WP PWIE: SP B final reporting 2022 / SP B elaborated plans for 2023

SPL B: Antti Hakola

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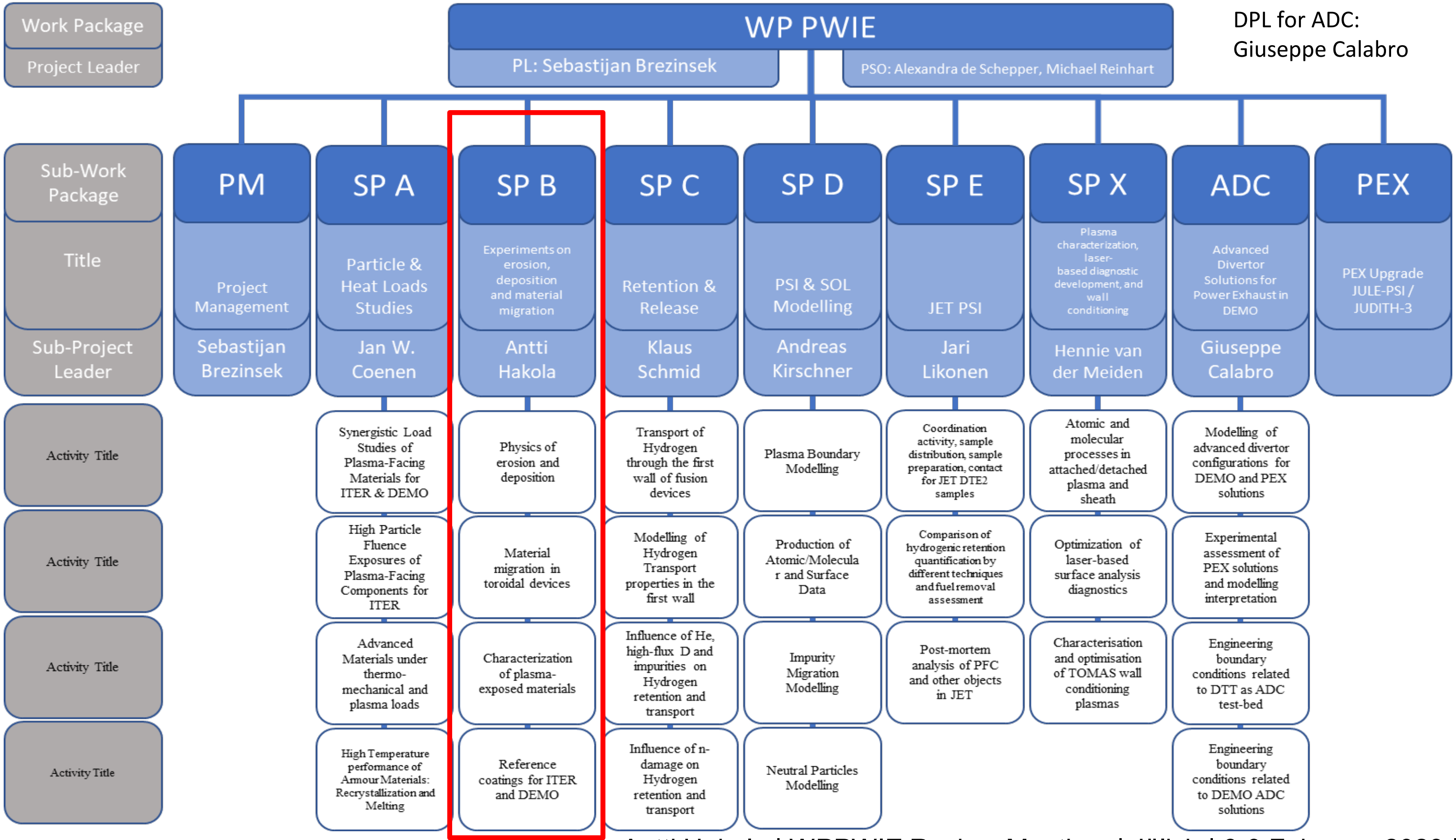
Introduction to SP B

- SP B deals with **experimental erosion, deposition, and material migration** investigations, in linear devices and laboratories as well as in EUROfusion toroidal devices
- Emphasis put on **post-exposure analyses (and pre-characterization)** besides the experiments
  - ✓ **NB!** In toroidal devices experiments primarily under other EUROfusion WPs (WP TE, WP W7X)

- The SP B work in **2022 was a direct continuation of the research themes introduced in 2021** – essentially a two-year program with small adaptations upon transition from 2021 to 2022
  - ✓ Details of individual tasks refined in a series of kick-off meetings (separately for each activity area) in March 2022
  - ✓ Task monitoring via email in July and September and in the PWIE Progress Meeting in October
- Emphasis put on defining deliverables to address **broader entities rather than manage a number of scattered tasks**
  - ✓ Comparative erosion experiments on the involved linear devices
  - ✓ Extracting material-migration pathways on AUG, WEST, and W7-X tiles and samples
  - ✓ Round-robin studies of produced reference coatings
- In addition, **thematic meetings** organized in smaller subgroups
  - ✓ Conclusions on the analysis campaign of WEST C3 marker samples – jointly with CEA
  - ✓ Role of surface roughness in sputtering/erosion – jointly with SP D
  - ✓ Brainstorming events on sample production, sample exposures and dust investigations
- All material of the past meetings available in INDICO, see https://indico.euro-fusion.org/category/325/

PWIE 2022: SP B

DPL for ADC:
Giuseppe Calabro



PWIE 2023: SP B

SP B will continue in 2023 **almost according to the breakdown established** back in 2021 – with the following changes:

- **Dust investigations** under a separate **activity area SP B.5** (new tasks and tasks shifted from SP B.1)
- Shifting **all ”service work”** related to surface analyses of tokamak/stellarator samples **under SP B.3**
  - ✓ SP B.2 concentrates on analysis of the outcomes of specific experiments
- Re-considering the program for producing Be samples **under SP B.4**
  - ✓ We may want to focus on JET-relevant deposits and assist in the preparation of the JET LIBS project

Updated activity areas:

- SP B.1: Physics of erosion and deposition (no dust)
- SP B.2: Material migration in toroidal devices (special experiments on AUG and W7-X)
- SP B.3: Characterization of plasma-exposed materials (all post-exposure analyses)
- SP B.4: Reference coatings for ITER and DEMO (including surface analyses of the reference layers)
- SP B.5: Production of metallic dust in toroidal devices (including dust production on AUG, WEST, MAGNUM-PSI)

- Only **small changes to the envelope of PMs** (=integral over all the activity areas) allocated to each RU
  - ✓ Reductions mainly due to limitations in the PWIE budget
- After this review event, the details of the tasks will be defined in a **series of kick-off meetings in March-April**

SP B Milestones 2022

Relevant Work Package Milestones for SP B extracted from WP PWIE PMP 2022

WM31	SP B	Effective sputtering yields and erosion rates of W model systems with varying impact angles, morphologies, and surface structures at varying plasma conditions available (ITER+DEMO)	31.12.2022
WM32	SP B	Erosion and re-deposition patterns on selected marker samples and plasma-facing components, extracted from ASDEX Upgrade (2019-2021), WEST (C4, C5), and W7-X (OP1.2B) elucidated (ITER+DEMO)	31.12.2022
WM33	SP B	Be- and W-based reference coatings produced with composition, fuel content, and structure similar to those of typical co-deposited layers in tokamaks (ASDEX Upgrade, WEST, JET) (ITER+DEMO)	31.12.2022
WM34	SP B	Post-mortem analysis of material samples and components exposed to medium and high flux operation campaigns 2021/2022 in MAGNUM-PSI and PSI-2 performed.	31.12.2022

Main reasons for delays:

(i) Unavailibity of MAGNUM-PSI and slow start of GyM

(ii) Lengthy process for defining specifications of samples and their exposures in linear facilities

(iii) No new WEST samples

SP B Milestones 2023

Relevant Work Package Milestones for SP B extracted from WP PWIE PMP 2023

WM57	SP B	Dependence of W erosion/deposition rates on plasma flux and impurity composition available for W model systems and role of CX neutrals on sputtering in past experiments reported. (ITER+DEMO)	31.12.2023
WM58	SP B	Erosion and re-deposition patterns and characteristics of W nanostructures on marker samples originating from ASDEX Upgrade helium experiments determined. (ITER+DEMO)	31.12.2023
WM59	SP B	W marker samples and ITER-like plasma-facing units removed after the WEST C5 campaign characterized and comparison made between C3, C4 , and C5 incl. helium results. (ITER+DEMO)	31.12.2023
WM60	SP B	Fuel-containing Be+O and W+O samples produced, exposed in linear facilities, and characterized for their similarities to existing or expected layers in tokamaks (ASDEX Upgrade, WEST, JET). (ITER+DEMO)	31.12.2023

New ingredients

- Role of CX neutrals on erosion and assessing the outcomes of most recent helium experiments
- Completing analyses of WEST C4 marker samples and starting C5 sample analyses
- Detailed comparison between reference layers and tokamak co-deposits

SP B Deliverables 2022

Activity	Deliverable ID(s)	Title
SP B.1	D001, D007 (2021 transfer)	Erosion rates of W model systems and composition and structure of re-deposited layers in MAGNUM-PSI at varying plasma conditions (DIFFER)
SP B.1	D002	Effective sputtering yields of W model systems with varying morphologies in pure and mixed plasmas in GyM and by hypervelocity dust impacts (ENEA)
SP B.1	D003	Erosion rates and angular distribution of W model systems with varying morphologies as well as composition and structure of re-deposited layers in PSI-2 at varying plasma conditions (FZJ)
SP B.1	D004, D006	Effective sputtering yields of W model systems with varying morphologies and structures, including angular distributions of sputtered particles, and re-deposited W layers following exposure to controlled D and impurity ion beams (ÖAW, VR)
SP B.1	D005, D008 (2021 transfer)	Size distribution and composition of Be and W dust formed during air and water leaks (IAP)
SP B.2	D001	Erosion, re-deposition, and fuel-retention patterns on selected WEST PFUs after C3, C4, and C5 campaigns (CEA)
SP B.2	D002, D003	Balance between gross and net erosion of plasma-facing materials, including components with different surface roughness and morphology, in controlled L- and H-mode plasma experiments (JSI, VTT)
SP B.2	D004, D005, D006, D007, D008, D009, D010, D11 (2021 transfer IPPLM)	Characterization of marker samples and coatings from selected plasma experiments on AUG, WEST, and/or W7-X with conclusions (FZJ, MPG, VR, IPPLM, RBI)
SP B.3	D001	Database on ageing, erosion, and fuel-retention behavior of selected WEST PFUs (CEA)
SP B.3	D002, D003, D004, D005, D006, D007, D008, D009 (2021 transfer IPPLM)	Characterization of selected AUG, WEST and/or W7-X wall tiles and plasma-exposed reference samples (FZJ, IPPLM, IST, IAP, MPG, NCSRD, VTT)
SP B.4	D001	W-based coatings with pre-defined properties (incl. SEM, AFM, TDS characterization) produced for analyses and plasma experiments (ENEA)
SP B.4	D002, D009 (2021 transfer)	Be and W-based coatings with pre-defined properties (incl. SEM, XRD, GDOES, TDS characterization) produced for analyses and plasma experiments (IAP)
SP B.4	D003, D004, D005, D006, D007, D008	Characterization of selected Be and/or W reference samples (CEA, CIEMAT, IST, JSI, RBI, VTT)

All deliverables reported and can be considered to be completed – except for technical shifts into 2023

SP B Deliverables 2023

Activity	Deliverable ID(s)	Title
SP B.1	D001	Erosion rates of W and W+O model systems in MAGNUM-PSI at varying fluxes, fluences, and impurity contents (DIFFER)
SP B.1	D002	Erosion rates of W and W+O model systems in GyM at varying fluxes, fluences, and impurity contents (ENEA)
SP B.1	D003	Erosion rates of W and W+O model systems in PSI-2 at varying fluxes, fluences, and impurity contents (FZJ)
SP B.1	D004, D005	Effective sputtering yields of nanostructured W model systems following exposure to controlled ion beams (ÖAW + VR for surface analyses)
SP B.2	D001	Erosion and deposition patterns on marker and ITER-like PFUs after WEST C5 campaign (CEA)
SP B.2	D002, D003, D004	Qualification of W fuzz production in AUG He plasmas (FZJ); Balance between gross and net erosion in AUG He plasmas and comparison with available D data (VTT); Erosion, deposition, and surface modification patterns on samples exposed to AUG He plasmas (MPG)
SP B.2	D005, D006	Erosion and deposition characteristics on samples exposed to OP1.2a, OP1.2b, and OP2 campaigns on W7-X (FZJ); Erosion and deposition characteristics of manipulator samples from OP2 experiments in W7-X (MPG)
SP B.3	D001-D010	Characterization of selected AUG, WEST and/or W7-X wall tiles and plasma-exposed reference samples (FZJ, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, VR, VTT)
SP B.3	D011 (2022 transfer IPPLM)	SEM, TEM and FIB characterization of selected samples from experiments on WEST and W7-X with conclusions (IPPLM)
SP B.4	D001	W-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (ENEA)
SP B.4	D002, D003	W-based coatings with pre-defined composition and morphology for experiments in linear plasma facilities (IAP); Be-based coatings with pre-defined composition and morphology for comparison with data from tokamaks (IAP)
SP B.4	D004-D010	Characterization of selected Be and/or W reference samples (CEA, CIEMAT, IPPLM, IST, JSI, RBI, VTT)
SP B.5	D001	Hypervelocity dust impacts on W and W+O model systems and comparison with data from tokamaks (ENEA)
SP B.5	D002	Database of the characteristics of produced Be and W dust particles and comparison with data from tokamaks (IAP)
SP B.5	D003	Document on the characteristics and amount of dust generated on ASDEX Upgrade and WEST during past experimental campaigns and on the connection of arcing on dust production (MPG)
SP B.5	D004	Document on the physical and remobilization characteristics of dust produced on ASDEX Upgrade and MAGNUM-PSI (VR)

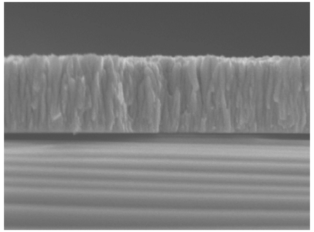
SP B.1 – Physics of erosion and deposition – selected results from 2022 and plans for 2023

SPB.1: Effective sputtering yields of W model systems and re-deposits in lab conditions

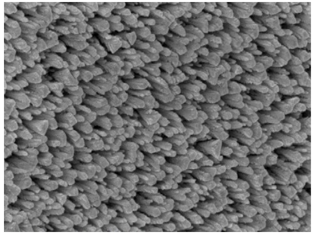
Key goals for the 2022 task:

- Describe **influence of morphology on sputtering** for Gaussian rough surfaces
- **Cooperation with UPM**: created oriented nanocolumnar W (NCW) on QCM samples
  - ✓ QCM experiments with Ar and D bombardment of NCW at TU Wien
- **Cooperation with University of Helsinki** for MD simulations of NCW
  - ✓ Comparison with SPRAY (see SP D task 2022) and MD-PARCAS, SDTrimSP-3D

SEM cross-section

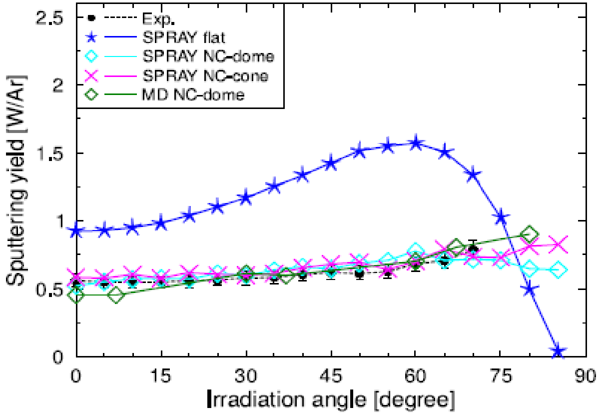


SEM top-view

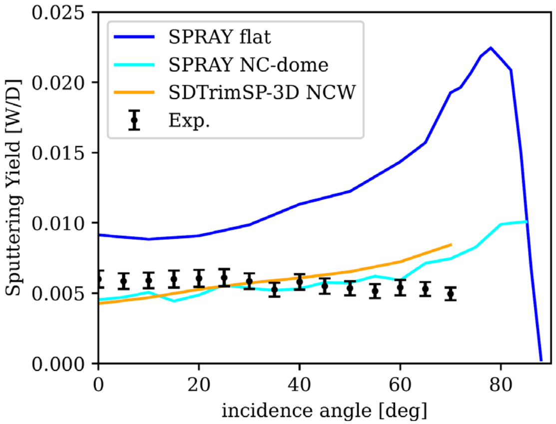


height = 500 nm, diameter = 50 nm, areal density = 58%

QCM vs. simulations 1keV Ar^+



QCM vs. simulations 1keV D^+



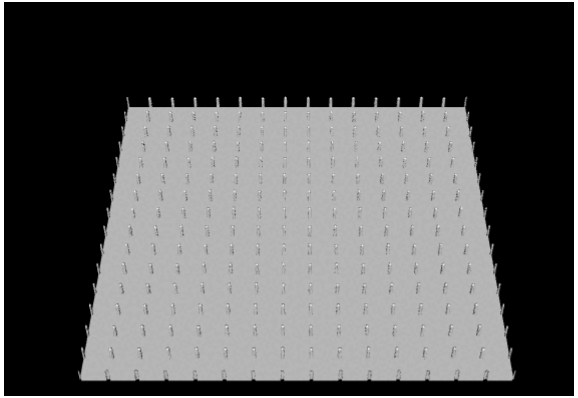
[1] https://doi.org/10.1016/j.surfin.2022.101924
[2] https://doi.org/10.1103/PhysRevMaterials.6.075402

