B.3.T-T005-D004 Surface modifications of selected WEST, W7-X, MAGNUM-PSI, PSI-2, and GyM samples (IPPLM)

PWIE-SP B.3.T-T005-D005 Composition and fuel content of layers on selected WEST monoblock samples and on samples originating from SP B.1 or SP X experiments (IST)

PWIE-SP B.3.T-T005-D006 Micro- and macroscale composition of layers on selected AUG, WEST, MAGNUM-PSI, PSI-2, and GyM samples (JSI)

PWIE-SP B.3.T-T005-D007 Surface modifications and erosion/deposition profiles of samples and wall tiles from AUG, WEST, and W7-X (MPG)

PWIE-SP B.3.T-T005-D008 Surface modifications and composition of layers on selected WEST, MAGNUM-PSI, PSI-2, and GyM samples (NCSRD)

PWIE-SP B.3.T-T005-D009 Micro- and macroscale composition of layers on selected AUG, WEST, MAGNUM-PSI, PSI-2, and GyM samples (RBI)

PWIE-SP B.3.T-T005-D010 Erosion and deposition patterns on selected WEST samples as well composition of plasma-exposed B and W layers (VR)

PWIE-SP B.3.T-T005-D011 Depth profiles and composition of deposited layers of selected samples from AUG, WEST, W7-X, MAGNUM-PSI, PSI-2, and GyM (VTT)

PWIE-SP B.3.T-T005-D012 Depth profiles for layers on selected WEST monoblock samples (UT)

PWIE-SP B.2.T-T005-D001 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)

PWIE-SP B.2.T-T005-D002 WEST campaigns: microscopy investigations of He-exposed PFUs after Phase 1 and Phase 2 operations on WEST (CEA)

PWIE-SP B.2.T-T005-D003 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)

PWIE-SP B.2.T-T005-D004 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)

PWIE-SP B.2.T-T005-D005 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)

PWIE-SP B.2.T-T005-D006 AUG campaigns: deposition profiles on samples originating from boronizations on AUG (RBI)

PWIE-SP B.2.T-T005-D007 AUG campaigns: changes in the surface properties of samples exposed to AUG plasmas and/or boronizations on AUG (FZJ)

PWIE-SP B.2.T-T005-D008 W7-X manipulator experiments: erosion and deposition characteristics on manipulator and other samples exposed to OP2 plasmas on W7-X (FZJ)

PWIE-SP B.2.T-T005-D009 W7-X manipulator experiments: erosion and depostion patterns on manipulator samples and wall components from OP2 experiments and/or boronizations on W7-X (MPG)

> All corresponding deliverables achieved and reported except for the one for RBI (D006, delayed)

> All corresponding deliverables achieved and reported except for the one for RBI (D009, delayed)

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

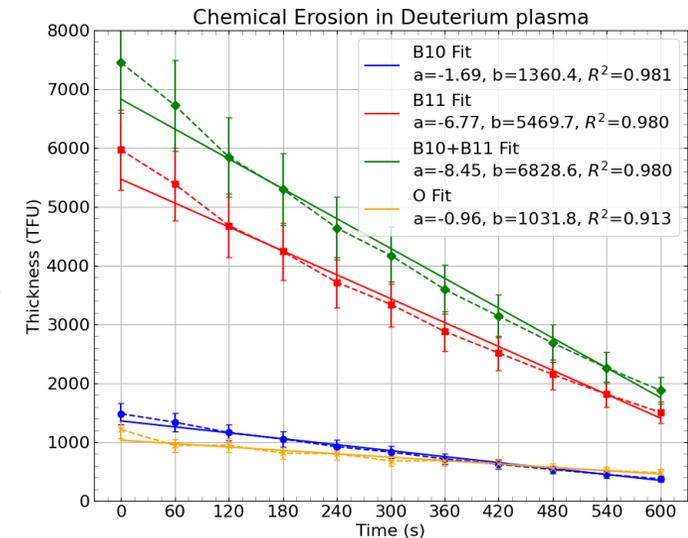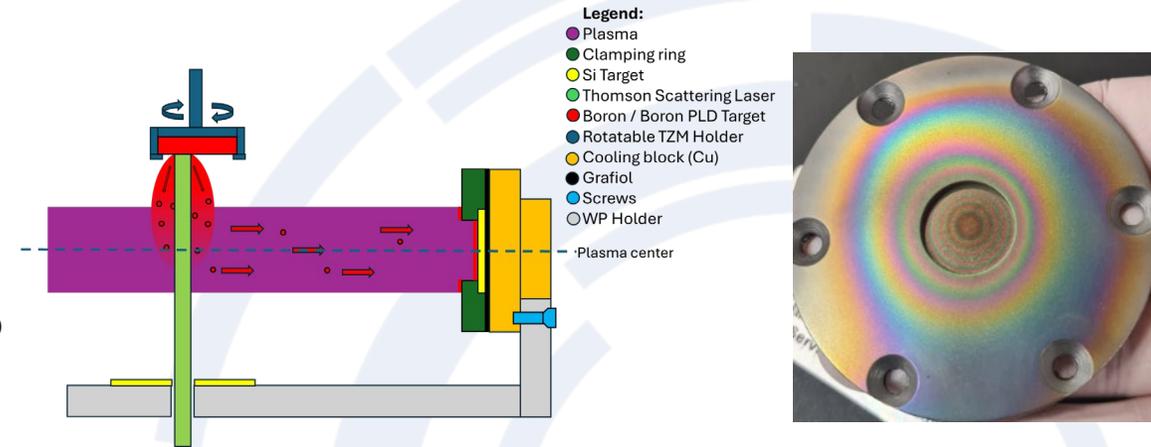## Task and questions to be addressed

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

Legend:
- Plasma
- Clamping ring
- Si Target
- Thomson Scattering Laser
- Boron / Boron PLD Target
- Rotatable TZM Holder
- Cooling block (Cu)
- Grafiol
- Screws
- WP Holder

Plasma center

Chemical Erosion in Deuterium plasma

B10 Fit
a=-1.69, b=1360.4, R^2=0.981
B11 Fit
a=-6.77, b=5469.7, R^2=0.980
B10+B11 Fit
a=-8.45, b=6828.6, R^2=0.980
O Fit
a=-0.96, b=1031.8, R^2=0.913

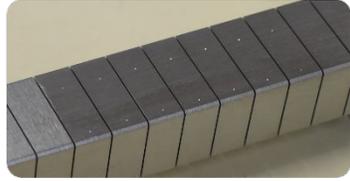Thickness (TFU) vs Time (s)

Deliverable: **PWIE-SP B.B1.T-T005-D001**
Status: ***completed***
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

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)
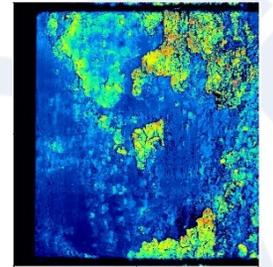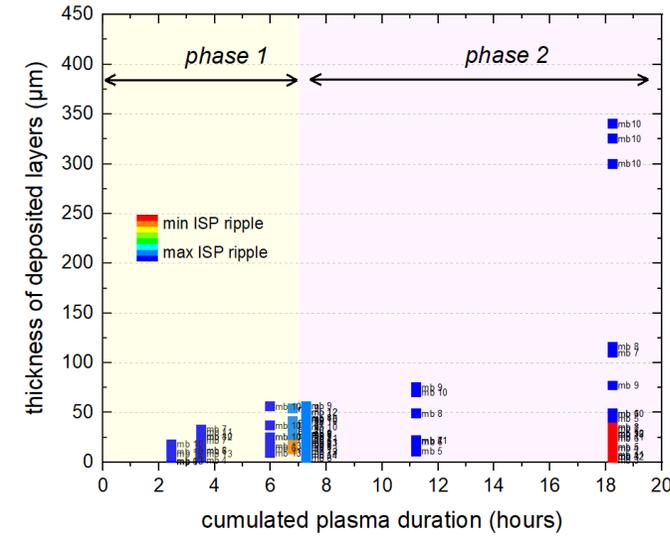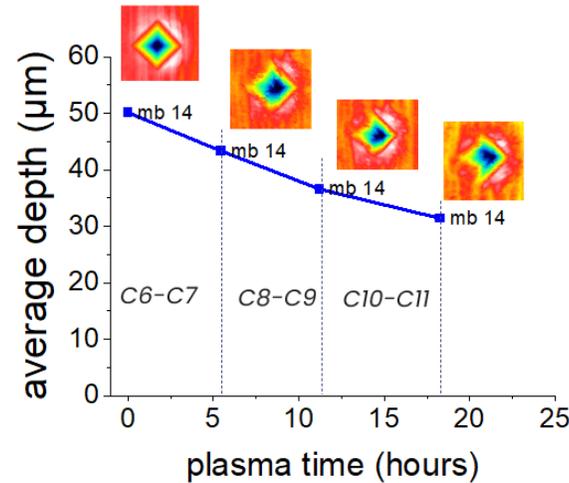- FIB analyses of the fiducials (MPG)

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*

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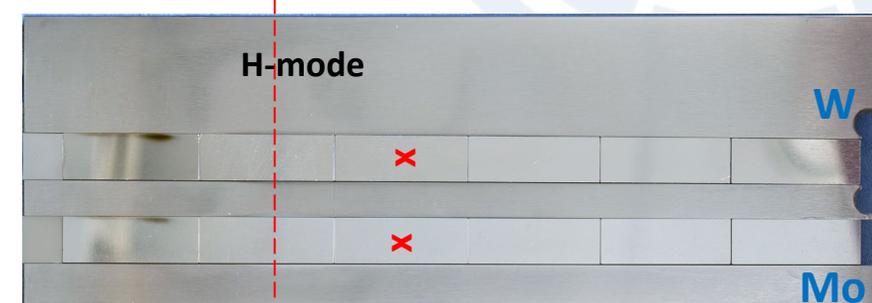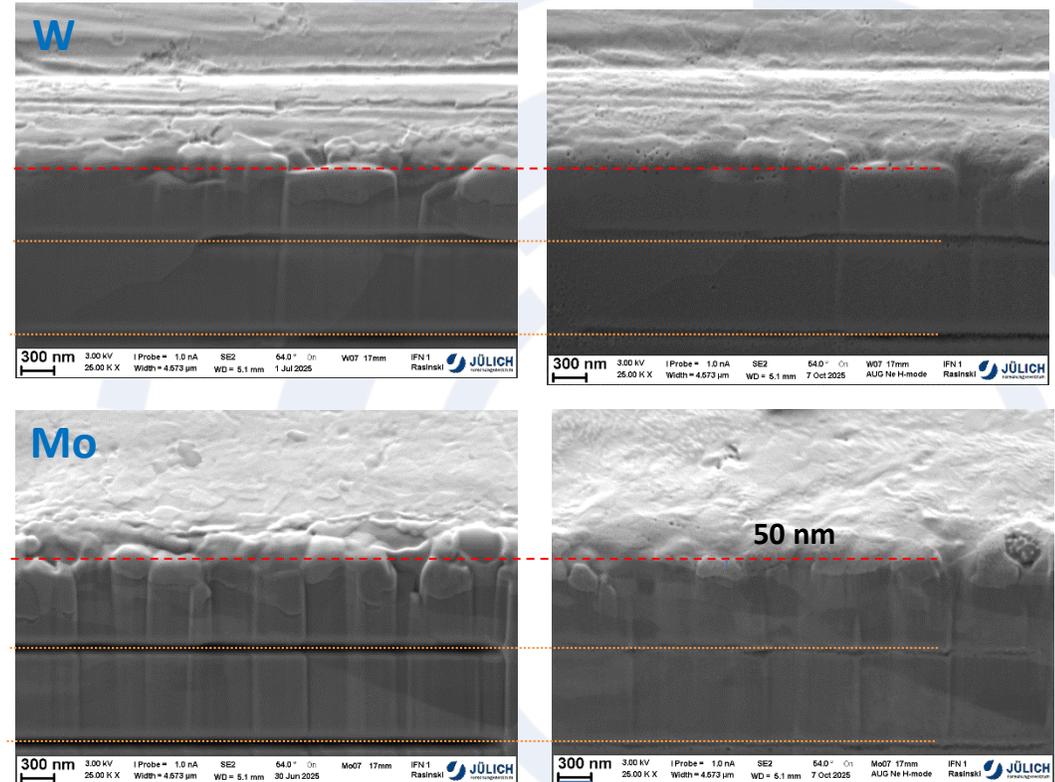
Deliverable: **PWIE-SP B.B2.T-T005-D007**
Status: *completed*
Facilities: -
Linked WP or TSVV: **WPTE**

before   after

M. Rasinski

PWIE-SP B.5.T-T003-D001 Database of the characteristics of produced W dust particles in the presence of different gas mixtures and comparison with data from tokamaks (IAP)

PWIE-SP B.5.T-T003-D002 Database of the characteristics of produced B dust particles in the presence of different gas mixtures and comparison with data from tokamaks (IAP)

PWIE-SP B.5.T-T003-D003 Surface analyses of dust generated on AUG, WEST, and W7-X and comparison to the data originating from laboratory experiments (MPG)

PWIE-SP B.5.T-T003-D004 Report on surface properties of boron dust on plasma-facing components and assessment for heat balance for boron powder injected into AUG plasmas (VR)

PWIE-SP B.5.T-T003-D005 Ion-beam analyses of dust samples originating from AUG, WEST, and W7-X (RBI)

PWIE-SP B.5.T-T003-D006 Microscopy and LIBS analyses of dust samples originating from AUG, WEST, and W7-X (FZJ)

PWIE-SP B.5.T-T003-D007 Ion-beam analyses of B dust originating from AUG, WEST, and W7-X (VR)

PWIE-SP B.5.T-T003-D008 Microscopy analyses of B dust originating from WEST and W7-X (IPPLM)

PWIE-SP B.5.T-T003-D009 Report on the properties, composition, and amounts of dust produced on WEST during the Phase 1 operations (CEA)

PWIE-SP B.5.T-T003-D010 Fracture and strength properties of B and W reference layers on W (UKAEA)

All corresponding deliverables achieved and reported

PWIE-SP B.6.T-T002-D001 Preparation and post characterization of exposed Mo mirrors (FZJ)

PWIE-SP B.6.T-T002-D002 Handling and exposure of Mo mirrors using AUG LBO-manipulator during boronizations (MPG)

PWIE-SP B.6.T-T002-D003 Handling and exposure of Mo mirrors using W7-X multipurpose manipulator during boronizations (MPG)

PWIE-SP B.6.T-T002-D004 Changes in the optical properties of the exposed Mo mirrors (EPFL)

All corresponding deliverables achieved and reported including PWIE-SP B6.T-T002-D004

PWIE-SP B.4.T-T005-D001 W- and B-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (ENEA)

PWIE-SP B.4.T-T005-D002 W-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (IAP)

PWIE-SP B.4.T-T005-D003 B reference layers with pre-defined composition and morphology for comparison with data from tokamaks (IAP)

PWIE-SP B.4.T-T005-D004 Microscopy investigations of selected B and W reference samples (IPPLM)

PWIE-SP B.4.T-T005-D005 Raman analyses of selected B reference samples (CEA)

PWIE-SP B.4.T-T005-D006 SEM and SIMS analyses of selected B and W reference samples (CIEMAT)

PWIE-SP B.4.T-T005-D007 LIBS and SEM analyses of selected B reference samples (FZJ)

PWIE-SP B.4.T-T005-D008 Ion-beam analyses of selected B and W reference samples (IST)

PWIE-SP B.4.T-T005-D009 XPS and TDS analyses of selected B reference samples (JSI)

PWIE-SP B.4.T-T005-D010 Ion-beam and structural analyses of selected B and W reference samples (NCSRD)

PWIE-SP B.4.T-T005-D011 TOF-ERDA analyses of selected B and W reference samples (RBI)

PWIE-SP B.4.T-T005-D012 Ion-beam analyses of selected B reference samples (VR)

PWIE-SP B.4.T-T005-D013 SIMS measurements and ion-beam analyses of selected B and W reference samples (VTT)