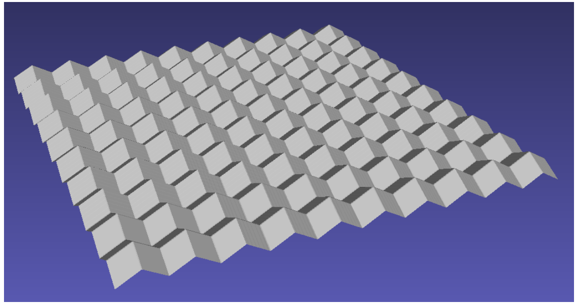
Deliverable: *PWIE.SPB.1.T002.D004, D006*
Status: *completed*
Facilities: *5 days accelerator (VR)*

Human Resources: *5 PM + 3 PM*
Involved RU: *ÖAW, VR*
Linked WP or TSVV: *WP ENR-MAT.01.VR, SP D.2.T002*

C. Cupak et al. (ÖAW), D. Primetzhofer et al. (VR)

SPB.1: Effective sputtering yields of nanostructured W model systems following exposure to controlled ion beams





Main plans for 2023:

- Nano-columnar tungsten (NCW):
  - ✓ Optimise shape of NCW with SPRAY to minimise sputter yields
  - ✓ Deploy optimised NCW as real samples on QCM (at UPM)
  - ✓ QCM experiments + simulations (static trends with SPRAY)
  - ✓ Study dynamic erosion of NCW both experimentally (QCM) and numerically (SDTrimSP-3D, MD-PARCAS)
- Pyramidal W samples:
  - ✓ Cooperation with ENEA (A. Uccello, D. Dellasega, M. Pedroni et al.)
  - ✓ Continue experimental investigations with QCM methods
  - ✓ Support with numerical simulations (SPRAY)
- In all cases co-operation with the SP D tasks

C. Cupak et al. (ÖAW), D. Primetzhofer et al. (VR)

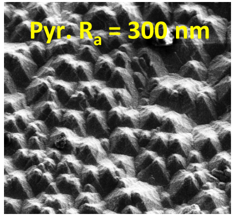
SPB.1: Role of roughness in sputtering of W by GyM He plasma

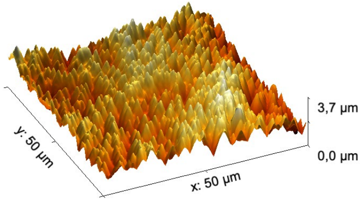
Exposure of W/Si samples: **6 He^+ energies @ 4.0e24 He^+ m^{-2}**

He^+ energy [eV]	30	80	150	200	250	350

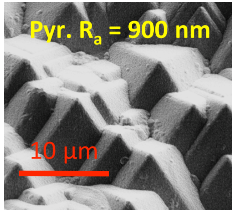
Sputtering E_{th} of W_{bulk} by He^+ ~110 eV [1]

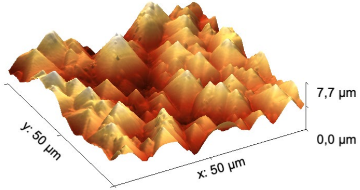
No significant topography and morphology modifications → quasi-static *Y*

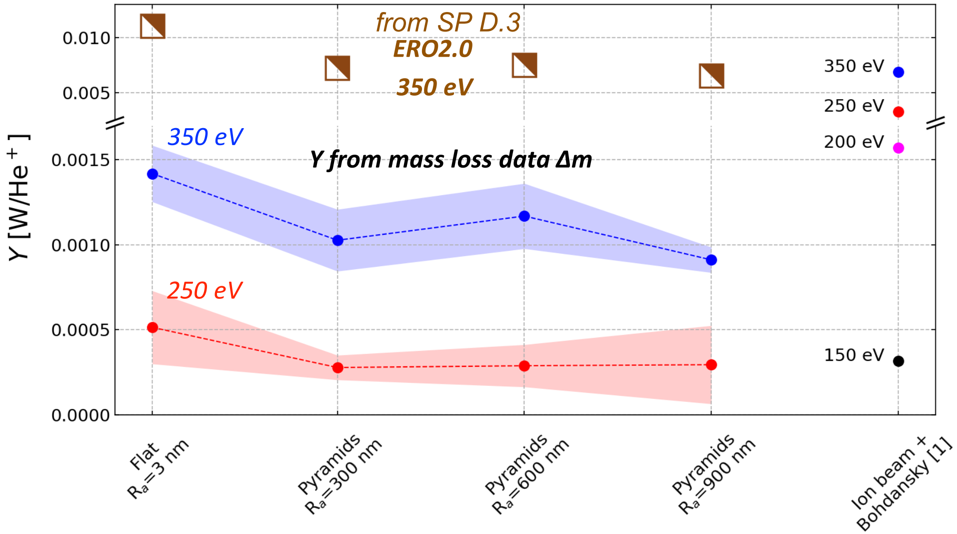




SP B.4







- **No erosion for E_{ion} ≤ 200 eV**
- $Y_{\Delta m} \ll Y_{Ion}$ → similar to what was observed in other LPD experiments [2]
  - ✓ He atoms on the surface potentially shield W lattice atoms reducing their sputtering probability
  - ✓ Also explains $Y_{\Delta m} \ll Y_{ERO}$ at 350 eV
- For **E_{ion} ≥ 250 eV** → $Y_{Flat,\Delta m} > Y_{Pyramids,\Delta m}$

[1] W. Eckstein, et al., IPP 9/82 Sputtering data
[2] R.P. Doerner, Scr. Mater. 143 (2018) 137-141

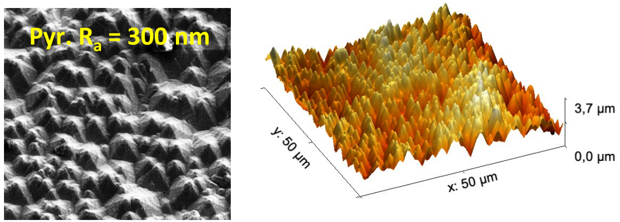
Deliverable: *PWIE.SPB.1.T002.D002*
Status: *in progress (estimated completion by 28.02.2023)*
Facilities: *20 days GyM – will be used fully*

Human Resources: *4 PM*
Involved RU: *ENEA*
Linked WP or TSVV: *SP D.1.T002, SP D.3.T002*

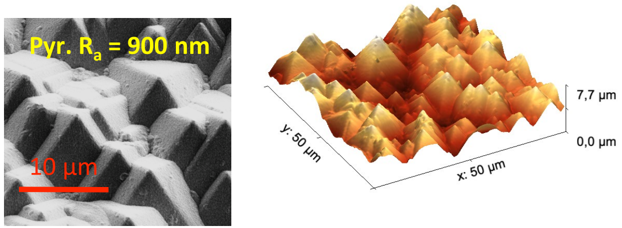
A. Uccello et al. (ENEA)

SPB.1: Role of roughness in sputtering of W by GyM He plasma

Exposure of W/Si samples: **6 He^+ energies @ 4.0e24 He^+ m^{-2}**



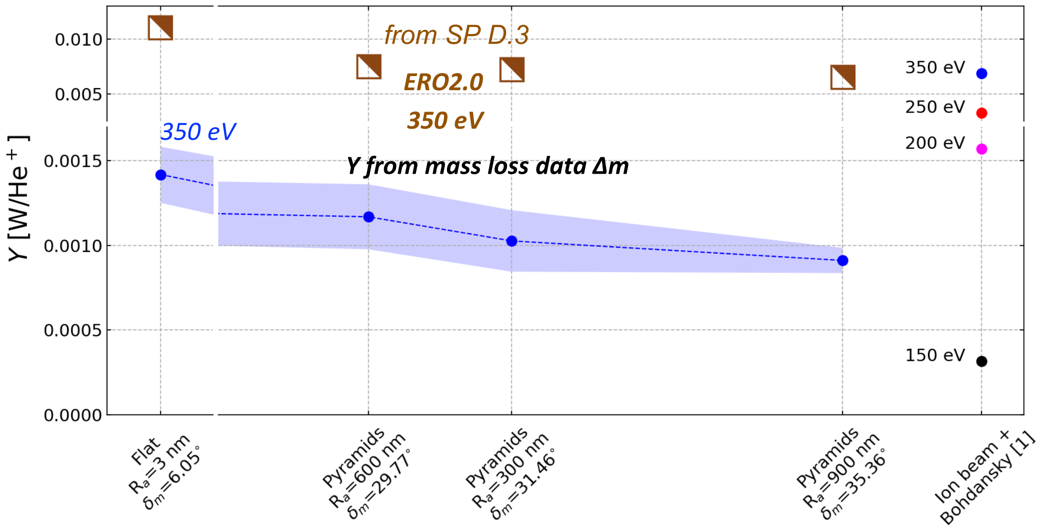
SP B.4



He^+ energy [eV]	30	80	150	200	250	350

Sputtering E_{th} of W_{bulk} by He^+ ~110 eV [1]

No significant topography and morphology modifications → quasi-static *Y*



- **Non-monotonous behaviour of $Y_{\Delta m}$ and Y_{ERO}** at E_{ion} = 350 eV if R_a is used for characterising surfaces
- **Mean value of surface inclination angle distribution, δ_m** → key-parameter determining erosion of samples, rather than R_a [3]

[1] W. Eckstein, et al., IPP 9/82 Sputtering data
[3] C. Cupak, et al., Appl. Surf. Sci. 570 (2021) 151204

Deliverable: *PWIE.SPB.1.T002.D002*
Status: *in progress (estimated completion by 28.02.2023)*
Facilities: *20 days GyM – will be used fully*

Human Resources: *4 PM*
Involved RU: *ENEA*
Linked WP or TSVV: *SP D.1.T002, SP D.3.T002*

A. Uccello et al. (ENEA)

SPB.1: Erosion rates of W and W+O model systems in GyM

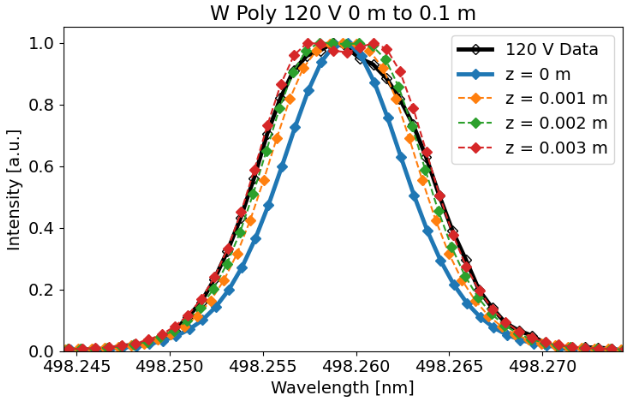
Task to be performed in 2023

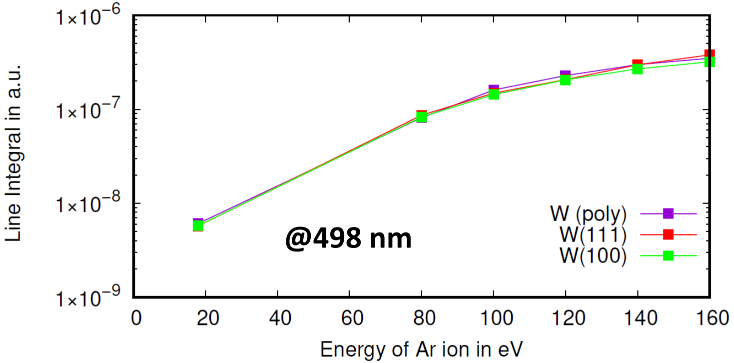
Elucidate sputtering and re-deposition properties of W and W+O model systems (from SP B.4) in specific plasma conditions of GyM

- Apply helium plasma with a few impinging He^+ energies and sample-holder bias voltage value
- Scan the fluence
- Participate in cross-machine experiments → PSI-2 and MAGNUM-PSI also involved
  - ✓ Possible goal: investigate effect of ion flux on exposure outcomes
  - ✓ How: select one fluence value (at least) accessible to all 3 LPDs
  - ✓ For example, ~1.5e25 He^+m^{-2} (i.e. He plasma fluence with GyM after a working-day)

SPB.1: Erosion rates of W model systems and composition of re-deposited layers in PSI-2

- **Erosion and re-deposition of W** studied using spectroscopy in PSI-2
  - ✓ W targets: poly W, W (111), W (110), W (100)
- First spectroscopic data sets available for benchmarking codes
  - ✓ Interpretation of the data is sensitive to the position of the line-of-sight (z in the figure on the right)
  - ✓ 3D emission model was developed and completed in 2022
- **Very small differences in erosion rates observed** between the different W targets in the studied energy range (see bottom figure on the right)
  - ✓ Results consistent for different gases (Ne, Ar, Kr) at 20 - 180 eV and different spectral lines (401 nm, 498 nm, 505 nm)





Deliverable: *PWIE.SPB.1.T002.D003*
Status: *completed*
Facilities: *15 days PSI-2*

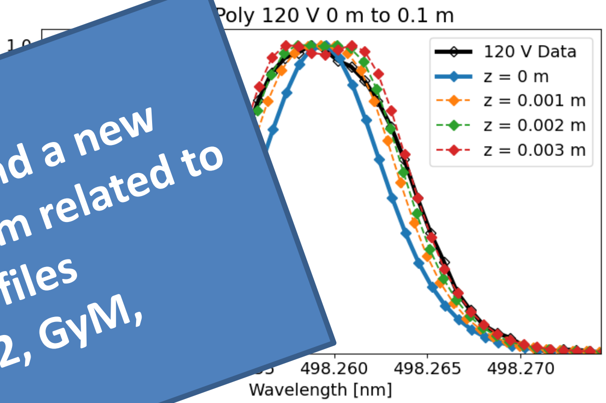
Human Resources: *7 PM*
Involved RU: *FZJ*
Linked WP or TSVV: *N/A*

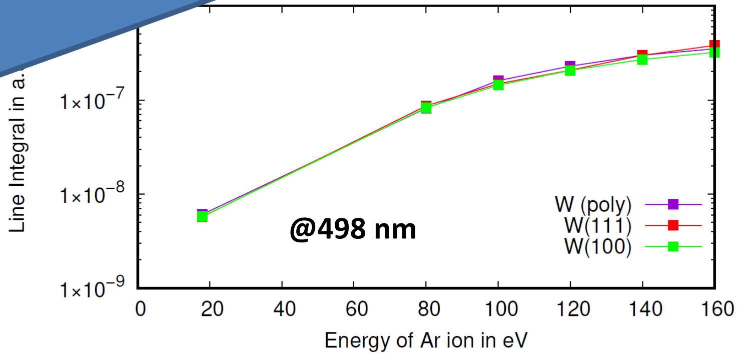
O. Marchuk et al. (FZJ)

SPB.1: Erosion rates of W model systems and composition of re-deposited layers in PSI-2

- **Erosion and re-deposition of W** studied using spectroscopy in PSI-2
  - ✓ W targets: poly W, W (111), W (110), W (100)
- First spectroscopic data sets available for benchmarking codes
  - ✓ Interpretation of the data is sensitive to the position of th… figure on the right)
  - ✓ 3D emission model was developed an…
- **Very small differences in eros…** targets in the studied…
  - ✓ Results … sp…

Plans for 2023:
- Using multi-pass laser absorption system at PSI-2 and a new position of the manipulator to alleviate the problem related to asymmetric line shapes due to hollow plasma profiles
- Participation in cross-machine experiments (PSI-2, GyM, MAGNUM-PSI)





Deliverable: *PWIE.SPB.1.T002.D003*
Status: *completed*
Facilities: *15 days PSI-2*