All corresponding deliverables achieved and reported

Example of SP B activities
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

Deliverable: **PWIE-SP B.B4.T-T005-D004**
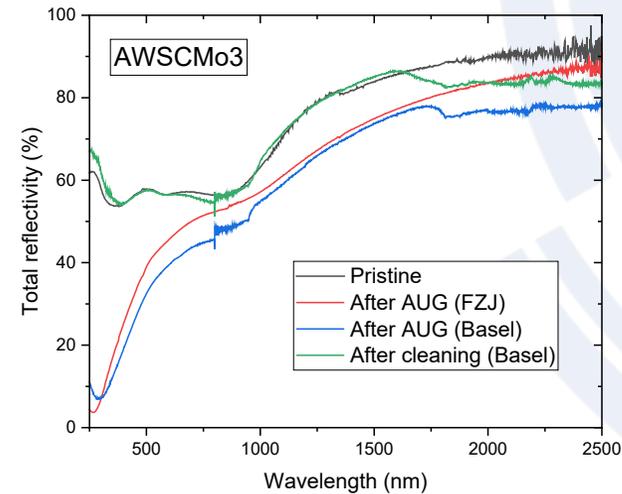Status: *completed*
Facilities: -
Linked WP or TSVV: -
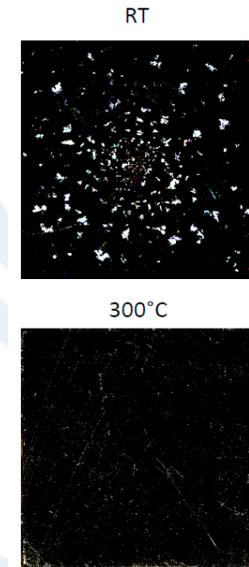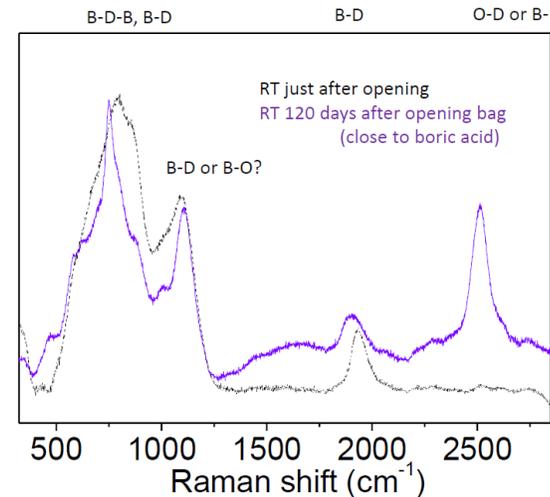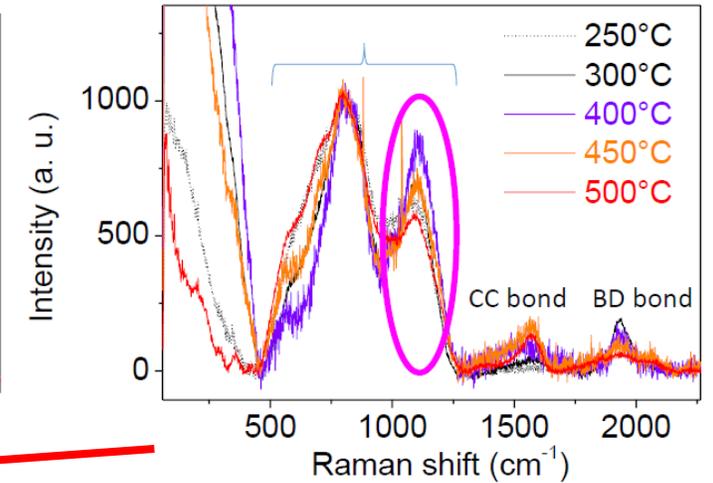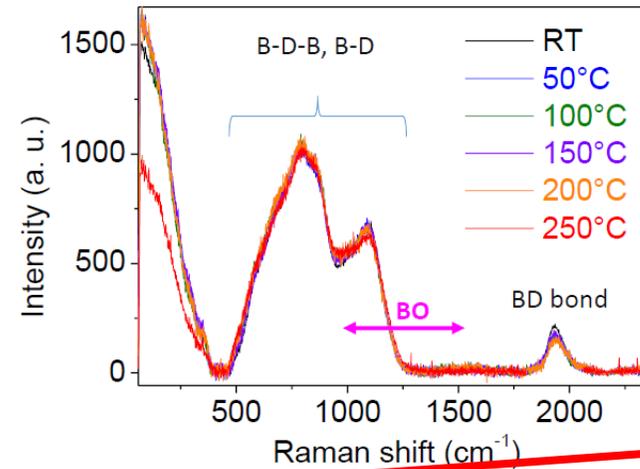
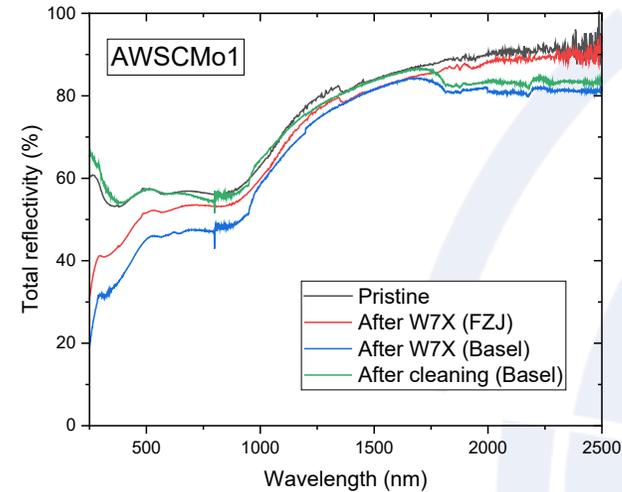*Examples of white crystals (RT) and more homogeneous surface (300°C) of the B+D_2(10%), samples from IAP*

C. Pardanaud, C. Martin, G. Giacommetti

Results

- Complete removal of boron films confirmed by XPS after plasma cleaning
- Recovery of the reflectivity after plasma cleaning. Diffuse reflectivity increases by a few percent after cleaning
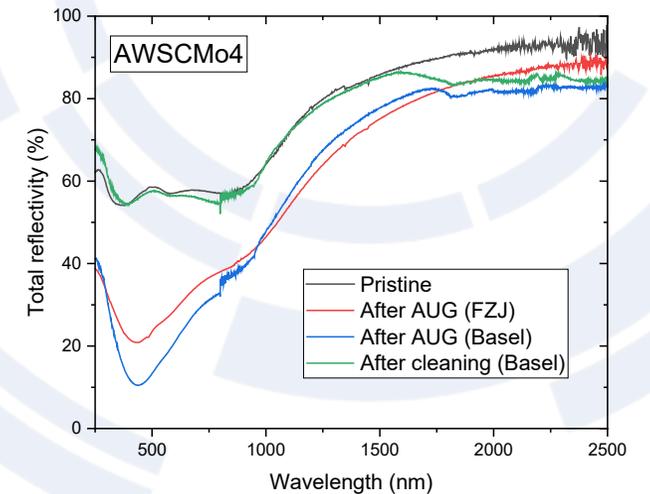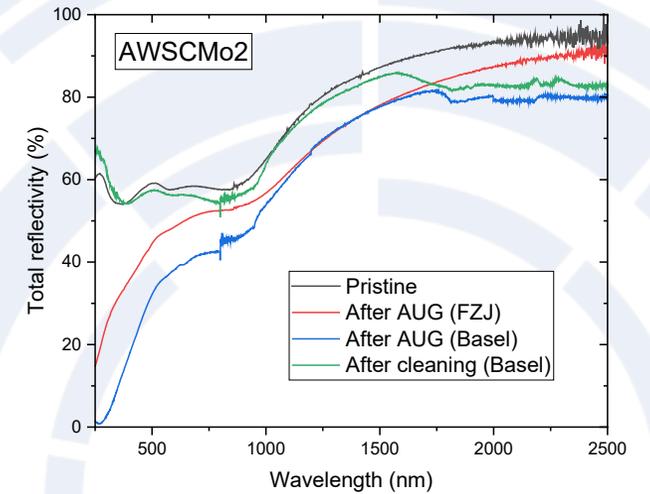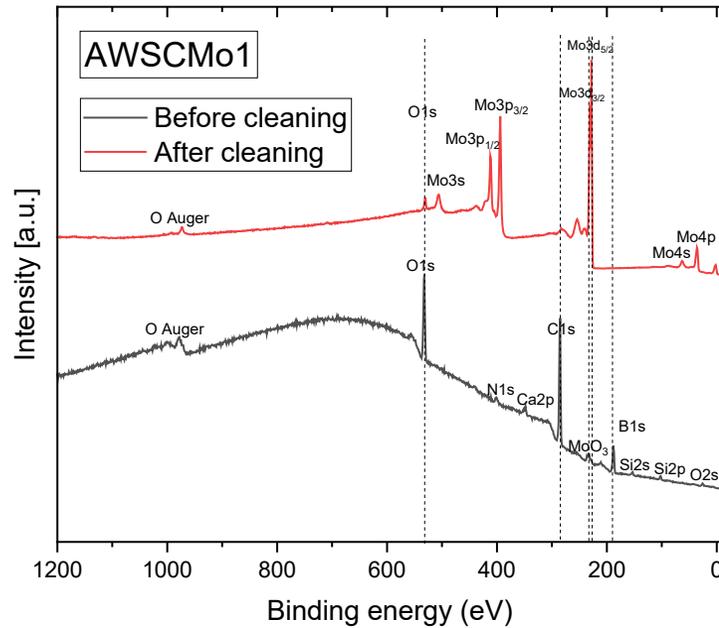
Deliverable: **PWIE-SP B.6.T-T002-D004**
Status: *completed*
Facilities: **-**
Linked WP or TSVV: **WPTE, WPW7X**

L. Marot

2026 Plans of SP B

PWIE Structure in 2026 and 2027

Project Leader: S. Brezinsek
Deputy Leader: D. Douai

PSO: D. Alyassin / NN

Project	Titel	Leader
SP A	Particle and heat load studies in preparation of the exploitation of ITER and a fusion power plant	J.W. Coenen
SP B	Experiments on erosion, deposition, and material migration	A. Hakola
SP C	Fuel retention and release	K. Schmid
SP D	Plasma-edge and plasma-wall interaction modelling	A. Kirschner
SP E	JET post-mortem analysis, LIBS and associated interpretation	J. Likonen
SP F	Wall conditioning and boronization physics	A. Goriaev
SP X	Plasma characterization and laser-based diagnostic development	I. Classen

In general: Tasks and Deliverables are prepared for 2026 and 2027
IMS entry of tasks and deliverables shall be completed by first week of March

2026 Tasks and Deliverables

SP B.1 Determine differences in erosion patterns on re-deposited vs. virgin W and W-B based co-deposits in high-flux and/or high-fluence conditions in linear devices and tokamaks

| Deliverable ID	Deliverable Title
D001	Report on erosion rates for B reference layers on MAGNUM-PSI as a function of their ion energy and temperature (DIFFER)
D002	Report on erosion rates for selected W and B reference layers on GyM/BiGyM as a function of the sample composition (ENEA)
D003	Report on erosion and re-deposition rates for selected W and B reference layers on PSI-2 as a function of sample composition (FZJ)
D004	Preliminary report on effective sputtering yields of 2D/3D microstructures exposed on MAGNUM-PSI (IPP.CR)
D005	Comparison between erosion rates of selected W and B reference layers in ion-beam exposures at different temperatures (ÖAW)

- The work will be based on corresponding activities in 2025 but now the **focus will be set on higher fluxes or fluences** than was the case in the period 2021-2025 to **reach conditions relevant for ITER and pilot plants**

- In addition, systematic studies on the **impact of sample composition, structure, morphology, and surface temperature** will be carried out – these were only superficially addressed in 2021-2025

- In many deliverables the work in 2026 will be summarized in a preliminary or interim report while the **final report with more detailed experimental data and full set of experiments will be provided in 2027**