Human Resources: *7 PM*
Involved RU: *FZJ*
Linked WP or TSVV: *N/A*

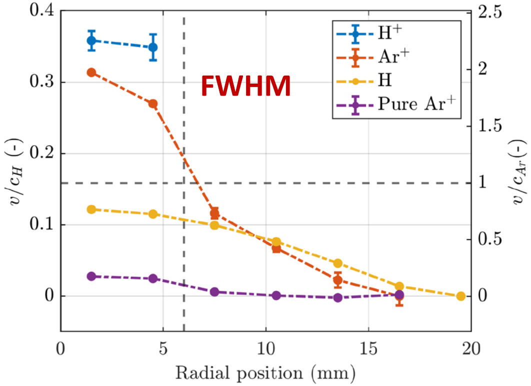
O. Marchuk et al. (FZJ)

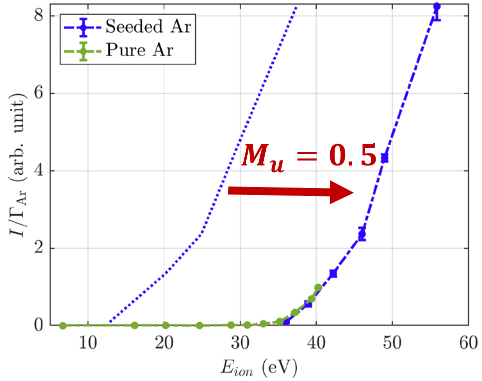
SPB.1: Entrainment under ITER-like plasma conditions and its influence on the erosion of tungsten

- ITER edge plasma will be much denser than for current tokamaks
  - ✓ The **high density allows for impurity entrainment**
  - ✓ **Seeded impurities are accelerated** towards the plasma flow velocity
- **Increase in sputtering by entrainment**
  - ✓ Ar+H plasma generated with Magnum-PSI
  - ✓ The velocity of argon impurities is close to the hydrogen flow velocity and exceeds c_{Ar}
  - ✓ Entrainment results in a **considerable increase in ion impact energy** for the argon impurities

$$E_{ion} = (fM_u^2 + 1.5)k_bT_i - eV_{bias}$$

f = mass ratio between impurity & plasma species
M_u = upstream Mach number





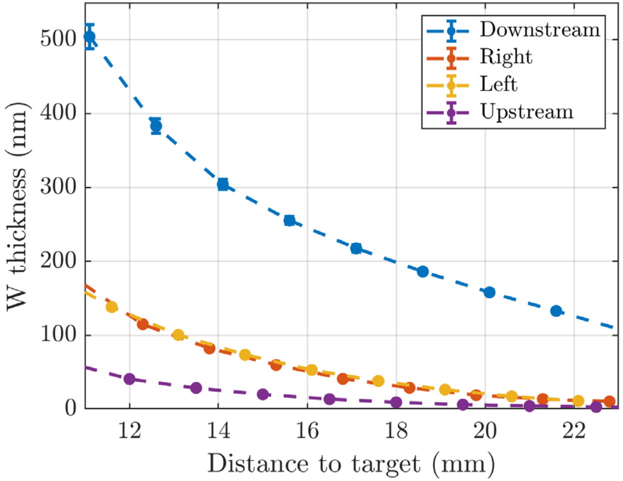
Deliverable: *PWIE.SPB.1.T002.D001, D007*
Status: *completed*
Facilities: 5 + 4 days MAGNUM-PSI, 0 + 1 days accelerator

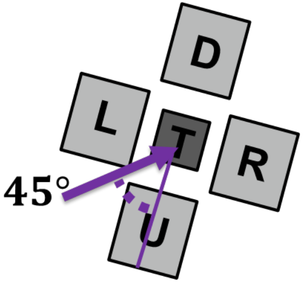
Human Resources: *4 PM + 4 PM*
Involved RU: *DIFFER*
Linked WP or TSVV: *None*

M. Cornelissen et al. (DIFFER)

SPB.1: Erosion rates of W and W+O model systems in MAGNUM-PSI at varying fluxes, fluences, and impurity contents

- Sputtered **tungsten may be re-deposited by entrainment**
  - ✓ Sputtered tungsten can be dragged back to the surface by the plasma flow
  - ✓ Seeded impurities are accelerated towards the plasma flow velocity
- Observed **increase in re-deposition by entrainment**
  - ✓ Dense Ar plasma generated with Magnum-PSI:
  - ✓ More tungsten re-deposition on witness plates downstream than upstream.
  - ✓ Re-deposition by entrainment is dominant for low T_e and high n_e plasmas.





2023 plans

- **Further entrainment studies**
  - ✓ **Measure entrainment closer to the plasma sheath edge**
  - ✓ **Acquire re-deposition rate from complete re-deposition profiles**
- **Comparative erosion studies of the model systems**
  - ✓ **Separate discussion to agree on the flux and fluence regimes for efficient cross-correlation between MAGNUM-PSI, PSI-2 and GyM**

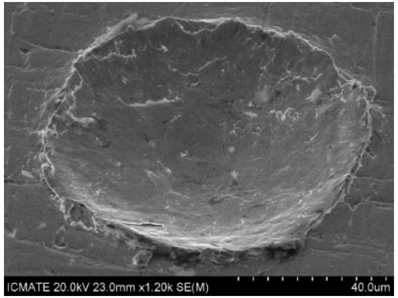
Deliverable: *PWIE.SPB.1.T002.D001, D007*
Status: *completed*
Facilities: *5 + 4 days MAGNUM-PSI, 0 + 1 days accelerator*

Human Resources: *4 PM + 4 PM*
Involved RU: *DIFFER*
Linked WP or TSVV: *None*

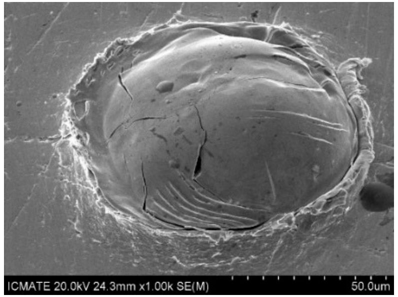
M. Cornelissen et al. (DIFFER)

SPB.1: Surface erosion by hypervelocity W dust impacts

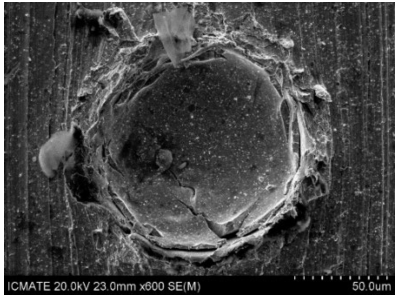
- Monodisperse W spherical dust has been shot on W samples at v_i impact velocity: *580* ≤ v_i [m/s] ≤ 3190 → three regimes of impacts identified.



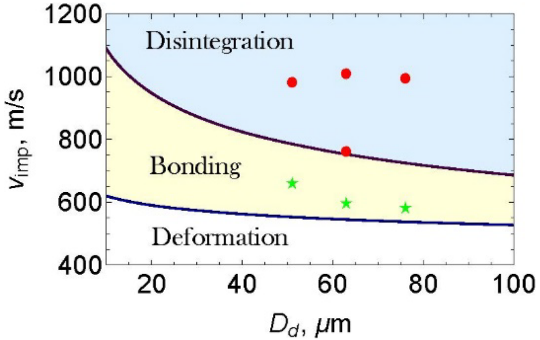
Deformation regime, 200 ÷ 600 m/s → shallow crater formation.



Bonding or cold spray regime, 600 ÷ 1000 m/s → sticking of dust on target.



Partial disintegration regime, 1÷ 4 km/s → material splash ejection and fragmentation.



- Empirical damage laws extracted from experimental data & found **critical erosion and bonding velocities** → results presented at SOFT 2022
- Excavated volume material estimated for single impacts.

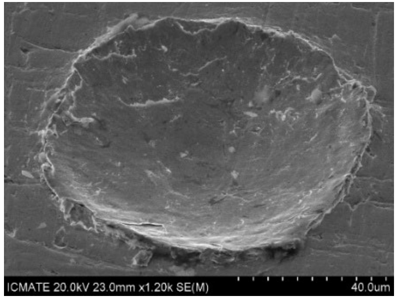
Deliverable: *PWIE.SPB.1.T002.D002*
Status: *completed*
Facilities: *None*

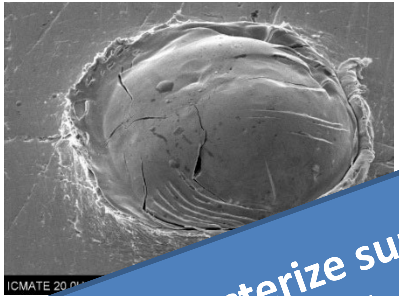
Human Resources: *4 PM*
Involved RU: *ENEA*
Linked WP or TSVV: *None (for this part)*

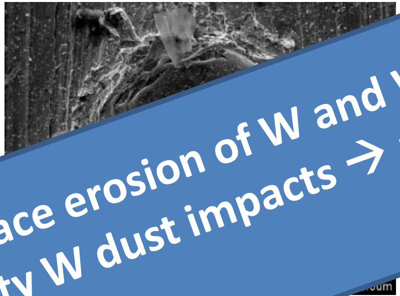
M. De Angeli et al. (ENEA)

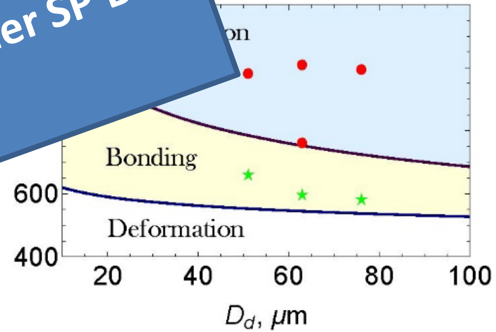
SPB.1: Surface erosion by hypervelocity W dust impacts

- Monodisperse W spherical dust has been shot on W samples at v_i impact velocity: $580 \le v_i$ [m/s] ≤ 3190 → three regimes of impacts identified.









Deformation regime, 200 ÷ 600 m/s → shallow … formation.

… *…gration …ne*, 1÷ 4 km/s → material splash ejection and fragmentation.

Plans for 2023: Characterize surface erosion of W and W+O model systems induced by hypervelocity W dust impacts → under SP B.5 (details to be agreed separately)

- Empirical damag… …m experimental data & found **critical erosion and bonding velocities** → resu… …ted at SOFT 2022
- Excavated volume material estimated for single impacts.

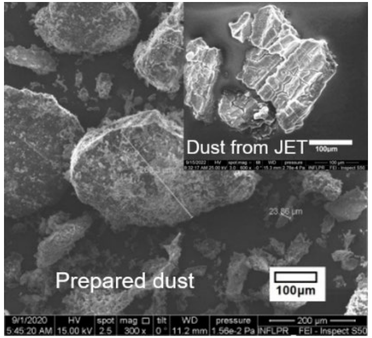
Deliverable: *PWIE.SPB.1.T002.D002*
Status: *completed*
Facilities: *None*

Human Resources: *4 PM*
Involved RU: *ENEA*
Linked WP or TSVV: *None (for this part)*

M. De Angeli et al. (ENEA)

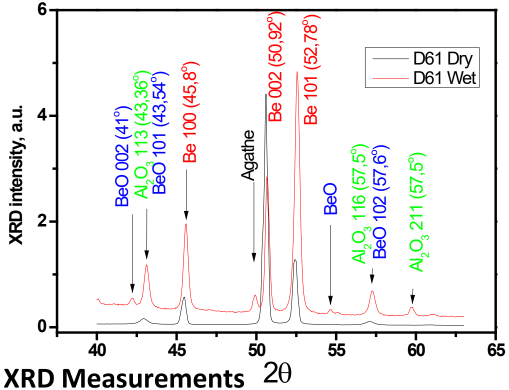
SPB.1: Be and W dust formed during air and water leaks

1. **Be dust generation in air and water environment** using alumina ball milling
2. **Particle size and morphology** determined using SEM microscopy
3. **Preferred crystal orientation** analyzed using XRD
4. **Thermal outgassing** using TDS, identified molecules: O_2, N_2, H_2O, BeO, Be_3N_2, $Be(OH)_2$



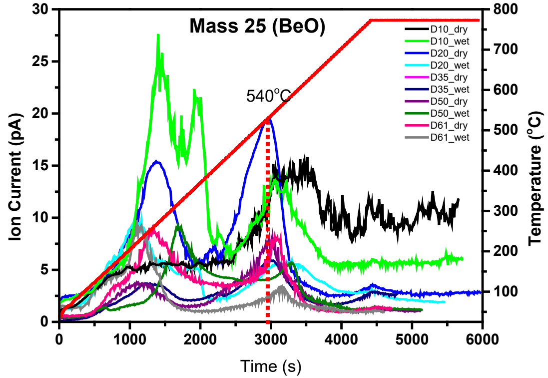
Particle size and morphology:

- 30-500 µm particles prepared & collected by sieving
- Rough surfaces for dust particles → **similarities to dust from JET**



XRD Measurements

- Shifts to small angles due to **tensile stress** in the Be polycrystalline structure.
- BeO diffraction present for samples prepared in wet conditions



TDS analysis of samples:

- More BeO, H_2O, N_2, $Be(OH)_2$ and less Be, O_2 and Be_3N_2 at wet conditions → water present in Be dust as pure H_2O, oxygen to form BeO and (OH) to form $Be(OH)_2$

Deliverable: *PWIE.SPB.1.T002.D005, D008*
Status: *completed*
Facilities: *None*

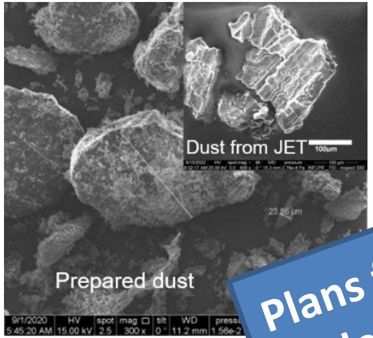
Human Resources: *2 PM + 2 PM*
Involved RU: *IAP*
Linked WP or TSVV: *WP ENR-MAT.01.IAP*

C. Lungu, T. Acsente et al. (IAP)

SPB.1: Be and W dust formed during air and water leaks

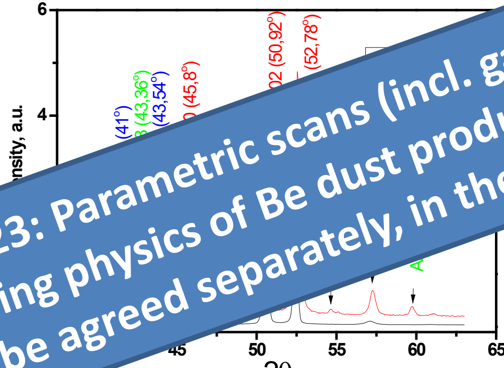
1. **Be dust generation in air and water environment** using alumina ball milling
2. **Particle size and morphology** determined using SEM microscopy
3. **Preferred crystal orientation** analyzed using XRD
4. **Thermal outgassing** using TDS, identified molecules: O_2, N_2, H_2O, BeO, Be

Plans for 2023: Parametric scans (incl. gas inclusions) for understanding physics of Be dust production → under SP B.5 (details to be agreed separately, in the light of ITER considerations)



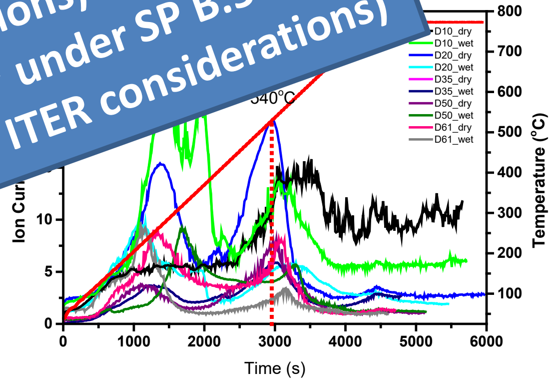
Particle size and morpho

- 30-500 µm particles collected by sieving
- Rough surfaces for dust particles → **similarities to dust from JET**



measurements

- Shifts to small angles due to **tensile stress** in the Be polycrystalline structure.
- BeO diffraction present for samples prepared in wet conditions



TDS analysis of samples:

- More BeO, H_2O, N_2, $Be(OH)_2$ and less Be, O_2 and Be_3N_2 at wet conditions → water present in Be dust as pure H_2O, oxygen to form BeO and (OH) to form $Be(OH)_2$

Deliverable: *PWIE.SPB.1.T002.D005, D008*
Status: *completed*
Facilities: *None*

Human Resources: *2 PM + 2 PM*
Involved RU: *IAP*
Linked WP or TSVV: *WP ENR-MAT.01.IAP*

C. Lungu, T. Acsente et al. (IAP)

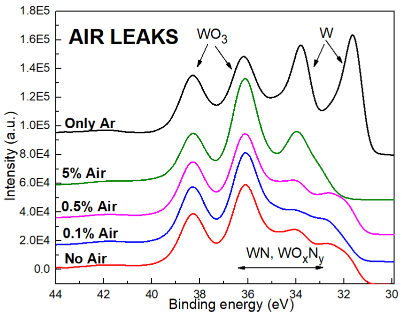
SPB.1: Be and W dust formed during air and water leaks

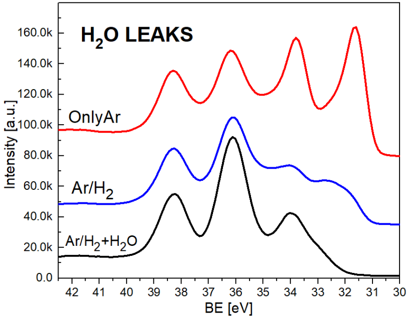
Synthesis of W dust in presence of air and H_2O leaks using MSGA (Magnetron Sputtering Gas Aggregation) operated with high H_2 contents:

- Air leaks (0.1-5%) obtained with low flow rate mass flow controllers
- Leaks of H_2O (~3e-7 Pa m^3 s^{-1}) performed using a homemade device

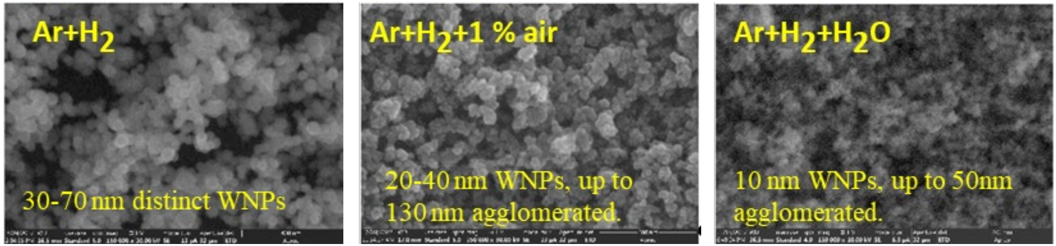
Synthesis of W dust in the presence of air and water leaks

- The W dust synthesis rate decreases rapidly in the presence of air or H_2O leaks due to the W target poisoning
- Results presented in SOFT 2022





Air and H_2O leaks lead to oxidation and nitriding of the W dust



Air and water leaks lead to agglomeration of the W dust

Deliverable: *PWIE.SPB.1.T002.D005, D008*
Status: *completed*
Facilities: *None*

Human Resources: *2 PM + 2 PM*
Involved RU: *IAP*
Linked WP or TSVV: *WP ENR-MAT.01.IAP*

C. Lungu, T. Acsente et al. (IAP)

SPB.1: Be and W dust formed during air and water leaks

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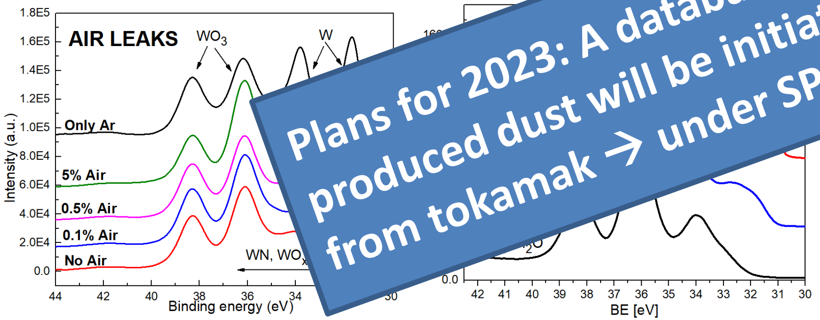
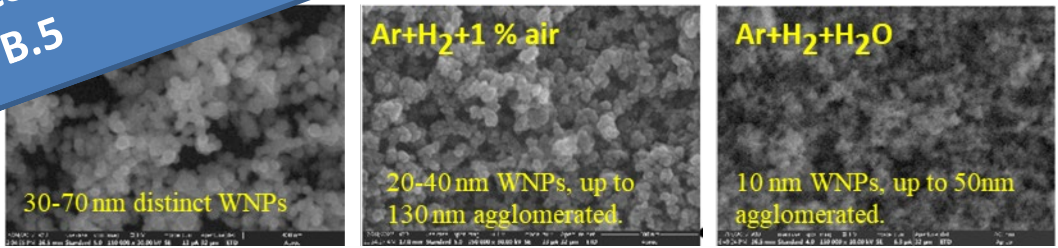
Synthesis of W dust in the presence of air and water leaks

- The W dust synthesis rate decreases rapidly in th… target poisoning
- Results presented in SOFT 2022

Plans for 2023: A database with characteristics of laboratory-produced dust will be initiated, for further comparison with data from tokamak → under SP B.5



Air and H_2O leaks lead to oxidation and nitriding of the W dust



Air and water leaks lead to agglomeration of the W dust

Deliverable: *PWIE.SPB.1.T002.D005, D008* Status: *completed* Facilities: *None*

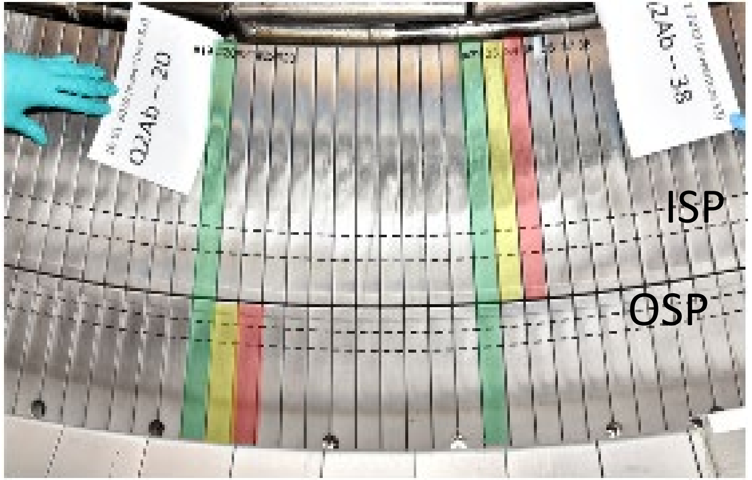
Human Resources: *2 PM + 2 PM* Involved RU: *IAP* Linked WP or TSVV: *WP ENR-MAT.01.IAP*

C. Lungu, T. Acsente et al. (IAP)

SP B.2 – Material migration in toroidal devices - selected results from 2022
SP B.3 – Characterization of plasma-exposed materials – selected results from 2022
+ plans for 2023

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

- **Goal #1**: Determine and compare erosion, (re-)deposition, and fuel retention patterns on C3, C4, and C5 marker Plasma Facing Units (PFUs) → joint exercise between 11 Research Units under SP B.2, SP B.3(,and SP X.2)

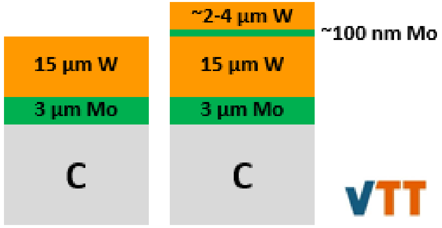


Status of the work (as of early February)

- Full-tile analyses (MPG)
  - ✓ completed for C3, C4, and C5 marker PFUs
- Core samples (VTT) and their analyses
  - ✓ completed for C3 marker PFUs
  - ✓ almost done for C4 marker PFUs → final analysis meeting pending
  - ✓ ongoing for additional standard PFUs → TOF-ERDA at RBI
  - ✓ scheduled for C5 marker PFUs in early 2023 (coring ongoing)

Plans for 2023:

- **Finish C4 sample analyses**
- **Proceed with C5 sample analyses**



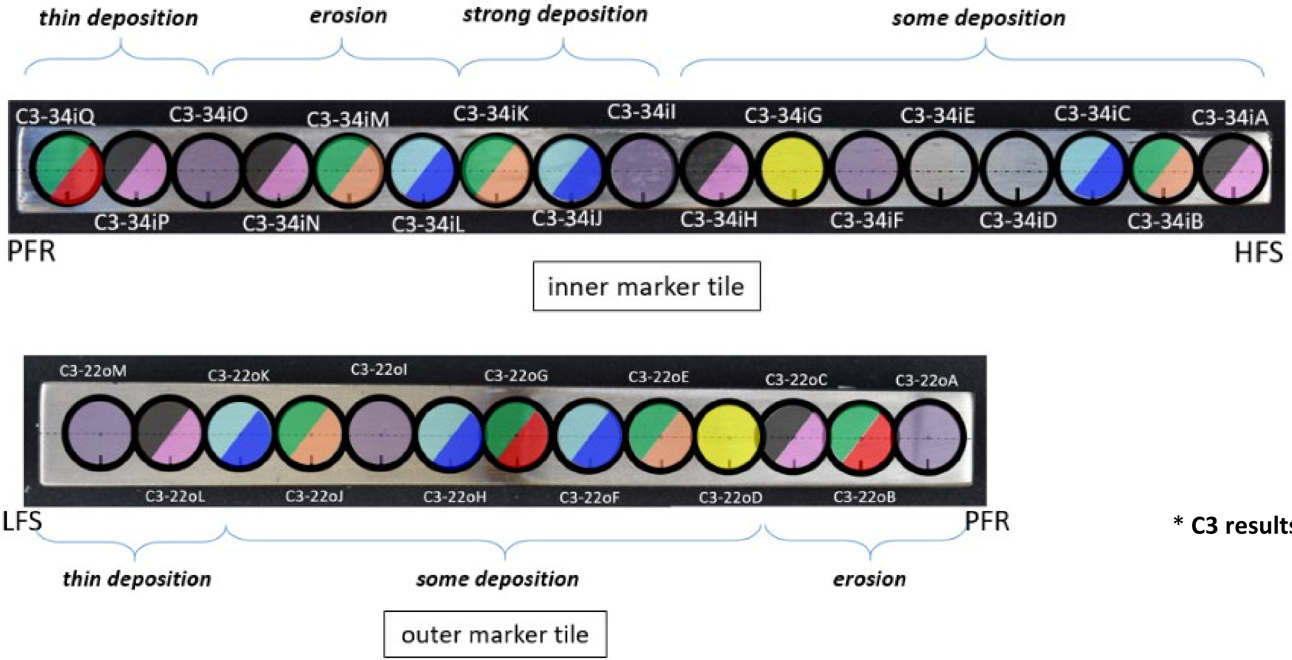
Deliverables: *PWIE.SPB.2.T002.D001, D007, D008, D009, D010, D011*
PWIE.SPB.3.T002.D001, D003, D004, D005, D006, D007, D008, D009
Status: *completed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

Coordinators: E. Bernard, M. Diez (CEA)

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

Distribution matrix of C3 and C4 and C5 core samples



- JSI, Slovenia: µNRA for D content
- UT, Estonia: LIBS for depth-profile analysis of the deposits *
- NCSRD, Greece: NRA for D content
- VTT, Finland: SIMS for depth-profiled analysis of the deposits *
- RBI, Croatia: ERDA for deposits content analysis
- IAP, Romania: GDOES for erosion measurement *
- IST, Portugal: ion beam analysis of the deposits
- VR, Sweden: depth-profiled analysis of the deposits
- IPPLM, Poland: microscopy

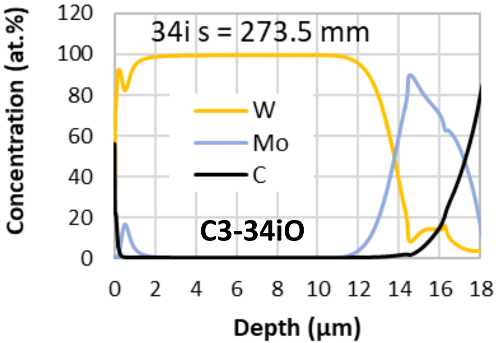
*** C3 results reported in I. Jogi et al., Journal of Nucl. Eng. 2023**

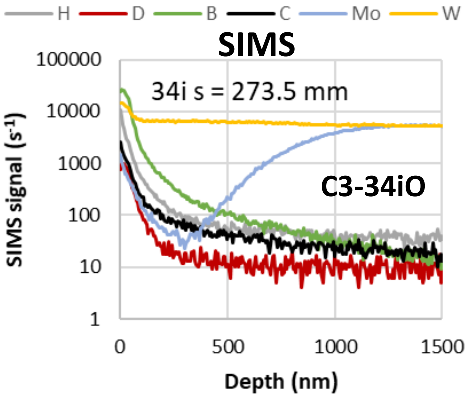
Deliverables: *PWIE.SPB.2.T002.D001, D007, D008, D009, D010, D011*
PWIE.SPB.3.T002.D001, D003, D004, D005, D006, D007, D008, D009
Status: *completed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

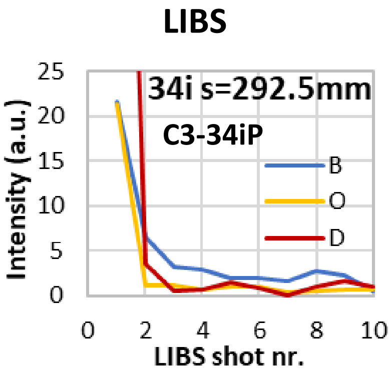
Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

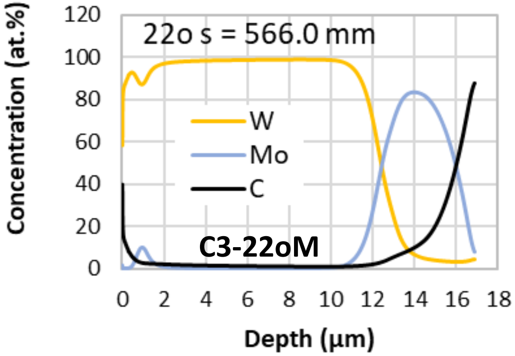
Coordinators: E. Bernard, M. Diez (CEA)

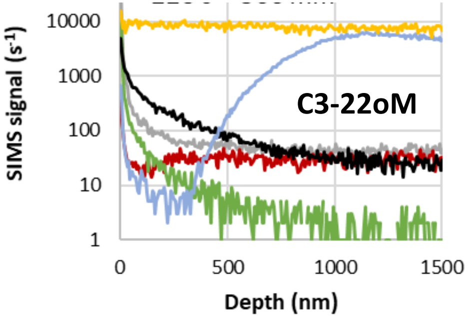
SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

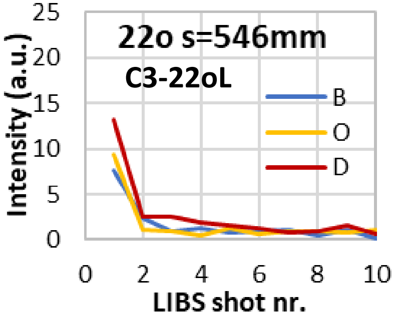












- Comparison made between GDOES, SIMS, and LIBS for the depth profiles of different elements on selected C3 samples
- LIBS also proven to be a **working tool for determining composition of deposited layers**

Deliverables: *PWIE.SPB.2.T002.D001, D007, D008, D009, D010, D011*
PWIE.SPB.3.T002.D001, D003, D004, D005, D006, D007, D008, D009
Status: *completed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

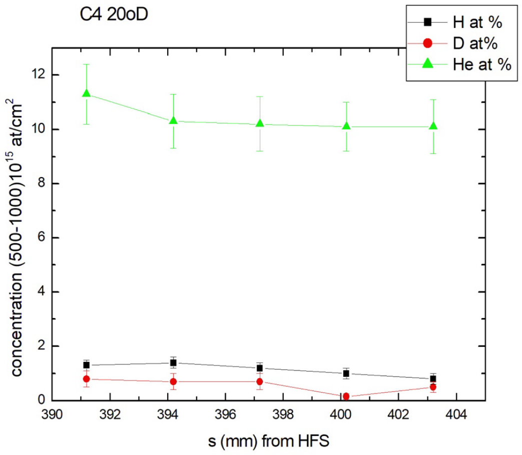
Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

I. Jõgi (UT, SP X.2), A. Hakola (VTT), E. Grigore (IAP)

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

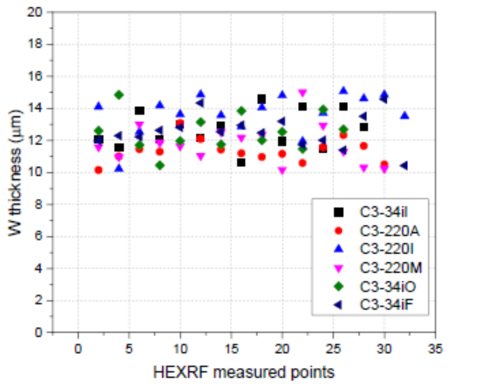
I. Bogdanovic Radovic (RBI), I. Tiseanu (IAP), S. Markelj (JSI), E. Alves (IST), P. Petersson (VR)