- **GyM upgrade – BiGyM Status and Outlook:**
  - ✓ Leak tests of the vacuum vessel are ongoing after its rearrangement to accommodate new vacuum sectors for the two 13.56 MHz, 10 kW birdcage helicon antennas
    - ○ (in collaboration with SPC-EPFL).
  - ✓ **First plasma is expected by June 2026**, with PMI experiments planned for the second half of 2026
  - ✓ First plasma campaign will focus on characterization of plasma parameters and their spatial profiles using Langmuir probes and optical emission spectroscopy, with particular emphasis on particle flux measurements
- First BiGyM PMI experiments on **W/B reference layers like those exposed in GyM** → in late 2026?
- Further BiGyM PMI experiments on **W/B reference layers with varying compositions,** such as B–O, B–O–N, and B–W → potentially in 2027
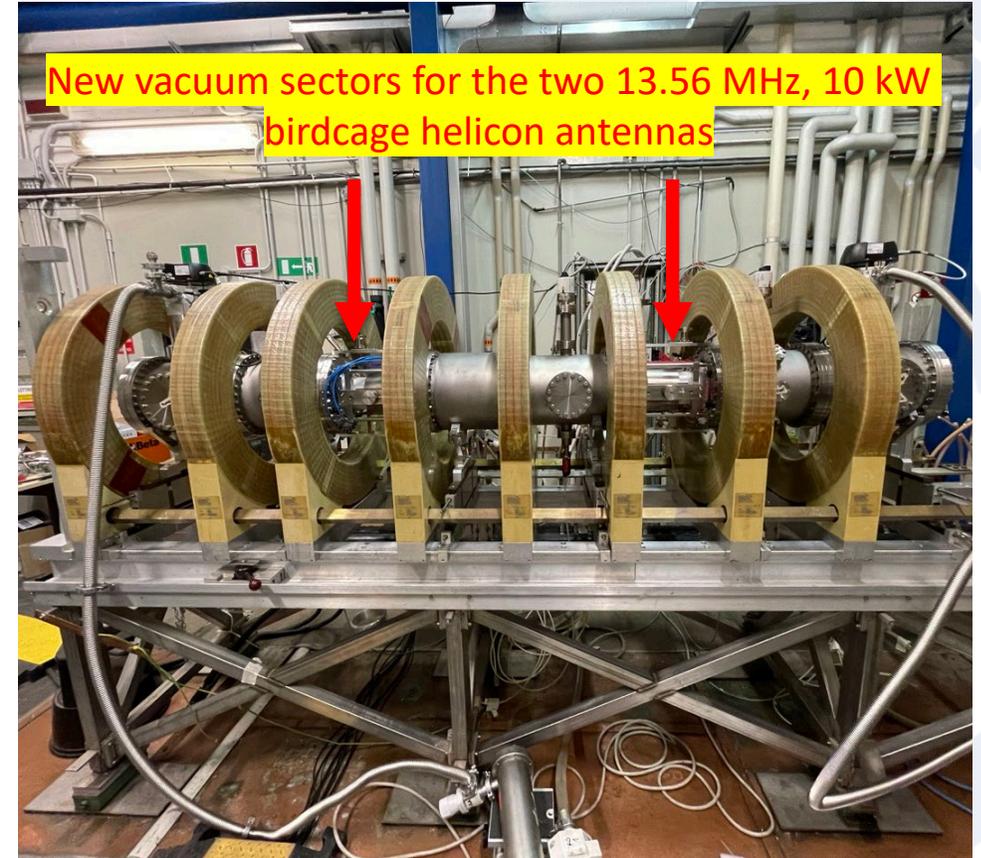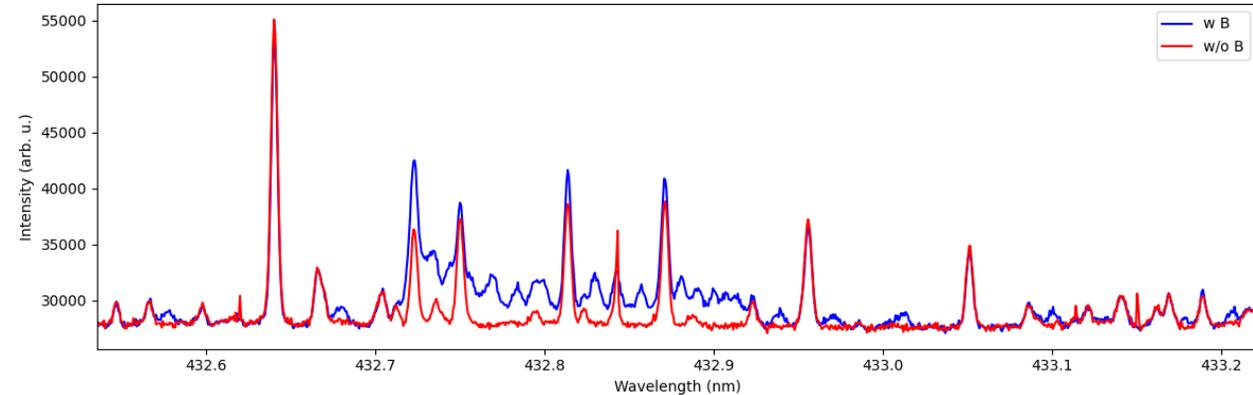

New vacuum sectors for the two 13.56 MHz, 10 kW birdcage helicon antennas

ENEA

Emission of BD molecules @ PSI-2

- **High resolution (HRS) and imaging spectroscopy (IS)** to be applied for bulk and re-deposited W and B layers on PSI-2

- Determining **sputtering rates** of W+B layers in PSI-2

- Analysis of **B I and BD lines** in UV/VIS at different D fluxes

- Discrimination between chemical and physical erosion

- Measurements of energy and angular distribution of B I lines

- Erosion rates of W in linear cross machine comparison study by **impact of different gases such as Ar or Ne**

Time-of-Flight Experiments @PSI-2
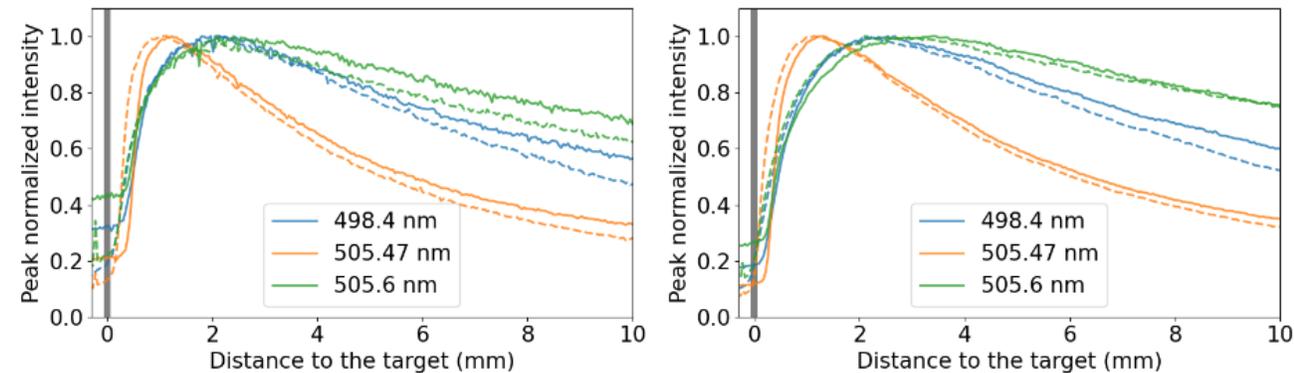
Sputtering of W(poly) (solid lines) and W(111) (dashed lines) by Ne ions. Emission of spectral lines from different excited levels will be analyzed

- Tungsten impurity is a major threat for future reactors – efficient cooler for fusion-relevant plasma core temperatures. It can prevent reaching desired values of Q or e.g. high confinement mode
- Sputtering from plasma-wetted areas (e.g. divertor strike points) is often not the main problem - W gets ionized close to the surface and then transported back onto the PFC
- **Tungsten PFCs with poor contact with plasma** (low T_e, n_e) allow the neutral W to travel far before it gets ionized → can be transported in the confined plasma. This was identified e.g. for JET [Kumpulainen NME 2022], where energetic neutrals originating from CX collisions were a major driver of the tungsten impurity. Simulations for CEFTR also suggest that first wall will be the main source of tungsten [Xu PST 2025]
- Most PFCs are currently optimised for power loading – small gaps, bevels etc. However, the **components with poor plasma contact may be instead optimized for low sputtering**
- Recent paper [Eksaeva NME 2019] suggest that **rough surface can reduce sputtering by a factor 4-6x!**
- Idea: let's **manufacture a tungsten surface** which would significantly reduce the effective sputtering yield and **test it in Magnum PSI**
- **Morphology: array of inverted pyramids 0.1 mm wide and 0.2 mm deep**
- First samples are expected to be ready for experiments by the end of **March 2026**