- Examples of additional results collected since the review meeting in October
  - ✓ **TOF-ERDA measurements** for the elemental maps on the C4 marker samples → focus on He and light impurities
  - ✓ **X-ray fluorescence studies** of several C3 marker samples → W thickness measurements agree with SEM
  - ✓ Additional **PIXE, RBS and NRA investigations** of C4 marker samples → determining D, B, C, O levels on the surface

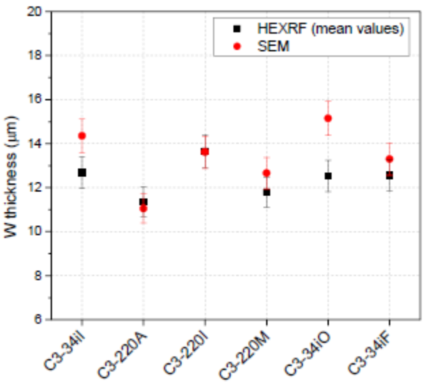


Example of TOF-ERDA results from sample C4-20oD

W thickness measurement by W K-line XRF



Comparison to SEM measurements (cross-section on mark)



Comparison between XRF and SEM analysis for W thickness on C3 samples

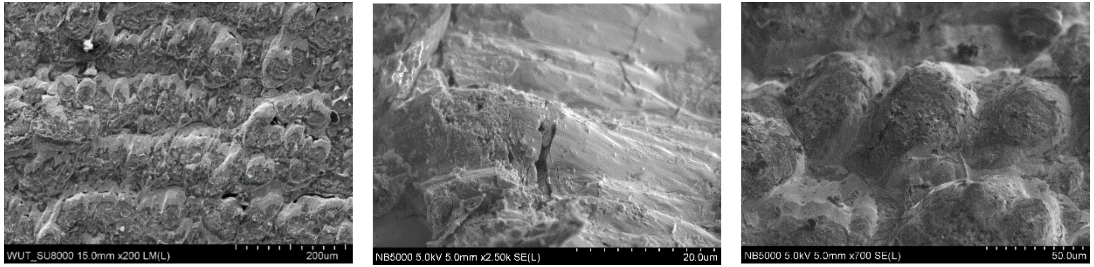
Deliverables: *PWIE.SPB.2.T002.D001, D007, D008, D009, D010, D011*
PWIE.SPB.3.T002.D001, D003, D004, D005, D006, D007, D008, D009
Status: *completed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

Human Resources: ~*20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

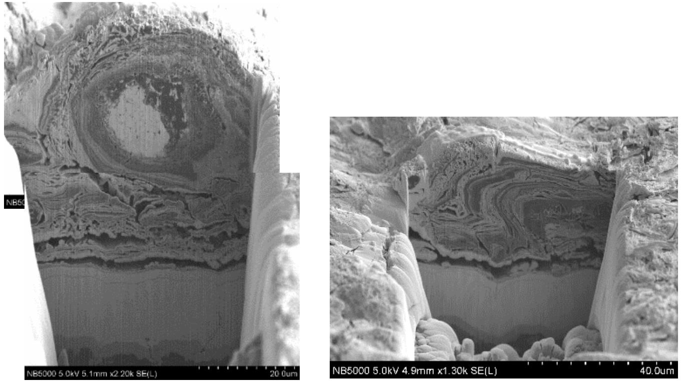
SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

Examples of microscopy studies of samples from the inner divertor after the C4 campaign

- **Thick deposits (>50 µm) with a complex structure** observed
- Some deposits **contain sheets/flakes, distributed inhomogeneously** which further contain spherical/elongated elements and stratified structures; directional bands rich in W visible on top
- EDS measurements indicate increased signals for B, O, C and Cu



SEM images of the deposit morphology, sample J.



SEM images of the deposit and marker layer cross-sections, sample J.

Deliverables: *PWIE.SPB.2.T002.D001, D007, D008, D009, D010, D011*
PWIE.SPB.3.T002.D001, D003, D004, D005, D006, D007, D008, D009
Status: *completed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

E. Fortuna et al. (IPPLM)

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

- **Goal #2:** Repeat the exercise for selected ITER-like PFUs removed after WEST Phase I operations

Focus on PFU#13 for the moment (exposed to C3+C4)

Status of the work:

Full-tile analyses: completed

@CEA

Confocal microscopy on the top surface

Microscopic observations

@ MPG

RBS/NRA + SEM/EDX/FIB on the top surface

RBS/NRA on the poloidal gaps

Monoblock samples and their analyses: Delayed

Completed/ongoing for some monoblocks

Samples cutting scheduled for beginning 2023

Samples analysis scheduled to start mid-2023

Deliverables: *PWIE.SPB.2.T002.D001, D004, D007, D008, D009, D010*
PWIE.SPB.3.T002.D001, D002, D003, D004, D005, D006, D007, D008
Status: *delayed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

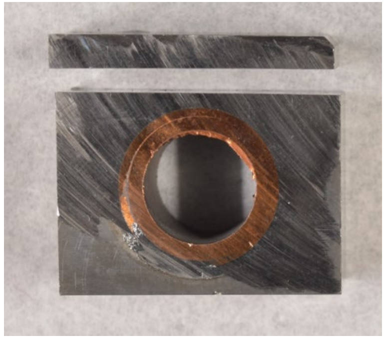
Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

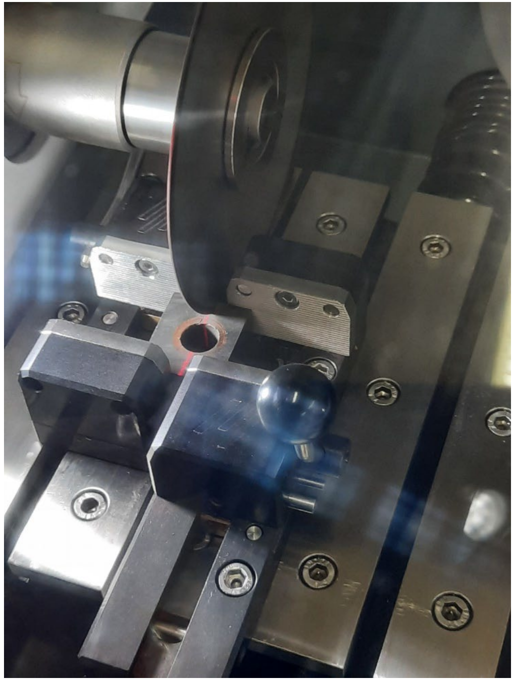
Coordinators: E. Bernard, M. Diez (CEA)

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

January 2023 : a new cutting machine has arrived to speed up the characterization of ITER-like PFUs

- water-free precision cutting machine
- equipped with a diamond saw to cut hard materials such as W

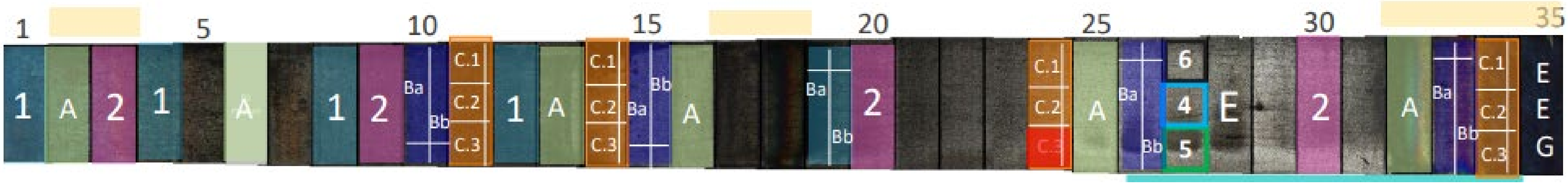




Coordinators: E. Bernard, M. Diez (CEA)

SPB.2 & SPB.3: Erosion and deposition patterns on WEST PFUs removed after C3 and C4 campaigns

Distribution matrix of C3+C4 ITER-like PFU#13



The sample analysis in 2023 is organized as follow:

- Batch A: composition variation on the plasma exposed surface
- Batch B: He and microstructure
- Batch C: fuel retention
- Batch D: optical Hot Spot
- Batch E: surface modification over toroidal direction

Will be discussed during a dedicated meeting → Doodle to come soon

Deliverables: *PWIE.SPB.2.T002.D001, D004, D007, D008, D009, D010*
PWIE.SPB.3.T002.D001, D002, D003, D004, D005, D006, D007, D008
Status: *delayed* Facilities: ~20 days accel. (IST, JSI, MPG, NCSRD, RBI, VR, VTT)

Human Resources: *~20 PM*
Involved RU: *CEA, IAP, IPPLM, IST, JSI, MPG, NCSRD, RBI, UT, VR, VTT*
Linked WP or TSVV: *WP TE*

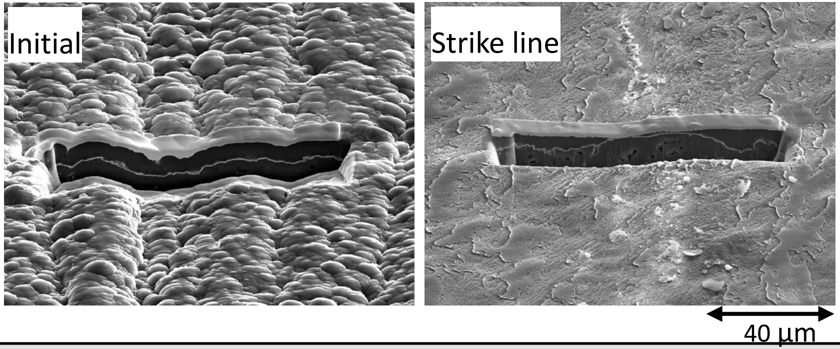
Coordinators: E. Bernard, M. Diez (CEA)

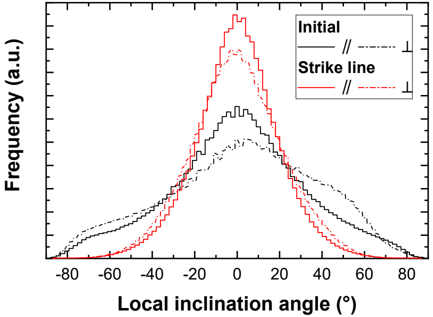
SPB.2 & SPB.3: Characterization of TDUs removed from W7-X after the OP1.2B campaign

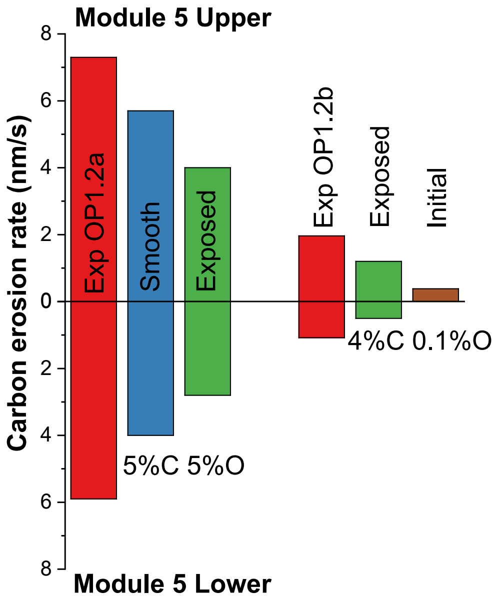
- Work concentrated on the analyses of different Test Divertor Units (TDUs) and other samples
  - ✓ **marker TDUs for erosion/deposition and surface-roughening studies during OP1.2B**

Main results

- Plasma exposure **smoothens the surface and creates specific surface patterns**
- Simulated and experimental erosion rates in **OP1.2A and OP1.2B agree within a factor of 2**; surface roughness plays a strong role
- Reduced erosion from OP1.2A to OP1.2B due to **smaller O concentration** (boronizations) → erosion in OP1.2B dominated by H







Deliverables: *PWIE.SPB.2.T002.D004, D006, D008, D009, D011*
PWIE.SPB.3.T002.D002, D003, D006
Status: *completed* Facilities: ~15 days accelerator (FZJ, MPG, VR, VTT)

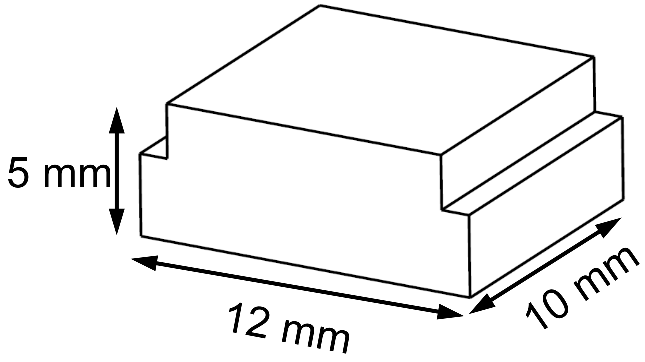
Human Resources: *~10 PM*
Involved RU: *FZJ, IPPLM, MPG, VR, VTT*
Linked WP or TSVV: *WP W7X*

M. Mayer et al. (MPG)

SPB.2: Erosion and deposition characteristics of manipulator samples from OP2 experiments in W7-X

Plans for 2023

- **Samples: Material qualified, manufactured, pre-characterised**
  - ✓ Fine-grain graphite, polished and unpolished
  - ✓ Al and Al with 7 or 30 nm a-C:D layer
- **Planned exposures with the multi-purpose manipulator**
  - ✓ Carbon erosion during glow-discharge cleaning
  - ✓ Boron deposition during boronizations
  - ✓ Carbon erosion during selected discharges in far scrape-off layer
  - ✓ Hydrogen deposition and charge-exchange fluxes in selected discharges in far scrape-off layer
  - ✓ Tungsten deposition and transport using laser blow-off



SPB.2 & SPB.3: Characterization of TDUs removed from W7-X after the OP1.2B campaign

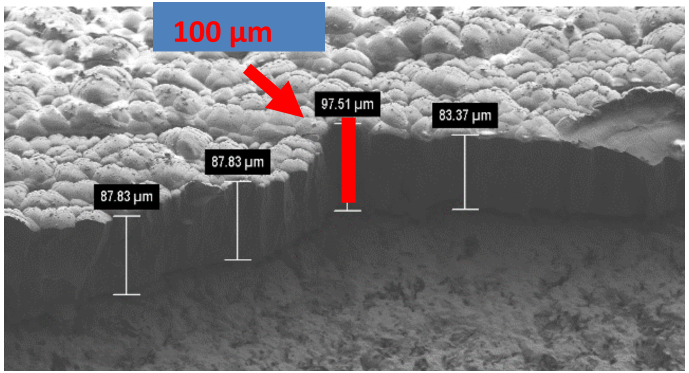
- Work concentrated on the analyses of different Test Divertor Units (TDUs) and other samples
  - ✓ selected TDUs/samples for determining deposition of impurities (incl. ^{13}C and various metals) and surface modification patterns

20 TDU target elements (TE) extracted for ^{13}C analyses, using the reaction $^{13}C(d,p_0)^{14}C$

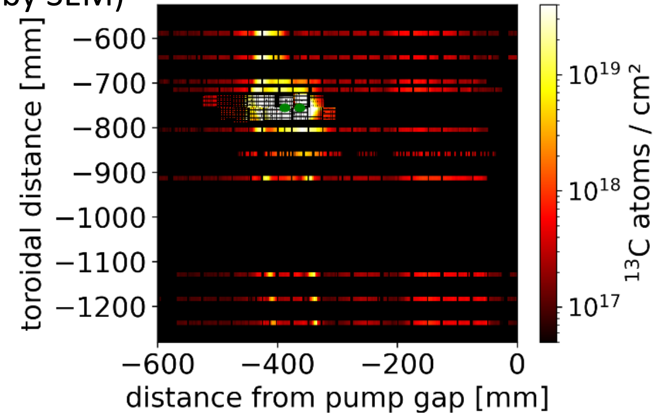
Additional $^{13}C(^{3}He,p)^{12}C$ measurements from the vicinity of gas puff location (not yet analyzed)

Main results

- High ^{13}C deposition around injection holes: **>10^{20} atoms cm^{-2} in 10 cm perimeter**
- Vicinity shows saturated regions (white), thickness > 6 µm (up to 100 µm by SEM)



SEM image of a delaminated layer ~1 mm apart from one injection hole



2D ^{13}C deposition on HM39TM200h+300h

Deliverables: *PWIE.SPB.2.T002.D004, D006, D008, D009, D011*
PWIE.SPB.3.T002.D002, D003, D006
Status: *completed* Facilities: ~15 days accelerator (FZJ, MPG, VR, VTT)