Morphology concept
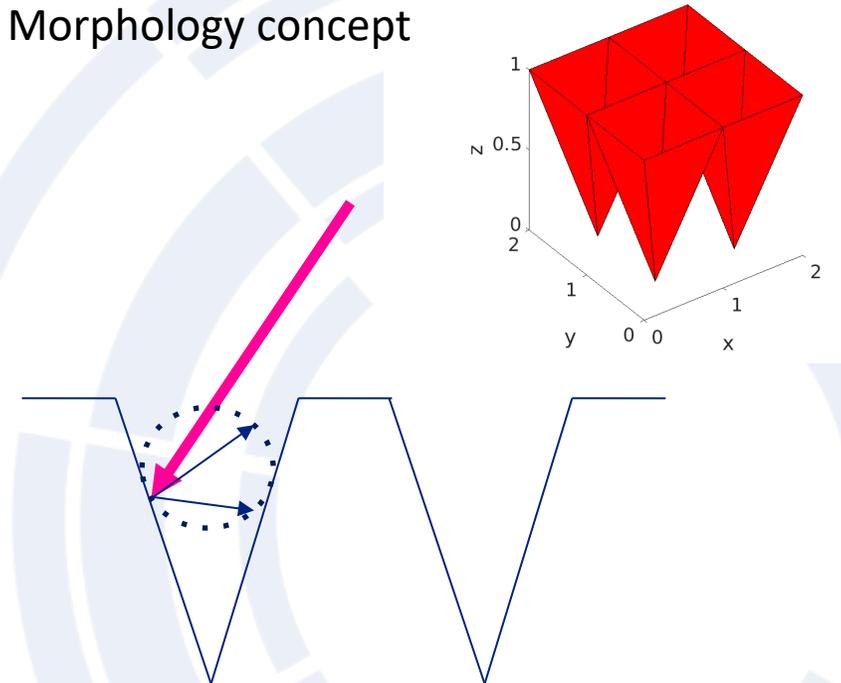
First sample produced by laser ablation at HiLASE facility

IPP.CR
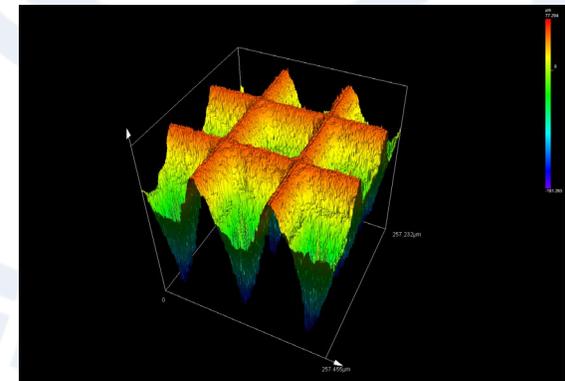
Example of SP B.1 Activities
D005: Temperature dependence for sputtering of W and B layers by ion beams

Motivation

- Wall conditioning via boronization will lead to locally different wall compositions ranging from W to B, thereby influencing the erosion properties of the first wall.
- The determined erosion rates of W and B reference layers measured in 2025 were found to be temperature dependent, especially for 2 keV D_2^+ irradiation on pure B.

Approach

- Utilization of a Quartz Crystal Microbalance (QCM) to perform angle dependent sputter yield measurements of samples with different tungsten-boron mixing ratio under 2 keV Ar^+ and 2 keV D_2^+ irradiation at different sample temperatures.

Human Resources (2026)

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

Sputter yields of 2 keV D_2^+ irradiation on W – B reference layers as a function of boron concentration (preliminary results)
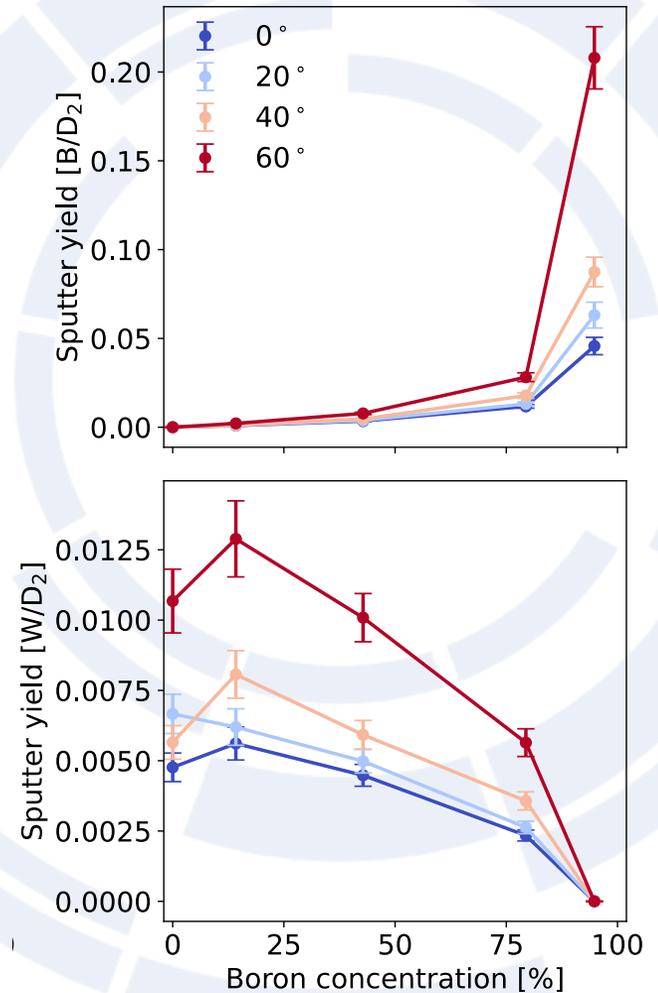
ÖAW

2026 Tasks and Deliverables

SP B.2 Characterize samples coming from PWIE experiments (under WPTE) in full-W devices (AUG, WEST): interpret results, assess changes in their surface state, erosion, and deposition patterns on them. Provide benchmarking data for modelling (SP D) and boron studies (SP F)

Deliverable ID	Deliverable Title
D001	Erosion and deposition patterns extracted for PFUs removed from WEST after C6-C12 campaigns (CEA)
D002	Interim report on microscopy investigations for various B-containing layers and ITER-like monoblocks removed from WEST after C6-C12 campaigns (CEA)
D003	Report on the feasibility of applying picosecond and top-hat laser beam profiles for analyses of WEST Phase 2 samples (CU)
D004	Composition of deposited layers on selected WEST PFUs from Phase 2 operations (IST)
D005	Interim report on erosion, deposition, and surface-modification patterns on selected WEST Phase 2 samples (MPG)
D006	Compositional and structural properties of selected samples following boronizations and high-fluence operations on WEST (NCSRD)
D007	LIBS elemental depth profiles for marker-tile samples from WEST Phase 1 operations (UT)
D008	Deposition patterns of B, D, and plasma impurities on the surface layers of different PFUs from WEST Phase 2 operations (VR)
D009	High-resolution depth profiles on WEST PFUs and samples removed after Phase 2 operations during C6-C12 campaigns (VTT)
D010	Interim report on the erosion properties of probes and marker samples exposed to specific AUG plasmas (FZJ)
D011	Interim report on erosion and deposition patterns on samples exposed to specific AUG plasmas and boronizations (MPG)

Deliverable ID	Deliverable Title
D012	Gross and net erosion patterns for marker-samples exposed to specific AUG plasmas (VTT)
D013	Comparative report on broad-beam and microbeam analyses for detailed elemental composition on selected WEST samples (JSI)
D014	Interim report on elemental concentrations on the surfaces of marker samples exposed to specific AUG plasmas at high spatial resolution (RBI)
D015	Erosion and deposition patterns on W7-X samples exposed during specific OP2 experiments (FZJ)
D016	Interim report of erosion and deposition patterns on W7-X samples exposed during OP2 (MPG)
D017	Interim report on surface changes on selected W7-X and WEST wall components and samples exposed to boronizations (IPPLM)
D018	Elemental depth profiles for B-containing samples from GyM/BiGyM experiments (CIEMAT)
D019	Erosion patterns on specific B- and W-containing samples from MAGNUM-PSI/UPP experiments (DIFFER)
D020	Interim report on changes in the surfaces of B- and W-containing samples during GyM/BiGyM experiments (ENEA)
D021	Erosion patterns on specific B- and W-containing samples from PSI-2 experiments (FZJ)

2026 Tasks and Deliverables

SP B.2 Characterize samples coming from PWIE experiments (under WPTE) in full-W devices (AUG, WEST): interpret results, assess changes in their surface state, erosion, and deposition patterns on them. Provide benchmarking data for modelling (SP D) and boron studies (SP F)

- SP B.2 is the largest of the three Tasks under SP B, addressing **surface analyses of components coming from various experiments in tokamaks/stellarators (AUG, WEST, W7-X) and linear devices (experiments under SP B.1)**

- Large part of the work will deal with **samples from WEST** with the focus set on the Phase 2 operations (only started in 2021-2025), in particular to the **samples originating from the different high-fluence campaigns** (in C7 and C12)

- The AUG work will be on detailed surface characterization of **exposed marker samples** (only erosion was investigated in 2025) and other **samples becoming available after the 2025 campaign** (incl. boronization samples)

- Concerning W7-X, there is an **extensive set of tiles + samples removed after the OP 2.3 campaign** – all pending for assessing their erosion and deposition patterns and to be compared with the OP 2.1/OP 2.2 data (in 2021-2025)

- Analyses of samples from SP B.1 will be a service task feeding back the information to planning additional experiments

- **Boronization samples will be studied jointly with SP F**: under SP B we will concentrate on the co-deposits and aspects related to material migration

- All the data can be used as **benchmarking cases for SP D activities**, up to the point of data validation

Example of SP B.2 Activities
D001: WEST analyses programme for 2026 and beyond

Priority#1 : high fluence campaigns and impact on divertor erosion/redeposition/fuel retention

2 high fluence campaigns in WEST :
- C7 (2023) : attached plasma, 3h30 → 1 PFU selected (max outer) for characterization
- C12 (2025) : XPR scenario, detached plasma, 4h30 → 1 PFU selected (max outer) for characterization

C7   C12

PFU	Cutting	Fuel retention		Thickness of deposited layers		Change of surface morphology		Composition of deposited layers
PFU High fluence C7	**done**	IBA @IST	**on going**	Manual removal of layers + confocal	scheduled in 2026	Roughness @Aix-Mar Uni.	X	XRF ? LIBS ? XPS ? **TOF-SIMS??**
PFU High fluence C12	scheduled for summer 2026		scheduled end of 2026+2027		scheduled in april 2026		**on going**	

Erosion indent before plasma exposure

Erosion indent after plasma exposure

Priority#2 : evaluation of divertor erosion (5 PFUs with erosion indents)
- Continue work on erosion PFU 357 exposed to C6-C9 (SEM, FIB @MPG)
- Start characterization on erosion PFU 356 exposed to C6-C12 (confocal @CEA)
- Start characterization on erosion PFU 091 exposed to C12 only (confocal @CEA)
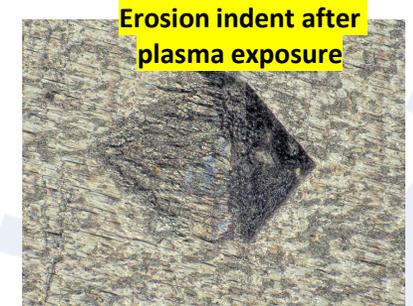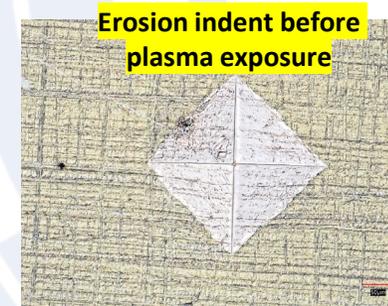
Priority#3 (2027)
- Evaluate thermal properties of deposited layers (flash method @IUSTI)
- Characterization of W emissivity (@IUSTI)

CEA

Work in 2026 :
- ❖ purchase of a new cutting machine (25kEur)
- ❖ new cutting campaign foreseen in the summer (erosion PFU, high fluence C12 PFU,...)

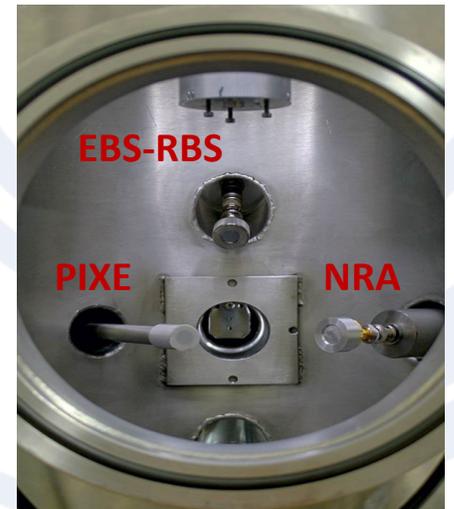**PFU 484 – exposed to C6/C7 (prepared for IBA at IST)**
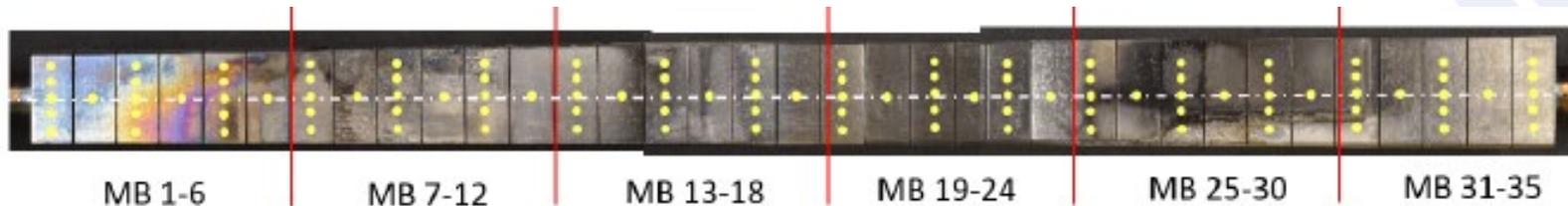
Experimental JET chamber prepared for the analysis:

new horizontal stage (50 mm) installed and tested

IBA over selected points:
- **Incident beam of 1 mm diameter**
- **Simultaneous RBS-NRA ($^3He^+$ beams)**
- **Simultaneous EBS-RBS ($^1H^+$ beams)**

- Erosion at the outer strike point of AUG studied by using **Pt marker layers on Mo substrates as proxies for W**
- Several ion-beam analyses performed – **in 2026 much more in-depth analysis of the samples scheduled including**
  - ✓ Analysis of the measured RBS, NRA, and PIXE data (VTT)
  - ✓ Micro-beam measurements for the samples (RBI)
  - ✓ Microscopy measurements on the areas of interest (MPG)
  - ✓ TOF-SIMS measurements for the surface layers (VTT)

- Initial results collected so far
  - ✓ No notable deposition of light elements observed
  - ✓ **Small erosion** but in line with predicted values
  - ✓ Little W being deposited on **areas in between the markers!?** → to be confirmed
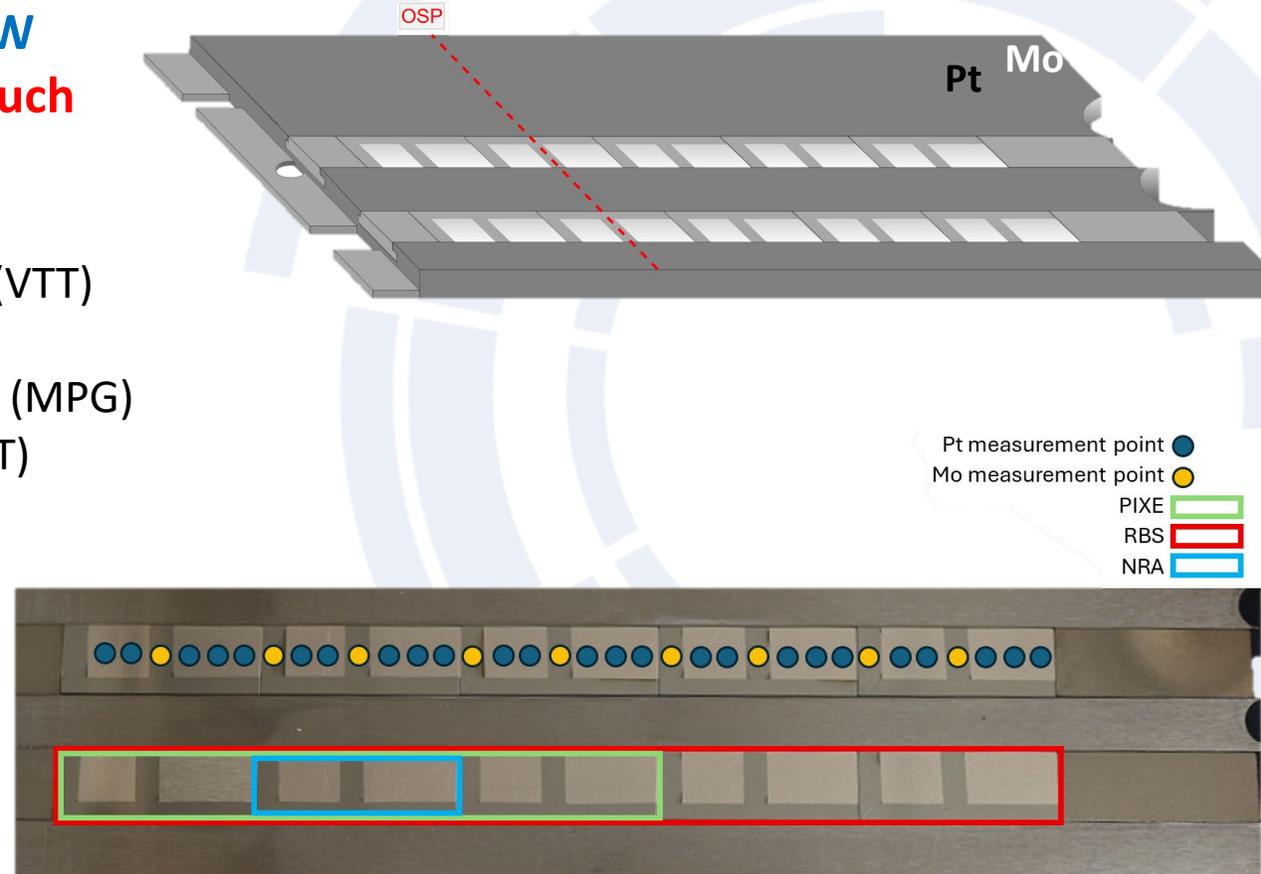
Pt measurement point ●
Mo measurement point ●
PIXE
RBS
NRA

- **Aim: Determine Erosion/deposition areas in W7-X**

- 33 tiles dismounted after OP 2.3
  - Inner wall tiles (graphite, W-coated graphite)
  - Baffle tiles (W, tungsten heavy alloys)

- Erosion at inner wall (W-marker layers)

- Deposition of boron, carbon at inner wall

- Deposition of boron, carbon on baffle tiles

- Analysis by ion beam analysis methods
  → Analysis just started and ongoing
  → Results will be presented at PSI 05/2026

MPG

Charge exchange (CX) fluxes measurements

- H^+ (fast) + H^0 (slow) → H^0 (fast) + H^+ (slow)

- 1st experimental approach: Collector probes

→Implantation of neutrals on suitable materials (*amorphous Carbon samples*)

  Number of implanted neutrals provides the total CX flux

  Depth profile of implanted neutrals provides flux energy distribution

→High-resolution TOF-ERDA able to provide the required depth resolution

- 2nd experimental approach: Layered samples

→Implantation of neutrals on special multi-layered samples

→*Barrier layer:* Al_2O_3, varying layer thickness allows the determination of the CX flux energy distribution