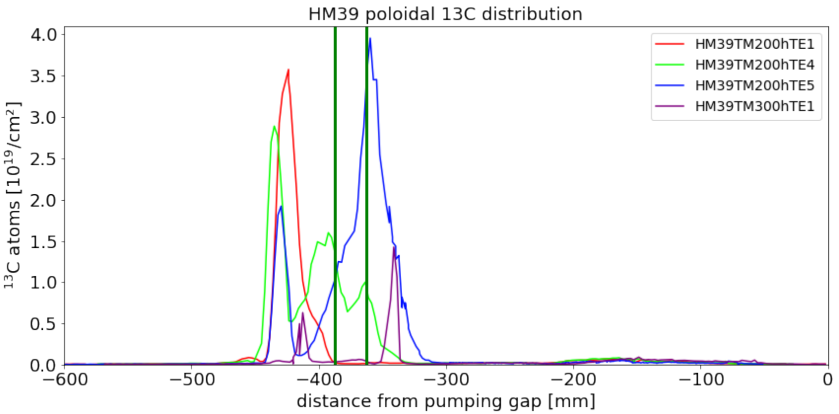
Human Resources: *~10 PM*
Involved RU: *FZJ, IPPLM, MPG, VR, VTT*
Linked WP or TSVV: *WP W7X*

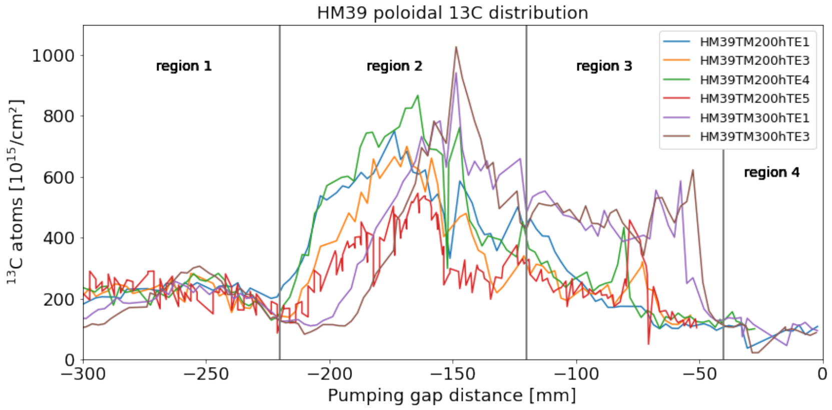
SPB.2 & SPB.3: Characterization of TDUs removed from W7-X after the OP1.2B campaign

- Work concentrated on the analyses of different Test Divertor Units (TDUs) and other samples
  - ✓ **selected TDUs/samples for determining deposition of impurities (incl. ^{13}C and various metals) and surface modification patterns**

Main results

- Direction to TM100h (top side): 1 peak, shifted away from the pumping gap
- Direction to TM300h (bottom side): splitting into 2 peaks
- Secondary peak along the strike line (-80-(-250 mm)): low deposition but regular pattern across the TE (nm range)





Deliverables: *PWIE.SPB.2.T002.D004, D006, D008, D009, D011*
PWIE.SPB.3.T002.D002, D003, D006
Status: *completed* Facilities: ~15 days accelerator (FZJ, MPG, VR, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, IPPLM, MPG, VR, VTT*
Linked WP or TSVV: *WP W7X*

M. Racinski et al. (FZJ)

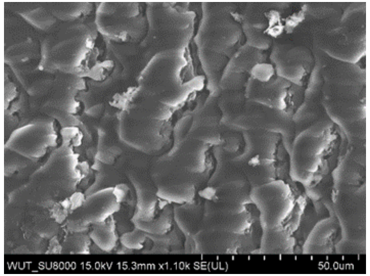
SPB.2 & SPB.3: Characterization of TDUs removed from W7-X after the OP1.2B campaign

- Work concentrated on the analyses of different Test Divertor Units (TDUs) and other samples
  - ✓ SEM/TEM/EDS observations of TDUs with damaged zones

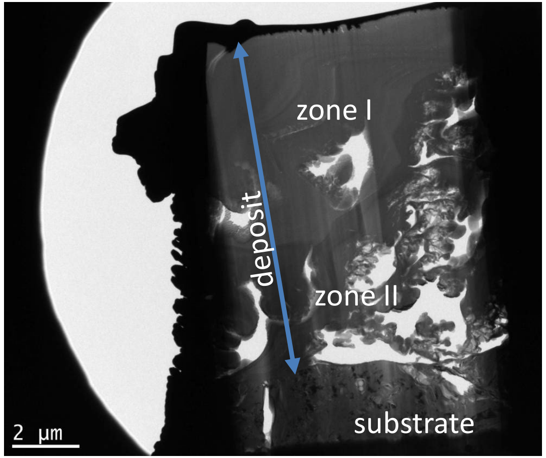
tile HM19TM400hTE1

Damaged zone on sample 5a

SEM image of the matte area below the damage. *Deposit with impurities present.*



TEM image from the matte area *showing homogeneous layer with some large pores (Zone I) and a heterogeneous layer (Zone II) with a clearly porous structure*



Deliverables: *PWIE.SPB.2.T002.D004, D006, D008, D009, D011*
PWIE.SPB.3.T002.D002, D003, D006
Status: *completed* Facilities: ~15 days accelerator (FZJ, MPG, VR, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, IPPLM, MPG, VR, VTT*
Linked WP or TSVV: *WP W7X*

SPB.2 & SPB.3: Analysis of AUG samples

A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Task running in 2023 (rows 1–5); Task from 2021 finished in 2022 (rows C)

	Sub-task	Coordination / samples	SEM / EDX / FIB / OM – pre	RBS / NRA - pre	DIM-experiment	SEM / EDX / FIB / OM - post	RBS / NRA - post	Evaluation	Other institutions	Status	Publication
1 2	AUG He-2022 (WP-TE): i) fuzz ii) Pt-marker/erosion	yes	done	no done	scheduled 19.07.2022	done ongoing	no done	done ongoing	ongoing	ongoing	PFMC pending
3 4	AUG depo-cracks i) 2021 tiles ii) 2022 tiles	No	no	no	campaign integrated	done started	no	done pending	no	finished	published pending
5 C	Melting: i) bridging ii) Ir, Nb	yes yes	done done	no	Apr 2021 5.7. 2022	done done	no	ongoing done	no	ongoing finished	ongoing finished
C	Au-marker (net/gross erosion)	2020	done	done	9.7. 2020	done	done	done	ongoing	finished	finished
C	Roughness (erosion)	2020	done	no	9.7. 2020	done	done	done	ongoing	finished	finished
C	B-dropper (2^{nd} - MEM)	yes	done	done	8.6. 2021	done	done	done	no	finished	finished
C	Gap load (2^{nd} - rev/co-field)	Yes	done	done	18.3.2021	done	no	done	done	finished	finished
C	IR-rel. tile	Yes	no	no	Mar 2021	done	no	done	no	ongoing	no
C	Arc inserts	no	no	no	campaign integrated	done	no	done	no	ongoing	finished

See next slides & separate talk

Rohde et al., 2023, NME 34, 101320

Ratynskaia et al., submitted NME

See next slides

Krieger et al., submitted NF

Krieger et al., submitted NME

Rohde et al., 2021, NME 29, 101083

Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

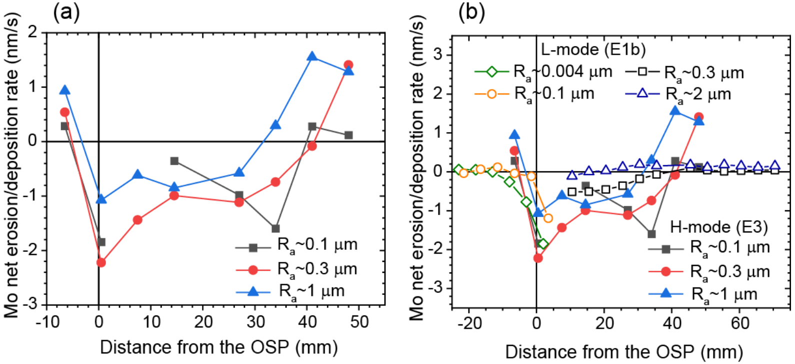
Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

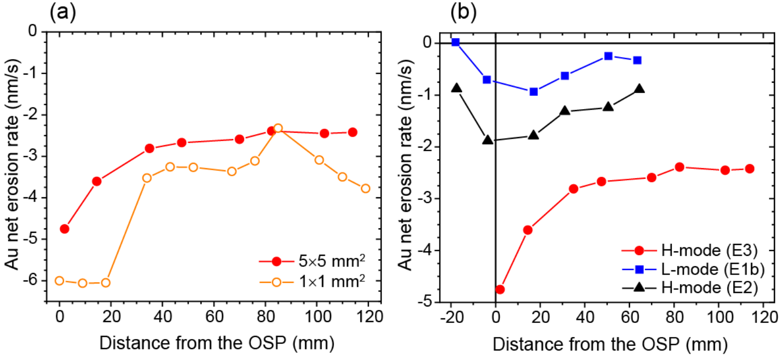
SPB.2 & SPB.3: Analysis of AUG samples

A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Au marker samples and roughness samples – reported in PSI 2022

- Study net/gross erosion of Au and effect of roughness on erosion in H-mode
- Increasing surface roughness **reduces net erosion but less than in L-mode**
- Net-erosion rates in **H-mode 2-5 times higher than in L-mode**
- Exposure to H-mode conditions results in strong local variations in the poloidal and toroidal erosion/deposition profiles





Top: Poloidal net erosion/deposition profiles for different roughness samples
Bottom: Poloidal net erosion profiles (a) for the 5×5 mm² and 1×1 mm² Au marker spots in H-mode and (b) for the 5×5 mm² Au marker spots during different L- and H-mode experiments

Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

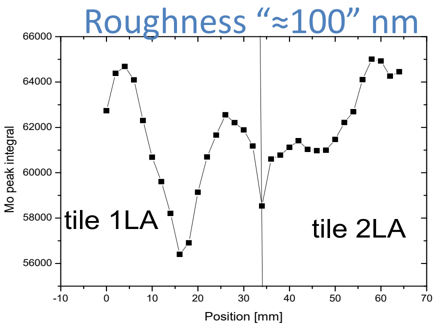
Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

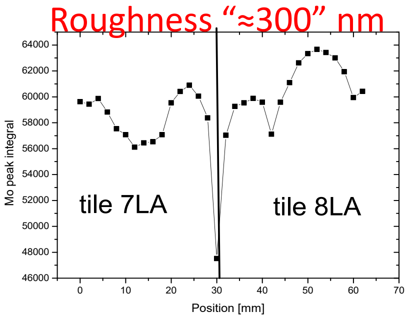
SPB.2 & SPB.3: Analysis of AUG samples

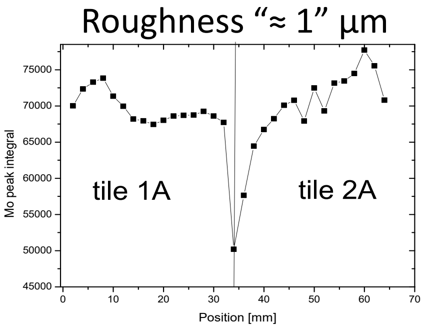
A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Detailed ion-beam measurements of the roughness samples

- Mo erosion at strike point **largest for the samples with the lowest roughness** – in agreement with lab studies
- RBS spectrum hard to model in SIMNRA → combination of roughness, material mixing, and oxidization







Measuring direction (poloidal)

Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

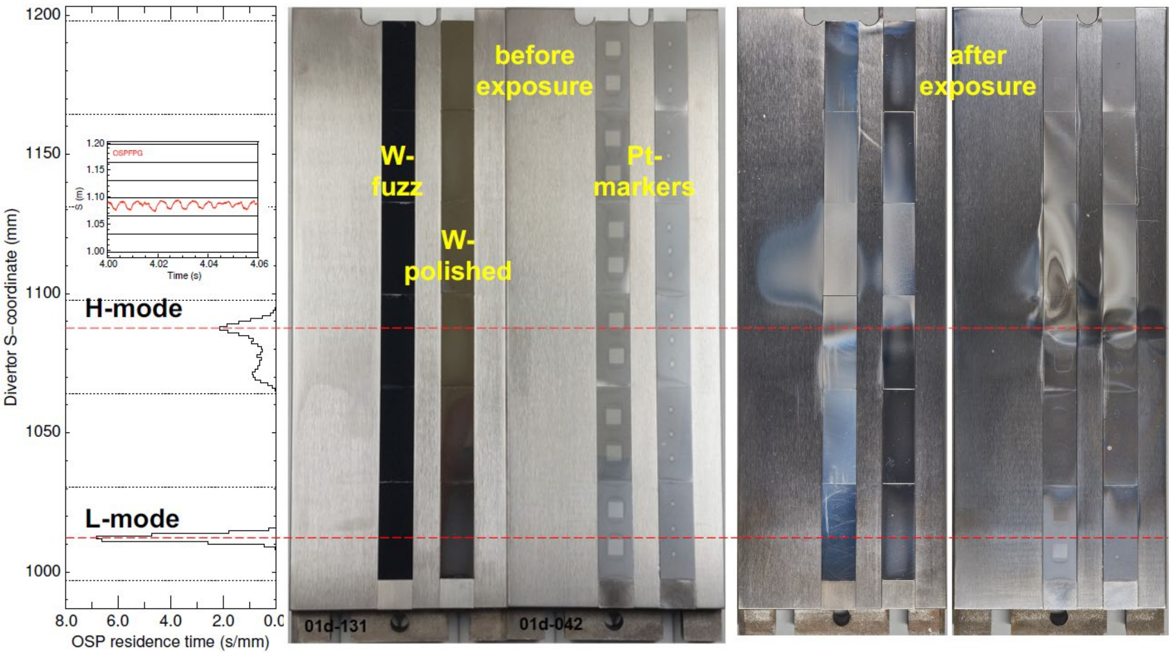
S. Markelj et al. (JSI)

SPB.2 & SPB.3: Analysis of AUG samples

A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Exposure of samples to helium plasmas

- Exposure of samples with (i) W fuzz, (ii) bulk W, and (iii) Pt markers to L- and H-mode discharges
- Main goals to study **formation & erosion of W fuzz and comparing erosion to published results from D plasmas**



Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

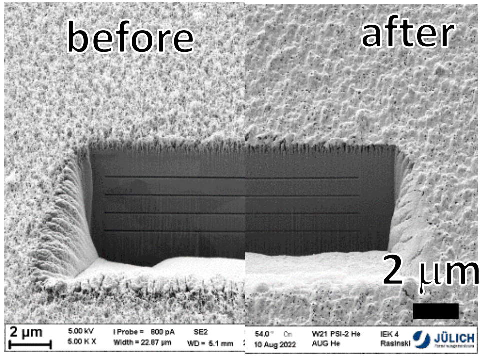
Human Resources: ~*10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

SPB.2 & SPB.3: Analysis of AUG samples

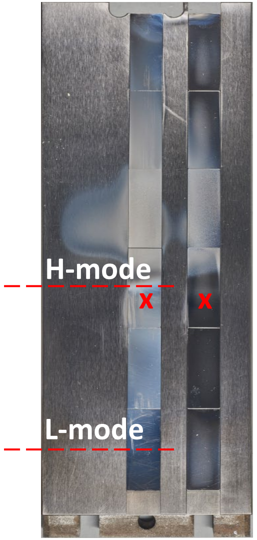
A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

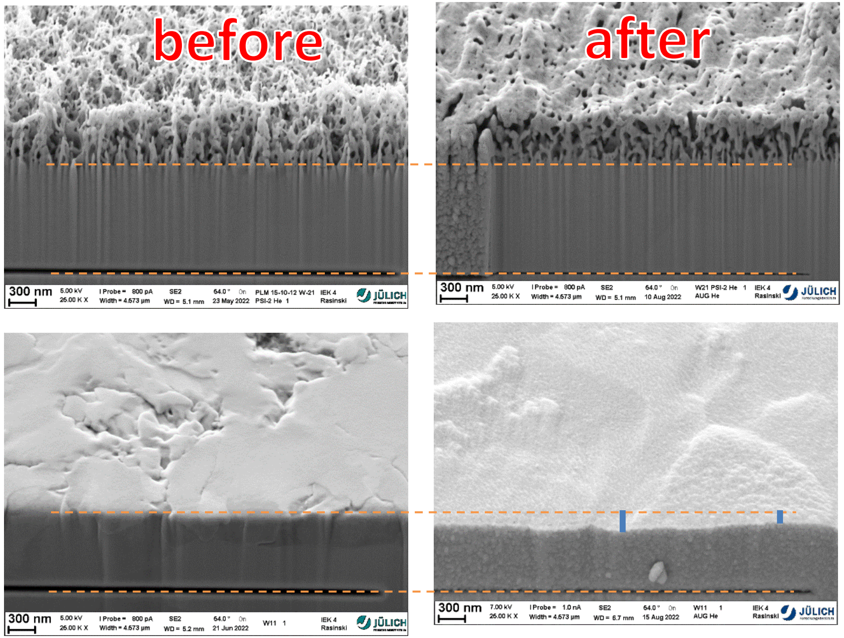
Status of analyses of W fuzz and bulk W samples