→*Diffusion layer:* Fe, separation of surface-barrier and getter layer signals

→*Getter layer:* Zr, thickness tens of nm to avoid possible saturation

H. Verbeek et al., Nuclear Fusion 38 (1998) 1789

W7-X sample Analysis
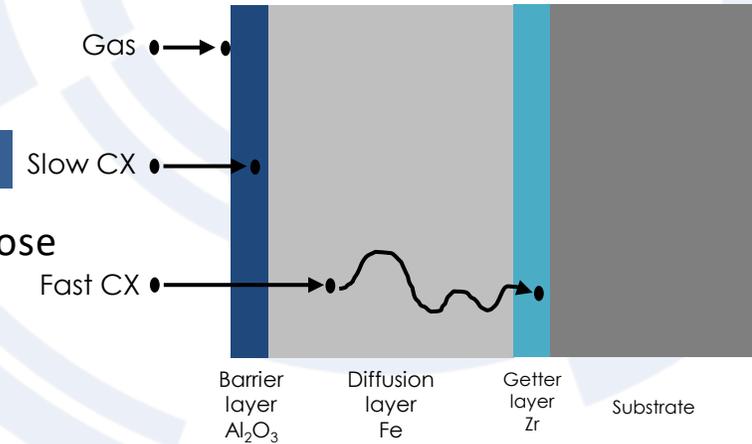
→Exposure of samples to boronization processes and plasma conditions using the multi-purpose manipulator (MPM)

  multiple types of material (C, Al, Tungsten alloys, stainless steel,…)

  polished and unpolished samples

MPG

**Task and questions to be addressed**

- Check the layer has the desired composition and properties using SIMS – comparison to VTT results
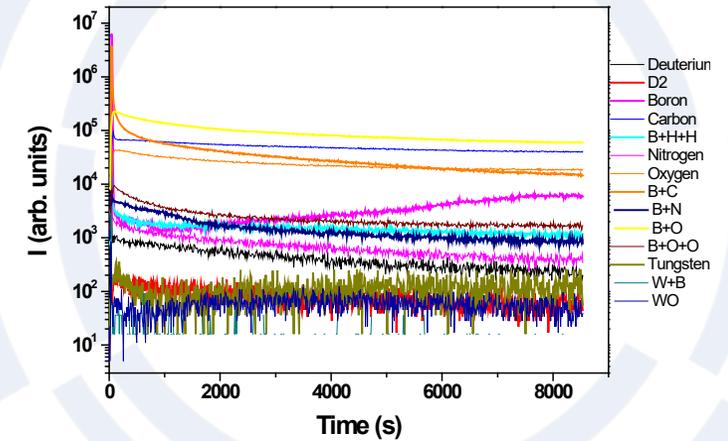
2025 results summary

- Boron signals have a strong matrix behaviour in our SIMS: B+O in pure boron layers, B in B+D films
- No effect of air storage: B-related signals were practically the same after 1 or three months.
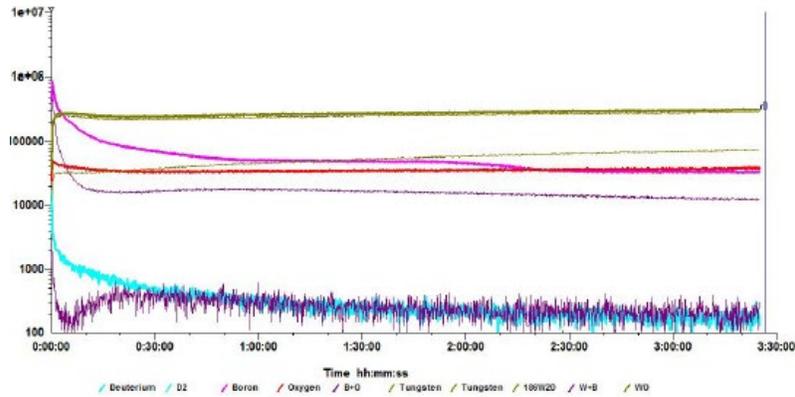
B+D on W: main signal is B *(pink)*.
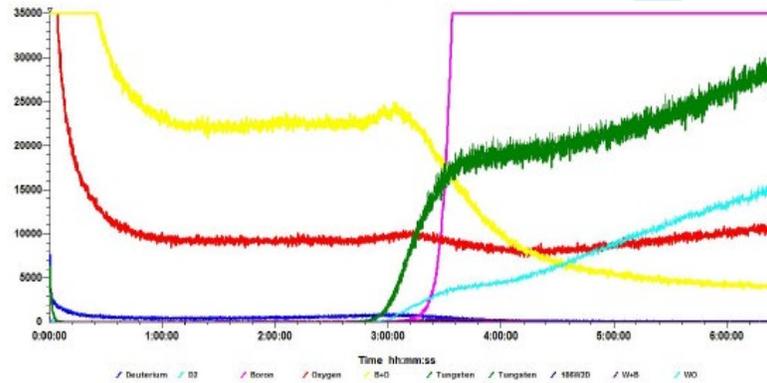
Pure B on W: main signal is B-O *(yellow)*.

Pure B discs: main signal is B-O *(yellow)*.

Results need to be put into perspective against new findings and data by other methods!

CIEMAT

2026 Tasks and Deliverables

SP B.3 Provision of reference layers (B layers with D, W+B layers etc.) and compare with layers obtained from tokamak experiments with focus on the composition and structure

Deliverable ID	Deliverable Title
D001	Characterized W and B reference coatings for laboratory and linear-machine experiments – initial batches (ENEA)
D002	Characterized B coatings for linear-machine experiments – initial batches (FZJ)
D003	Characterized W reference coatings for laboratory and linear-machine experiments – initial batches (IAP)
D004	Characterized B reference coatings for laboratory and linear-machine experiments and for permeation studies – initial batches (IAP)
D005	Characterized B reference coatings for linear-machine experiments and oxidization studies – initial batches (VR)
D006	Interim report on the characteristics of different B reference coatings with focus on retention and compositional properties (VTT)
D007	Interim report on Raman characterization of the produced B and W reference layers with focus on their structural and chemical properties (CEA)
D008	Interim report on microscopy investigations of the produced W and B reference layers with focus on their surface morphology (IPPLM)
D009	Interim report on the characteristics of the produced B and W reference layers with focus on their retention and permeation properties (JSI)
D010	Interim report on the characteristics of the produced B and W reference layers with focus on mechanical and compositional properties (NCSRD)
D011	Elemental composition for the produced B and W reference layers – interim report (RBI)

- In 2026, several **W- and B-based reference layers will be produced and characterized** for their properties – to be further provided in experiments under SP B.1/SP B.2 as well as SP A, SP C, SP F, and SP X
- Different from 2021-2025, the B layers will exhibit **more complex compositions** (mixed W+B layers, D and seeding impurity inclusions)
- Concerning the W layers, the focus will be on **layers simulating re-deposits** – in 2021-2025, virgin W coatings as well as W co-deposits were produced

Production plan for 2026:

- **Compact** B, B-O, B-O-N and B-W coatings produced via nanosecond Pulsed Laser Deposition (PLD), from 100 nm/s to µm/s
- **Thin compact** B produced by RF-MS
- **Porous** B and B-W coatings ranging from rough to dusty with thicknesses from 100s nm to several µm/s via femtosecond Pulsed Laser Deposition
- Possibility to grow multilayer systems
- Different kinds of W (Nanocolumnar W, compact W and porous W-O) to support LIBS studies (SP X)

Boron coatings can be used in LPDs to study **erosion yield as a function of morphology, porosity and composition**. There is also the interest in thick B coatings for permeation studies (JSI)

500 nm

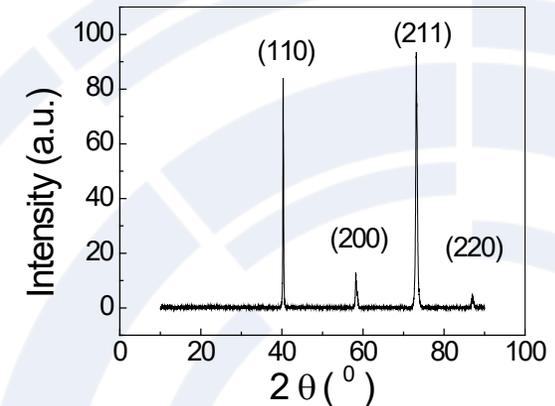800 nm
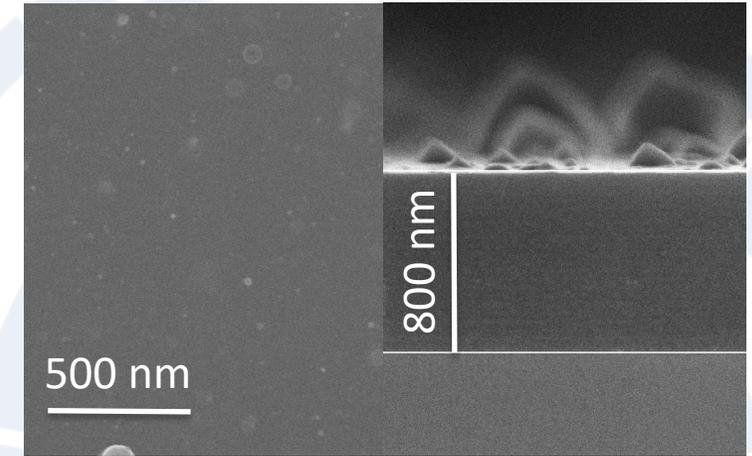
Example of a boron coating

ENEA

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

- *Use of different deposition methods (DC magnetron sputtering DCMS, HiPIMS, CMSII etc) at different deposition parameters to produce W coatings*
- *Preliminary experiments showed a different crystallographic structure for coatings deposited by different deposition methods*
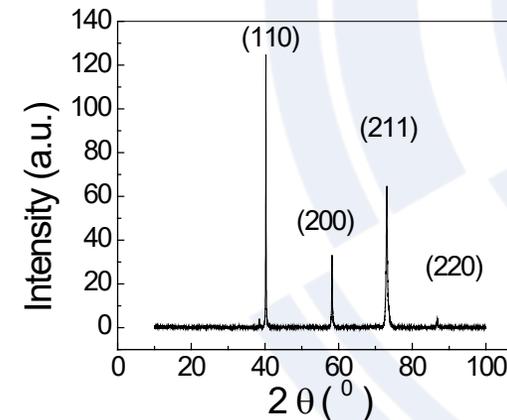

XRD pattern for W coating deposited by CMSII

What we know by now:

- *CMSII* coatings: strong reflection along (211) direction of the W phase
- *DCMS* coatings: strong reflection along (211) direction of the W phase
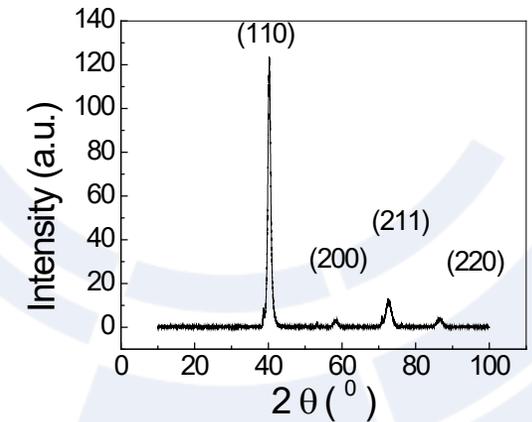- *HiPIMS* coatings: strong reflection along (110) direction of the W phase

XRD pattern for W coating deposited by DCMS

XRD pattern for W coating deposited by HiPIMS

Possible retention capabilities or other properties are influenced by crystallographic orientation?

IAP

**Coatings to be produced for SP B.1 and SP X**:

- Deposition of B (5 µm) on Mo - study the impact of roughness on erosion characteristics and LIBS spectra

Coatings to be produced for SP C (permeation studies):

- Up to 5 µm B layers (pure and with D) on Eurofer and W (and Si) → V. Nemanic @JSI

Experiments agreed with colleagues under SP B:

- B coatings with D inclusions (10 at.%) and annealed at 50–500°C → C. Pardanaud @CEA

- Oxidation under controlled thermal conditions for B layers on W → R. Mateus @IST
  - ✓ Vary O_2 partial pressure (10^{-2}-10 mbar), surface T (100-1000 °C), and D ion energy (40-200 eV)

- Micromechanical studies on W-B layers with and without D → Y. Zayachuk @UKAEA

- LIA-LIBS-QMS and detection and separation of H isotopes in B-D samples using laser ablation and MW-plasma, collaboration with Institute of Physics Belgrad [1]

- Other samples to be discussed later in 2026
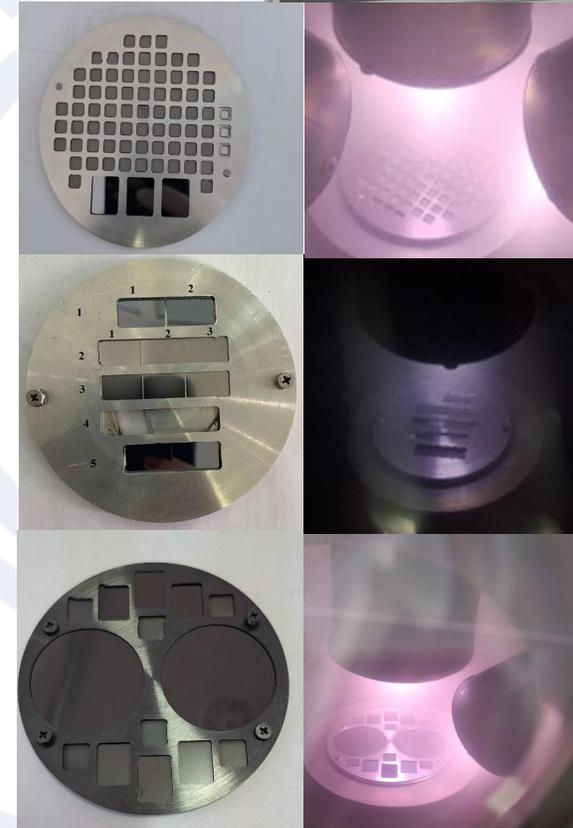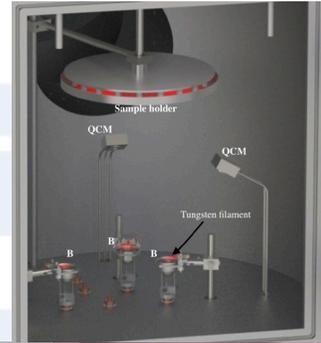
[1] Vujadinović, N. et. al, Detection of hydrogen isotopes in fusion-relevant targets using laser ablation and microwave-induced plasma. *Eur. Phys. J. Plus* **141**, 157 (2026). https://doi.org/10.1140/epjp/s13360-026-07406-0

- **Raman analyses to be performed** for as-produced B reference samples as well as following their exposure to GyM/BiGyM plasmas

- **Main results so far**

  ✓ **Non exposed samples**: amorphous boron
  ✓ **Exposed samples**: amorphous + presence of hot spots (<10%) and no BD chemical bonds
  ✓ **Exposed samples**: no BD chemical bonds observed
 ✓ Hotspots crystalline in boron beta-phase

- **Plans for 2026**

  ✓ Study the origin for the formation of the crystalline phase in hotspots
  ✓ Detailed investigations of the Raman spectra to control oxidation of H/D-containing B samples produced at different temperatures
  ✓ Disentangle structural and chemical influence on local organization and oxidation of B samples

CEA
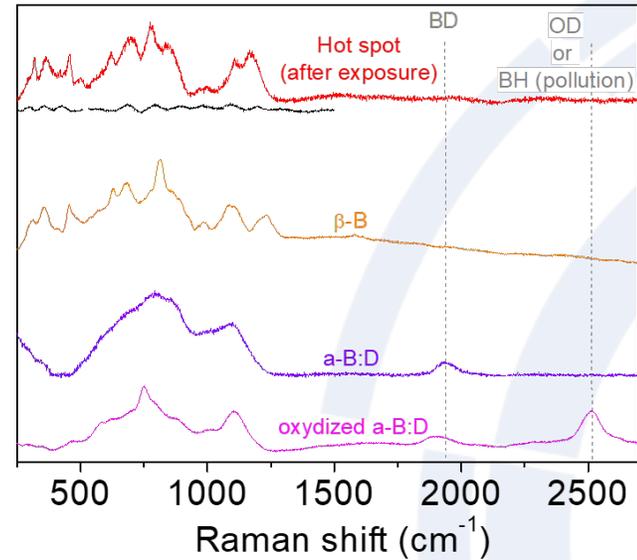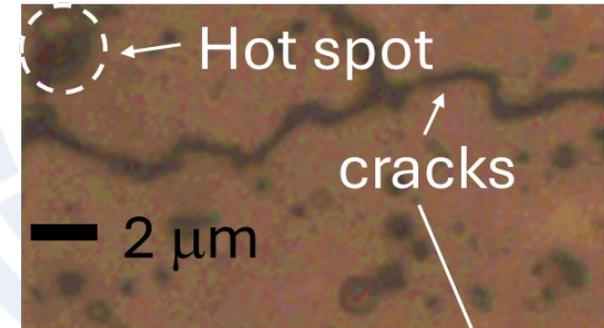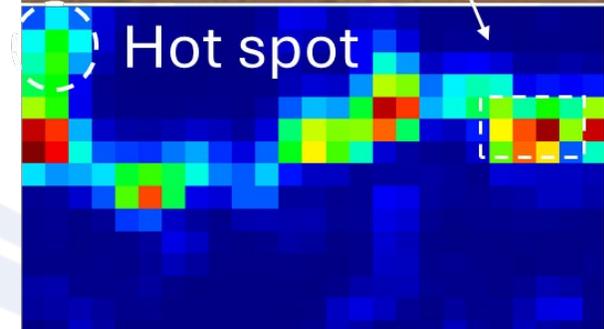
Concluding remarks

- SP B will continue with **3 different activity areas during the period 2026-2027:**
  - ✓ **SP B.1**: Erosion and re-deposition experiments in linear plasma devices and laboratory conditions
  - ✓ **SP B.2**: Surface analyses of samples from tokamaks/stellarators and linear plasma devices and identifying material migration pathways in W machines
  - ✓ **SP B.3**: Production of B and W reference layers
- SP B.1 will put the focus on **higher fluxes and fluences and broader varying of sample and exposure parameters** than in 2021-2025
- In SP B.2, concentrate on the outcomes of **high-fluence campaigns on WEST**, detailed characterization of **samples originating from specific AUG experiments**, and studying B-based co-deposits from AUG, WEST, and W7-X
- SP B.3 will produce **B samples resembling co-deposits and W samples simulating re-deposits** together with reference layers for dedicated experiments