- Around the H-mode strike line: (i) W fuzz samples show partial fuzz erosion; (ii) bulk W samples (polished) show erosion (100 – 250 nm)



SEM image of a cross-section before and after AUG He campaign





Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

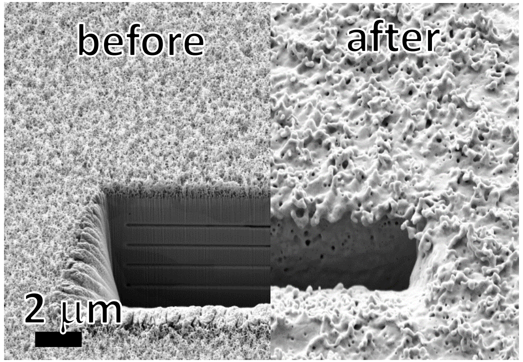
M. Rasinski et al. (FZJ)

SPB.2 & SPB.3: Analysis of AUG samples

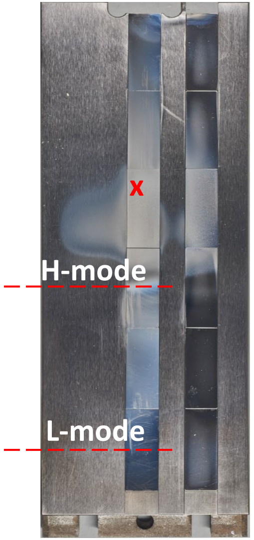
A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Status of analyses of W fuzz and bulk W samples

- Above the H-mode strike line: W fuzz samples show fuzz being removed/modified, formation of new fuzz with thickness <1 μm, and formation of nano-bubbles below the surface



SEM image of a cross-section before and after AUG He campaign



Main results so far

- **Below H-mode strike line**: deposition of W
- **Near the H-mode strike line**: erosion of fuzz and bulk W samples
- **Above H-mode strike line**: formation of new fuzz and existing fuzz being removed/modified
- Visible **traces of arcing**, mostly at fuzzy surfaces
  - ✓ Arcs removed fuzz but did not damage underlying material

Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

Human Resources: ~*10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

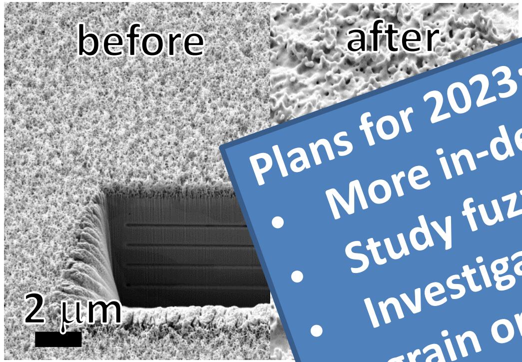
M. Rasinski et al. (FZJ)

SPB.2 & SPB.3: Analysis of AUG samples

A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. ... kelj and M. Kelemen et al. (JSI)

Status of analyses of W fuzz and bulk W samples

- Above the H-mode strike line: W fuzz samples show fuzz being remo... fuzz with thickens below 1 mm, and formation of nano-bub...



SEM image of a cross-s... before and after AUG He...

...ition of W

...line: erosion of fuzz and bulk W

...e H-mode strike line: formation of new fuzz and existing fuzz being removed/modified

- Visible traces of arcing, mostly at fuzzy surfaces
  - ✓ Arcs removed fuzz but did not damage underlying material

Plans for 2023:
- More in-depth analysis of the exposed samples
- Study fuzz formation in detail
- Investigation on the localized fuzz growth – correlation with W grain orientation

Deliverables: *PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
PWIE.SPB.3.T002.D002, D006, D008
Status: *completed* Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

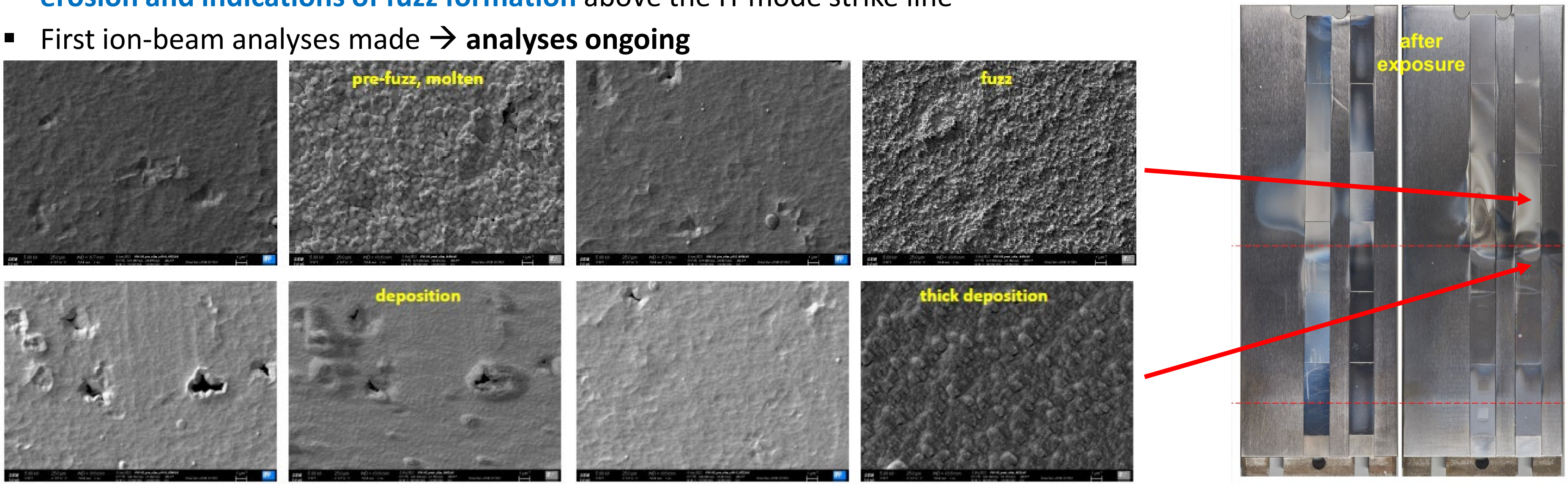
M. Rasinski et al. (FZJ)

SPB.2 & SPB.3: Analysis of AUG samples

A. Hakola et al. (VTT), M. Balden and K. Krieger et al. (MPG), M. Racinski et al. (FZJ), I. Bogdanovic Radovic et al. (RBI), S. Markelj and M. Kelemen et al. (JSI)

Status of analyses of the Pt markers

- SEM analyses indicate (i) **coverage of the markers with deposits** below/around the H-mode strike line and (ii) strong **erosion and indications of fuzz formation** above the H-mode strike line
- First ion-beam analyses made → **analyses ongoing**



Deliverables:	*PWIE.SPB.2.T002.D002, D003, D004, D005, D010*
	PWIE.SPB.3.T002.D002, D006, D008
Status: *completed*	Facilities: ~13 days accelerator (JSI, MPG, RBI, VTT)

Human Resources: *~10 PM*
Involved RU: *FZJ, JSI, MPG, RBI, VTT*
Linked WP or TSVV: *WP TE*

M. Balden et al. (MPG)

SP B.4 – Reference coatings for ITER and DEMO – selected results from 2022 and plans for 2023

SPB.4: Overview of activities

- SP B.4 deals with **production of W and Be reference samples according to agreed Master Excel** – latest update in September 2022 to come up with a manageable plan for the period 2021-2022
- Several RUs involved in **characterization of the produced reference layers as well as the outcomes of their exposure** into plasmas in linear machines (MAGNUM-PSI, PSI-2, GyM)

Excerpt from the Master File – this particular table contains 251 lines…

Research Unit	Specifications	Size (mm3)	Thickness (um)	Gas	Temperature (deg C)	Substrate	# of samples	To whom?	Comments	WP and SP	Produced by
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, polished	1	FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, low roughness, Ra = 100 nm	1	FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, medium roughness, Ra = 300 nm	1	FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, polished	6	FZJ	PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, low roughness, Ra = 100 nm	6	FZJ	PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4		Nominal	graphite, medium roughness, Ra = 300 nm	6	FZJ	PSI-2 experiments	SP B.1	06/2022

SPB.4: Overview of activities

- SP B.4 deals with **production of W and Be reference samples accordin**[...] atest update in September 2022 to come up with a manageable plan for the [...]
- Several RUs involved in **characterization of the prod**[...] **f their exposure** into plasmas in linear machines (MAGNUM[...]

Excerpt from the Master File – [...]

Research Unit								...ments	WP and SP	Produced by
ENEA-POLIMI							FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI					..., Ra = 100 nm	1	FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI				Nominal	graphite, medium roughness, Ra = 300 nm	1	FZJ	FIB marking @ FZJ before PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI				Nominal	graphite, polished	6	FZJ	PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-...	...geometry	>0,4	Nominal	graphite, low roughness, Ra = 100 nm	6	FZJ	PSI-2 experiments	SP B.1	06/2022
ENEA-POLIMI	W-HiPIMS	PSI-2 geometry	>0,4	Nominal	graphite, medium roughness, Ra = 300 nm	6	FZJ	PSI-2 experiments	SP B.1	06/2022

Plans for 2023: Produce a new Master File based on the present priorities in the ITER and DEMO research plans → W layers should have an even higher emphasis

- **W and W+O coatings with well-defined compositions and morphologies for "comparative" PSI-2, MAGNUM-PSI, and GyM erosion experiments**
- **Production of a series of JET-relevant Be samples (TBD) for assisting LIBS commissioning**
- **Comparison of implanted and co-deposited W+O+D layers**

Coordinator: A. Hakola (VTT)

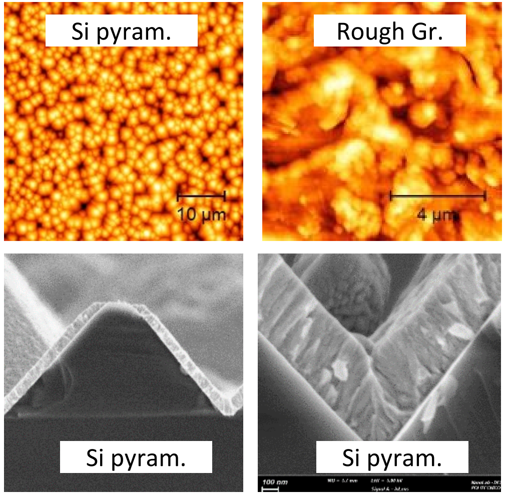
SPB.4: Production of W-based reference coatings

Main research areas in 2022:

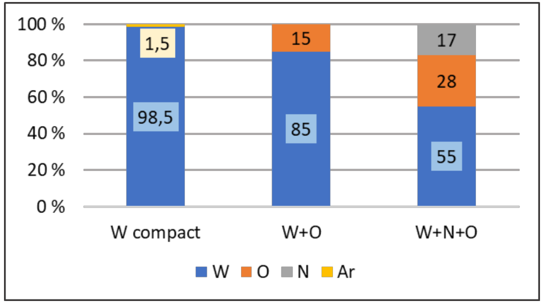
- W coatings on flat and rough surfaces, 500 nm thick (GyM, ÖAW) ~60 samples
  - ✓ substrate preparation by ISTP-CNR (chemical/plasma etching) + W deposition by HiPIMS
  - ✓ Flat and pyramidal-Si substrates as well as flat and rough graphite
- W coatings on Mo, 1 µm thick, for the LIBS studies ~100 samples
  - ✓ Compact W films (HiPIMS)
  - ✓ Amorphous-like W+O and W+N+O films, with varying O and N concentrations (PLD)
  - ✓ SIMS of W+O films (CIEMAT) indicate transition from W+O at ~1.1 µm to a W layer (thickness ~0.2 µm); O variations between or across samples cannot be determined

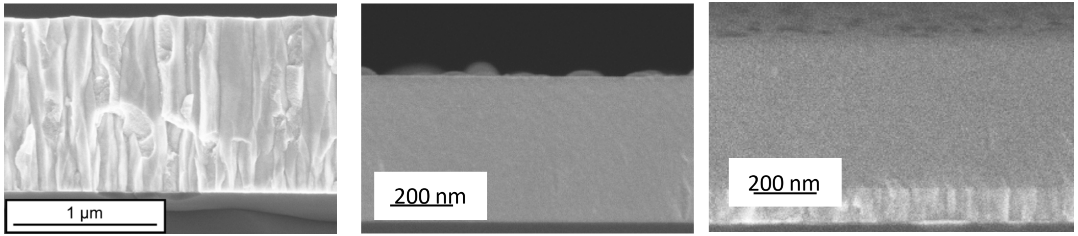
AFM

SEM



EDXS





W compact **W+O** **W+N+O**

Deliverable: *PWIE.SPB.4.T002.D001, D004*
Status: *completed*
Facilities: None

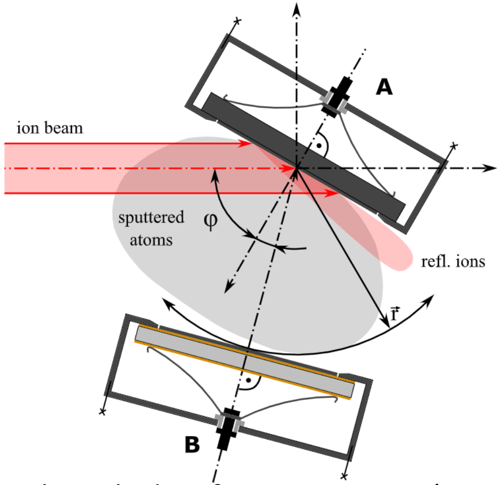
Human Resources: 3 *PM* + 3 *PM*
Involved RU: *ENEA, CIEMAT*
Linked WP or TSVV: *SP X.2.T002, SP B.1.T002.D001-D003*

M. Passoni et al. (ENEA), D. Alegre et al. (CIEMAT)

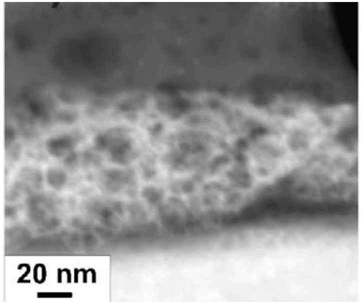
SPB.4: Production of W-based reference coatings

Plans for 2023

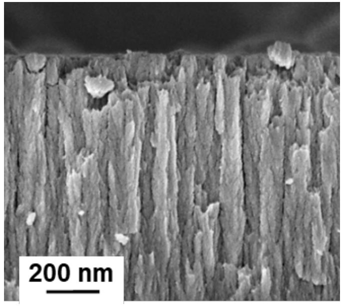
- **Production of crystalline oriented W-based coatings for ion beam exposures – SP B.1 (ÖAW)**
  - ✓ determine the dependence of the sputtering yield on impact angle and crystallographic orientation
- **Production of compact and amorphous W-based coatings for Linear Plasma Devices – SP B.1**
  - ✓ comparative exposures in non-fuzzy regime in GyM, PSI-2 and MAGNUM
  - ✓ exposures in fuzzy regime (PSI-2) of different kinds of W to highlight fuzzy W growth dynamics
- **Work on tailoring of porous W-based coatings to better mimic layered porous redeposits found in tokamaks**



C. Cupak et al. Applied Surface Science ***570*** *(2021) 151204*



M. Rasinski et al, Fus. Eng. & Des. ***86*** *(2011) 1753*



Porous W

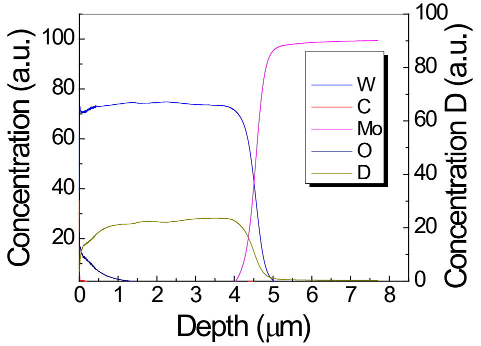
SPB.4: Production of Be- and W-based reference coatings

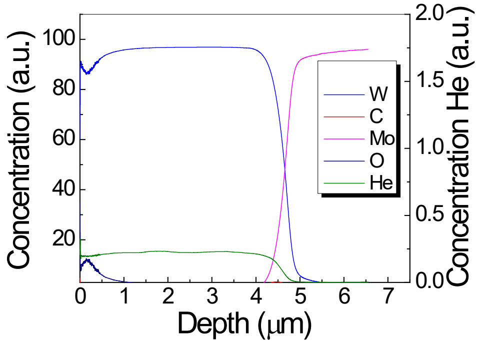
Main research areas in 2022:

- **Production of W-based layers** – mainly for LIBS development and exposures in linear devices
  - ✓ W+He(5 at.%)+D(5 at.%); W+Ne (5 at.%); W+Ne(5 at.%)+D (5 at.%); W+O(5 at.%); W+O(5 at.%)+D(10 at.%)
  - ✓ Samples exhibit smooth and uniform profiles for the gases – however, Ne detection difficult
  - ✓ TOF-ERDA analysis in agreement with GDOES and used for calibrating the H/D/He concentrations

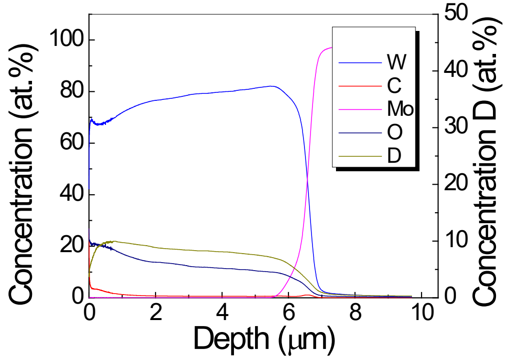
sample	H (at.%)	D (at.%)	He (at.%)	^{14}N (at.%)	^{16}O (at.%)	W (at.%)
W+He+D	1.7 ± 0.3	8.9 ± 1.4	18 ± 1	4.5 ± 0.6	4.4 ± 0.6	59 ± 4
	1.1 ± 0.2	11.2 ± 1.5	16.2 ± 1.5	4.7 ± 0.6	4.4 ± 0.6	61 ± 4

TOF-ERDA data for two W+He+D coatings





GDOES depth profiles for a W+He+D coating (left D profile, right He profile)



GDOES depth profiles for a W+O+D coating

Deliverable: *PWIE.SPB.4.T002.D002, D007, D009*
Status: *completed*
Facilities: 5 days accelerator (RBI)

Human Resources: 9 *PM + 2 PM*
Involved RU: *IAP, RBI*
Linked WP or TSVV: *SP X.2.T002, SP B.1.T002.D001-D003*

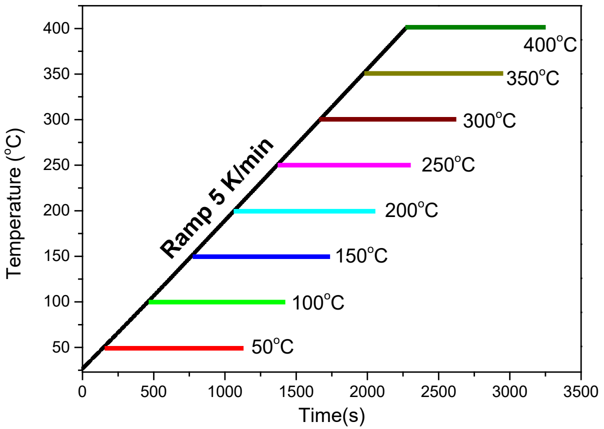
E. Grigore et al. (IAP), I. Bogdanovic Radovic et al. (RBI)

SPB.4: Production of Be- and W-based reference coatings

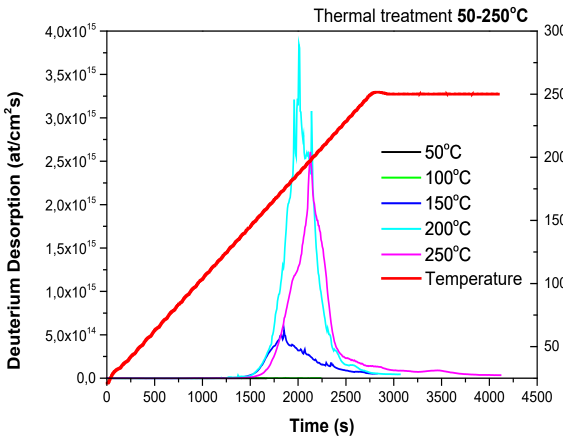
Main research areas in 2022:

C. Porosnicu et al. (IAP), I. Bogdanovic Radovic (RBI), A. Hakola (VTT)

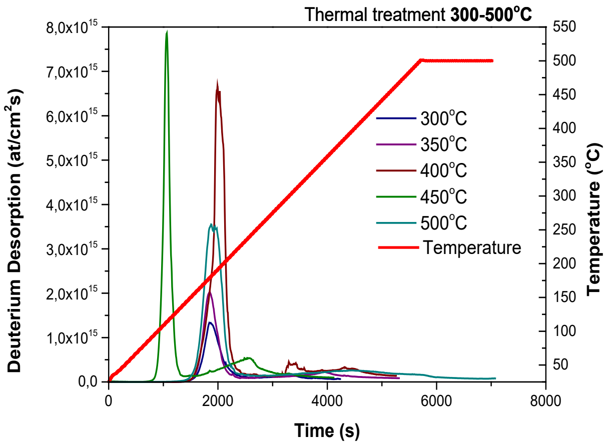
- **Production of Be-based layers** – for systematic parametric studies
  - ✓ **Be+O+D (5, 10 and 20 at.%) – 16 samples – and Be+D (5-10 at.%) at 4 different temperatures - 44 samples**
  - ✓ **Be with D or H (~20 at.%), 5 µm thick – 110 samples in total - thermally treated at different temperatures**
  - ✓ Clear differences in the D release patterns observed with the annealing temperature!



Thermal treatment scheme for Be-D and Be-H



D release from Be-D samples (on Si)



D release from Be-D samples (on W)

Deliverable: *PWIE.SPB.4.T002.D002, D007, D008, D009*
Status: *completed*
Facilities: 5 + 1 days accelerator (RBI, VTT)

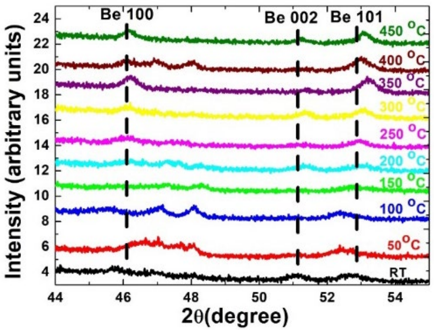
Human Resources: 9 *PM* + 2 *PM* + 2 *PM*
Involved RU: *IAP, RBI, VTT*
Linked WP or TSVV: *SP X.2.T002, SP B.1.T002.D001-D003*

SPB.4: Production of Be- and W-based reference coatings

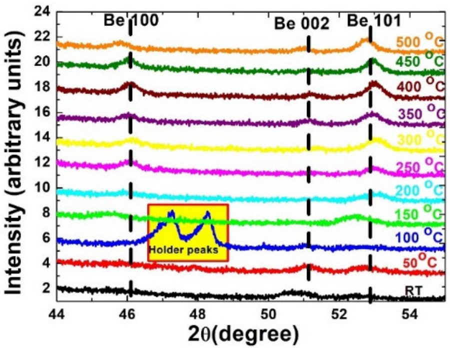
Main research areas in 2022:

- **Production of Be-based layers** – for systematic parametric studies
  - ✓ **Be with D or H (~20 at.%), 5 μm thick – 110 samples in total - thermally treated at different temperatures**

Be+D



Be+H

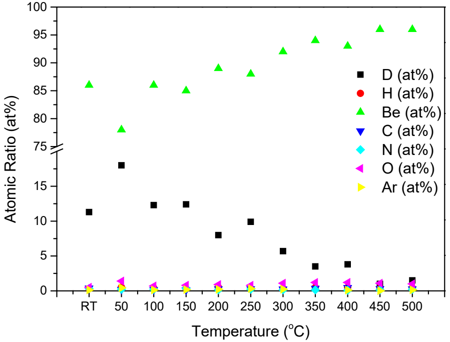


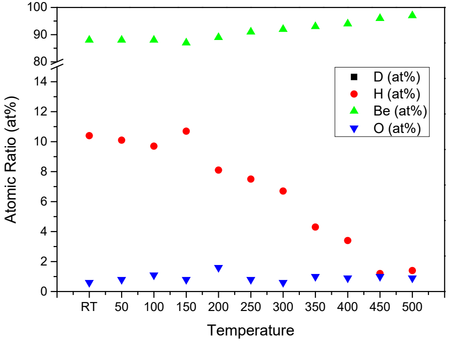
Top: XRD results indicate

- Shift of the (1 0 1) peak at > 300°C due to tensile stress
- Grain size to decrease from 52 to 18 nm with the annealing temp.

Bottom: TOF-ERDA results show

- D or H ratio to drop systematically with the annealing temperature
- Oxygen below 1 at. %, H levels stay at ~10 at.% at RT
- No other impurities → high quality of the coatings





C. Porosnicu et al. (IAP), I. Bogdanovic Radovic (RBI), A. Hakola (VTT)

Deliverable: *PWIE.SPB.4.T002.D002, D007, D008, D009*
Status: *completed*
Facilities: 5 + 1 days accelerator (RBI, VTT)

Human Resources: 9 *PM + 2 PM + 2 PM*
Involved RU: *IAP, RBI, VTT*
Linked WP or TSVV: *SP X.2.T002, SP B.1.T002.D001-D003*

SPB.4: Production of Be- and W-based reference coatings

Main research areas in 2022:

- **Production of Be-based layers** – for systematic parametric studies
  - ✓ **Be with D or H (~20 at.%), 5 μm thick – 110 samples in total - thermally treated at different temperatures**

Top: XRD results indicate

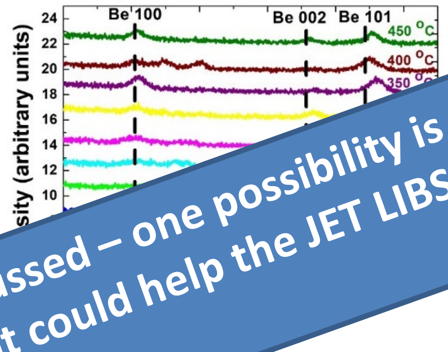
- Shift of the (1 0 1) peak at > 300°C due to ten
- Grain size to decrease from 52 to 18

Bottom: TOF-ERDA r

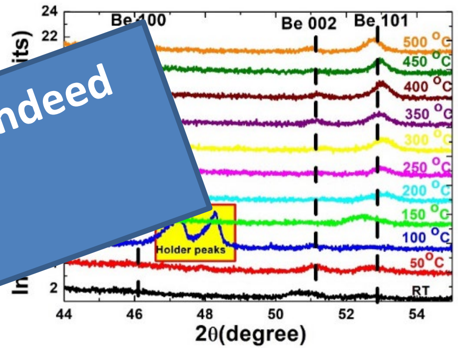
- D or H ratio to drop … temperature
- Oxygen below 1 at. … % at RT
- No other impurities … of the coatings

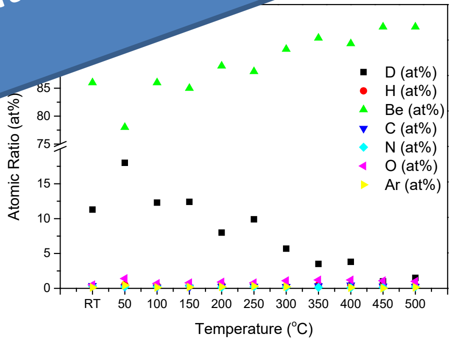
Plans for 2023: Details to be discussed – one possibility is indeed to produce relevant Be layers that could help the JET LIBS commissioning project

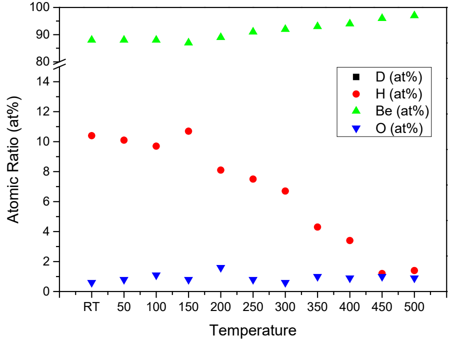
Be+D



Be+H







C. Porosnicu et al. (IAP), I. Bogdanovic Radovic (RBI), A. Hakola (VTT)

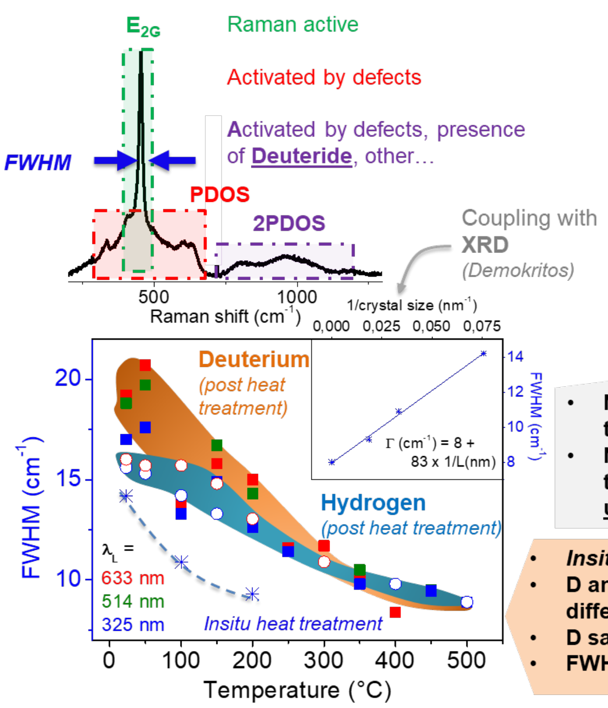
Deliverable: *PWIE.SPB.4.T002.D002, D007, D008, D009*
Status: *completed*
Facilities: 5 + 1 days accelerator (RBI, VTT)

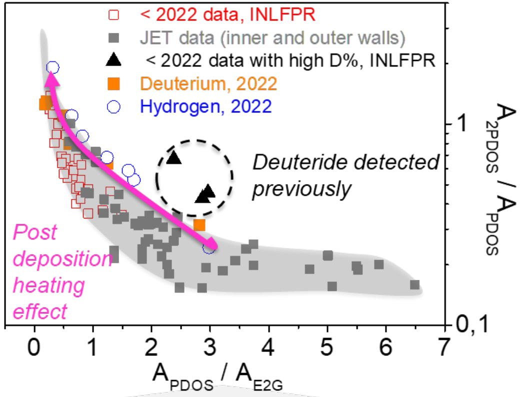
Human Resources: 9 *PM + 2 PM + 2 PM*
Involved RU: *IAP, RBI, VTT*
Linked WP or TSVV: *SP X.2.T002, SP B.1.T002.D001-D003*

SPB.4: Raman studies of Be+H/Be+D samples

- The produced Be+D and Be+H films analyzed using Raman spectroscopy
- The results for the FWHM of the main Raman peak indicate
  - ✓ **Less defects by heating**
  - ✓ Clear difference in H and D samples at T < 150°C – samples with D more defective
- The relevant A_{PDOS}/A_{E2G} and A_{2PDOS}/A_{PDOS} parameters evolve with heating
  - ✓ No correlation with grain size as obtained by XRD
  - ✓ **Defects most likely in crystallites in the bulk**
  - ✓ **No clear detection** of BeD or BeH formation!?

Typical Raman spectrum:





- **New post heated samples behaves roughly as the old ones**
- **No clear detection of deuterides nor hydrides in the 2PDOS spectral region→ has to be understood**

- ***Insitu* and post heat treatment: different effects**
- **D and H samples with high D amount could be differenciated by Raman FWHM below 150°C**
- **D samples (T<150°C) more defective than H samples**
- **FWHM related to crystal size:** better correlation on going

Deliverable: *PWIE.SPB.4.T002.D003*
Status: *completed*
Facilities: None

Human Resources: 2 *PM*
Involved RU: *CEA*
Linked WP or TSVV: *None*

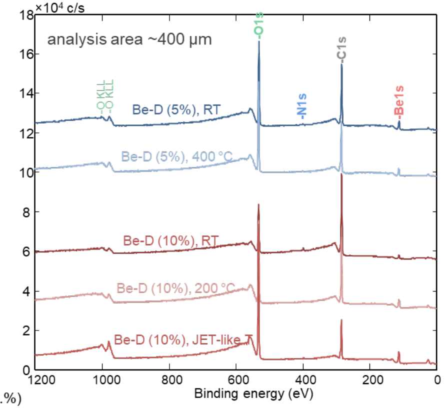
C. Pardanaud et al. (CEA)

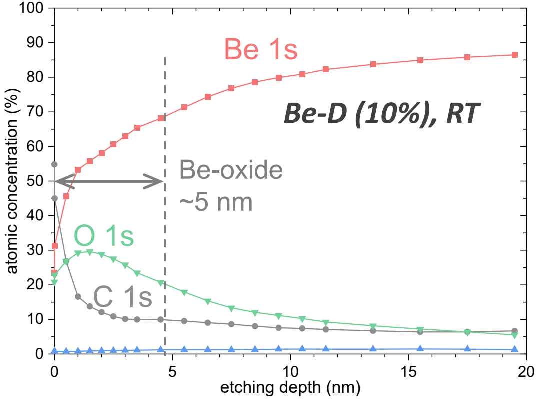
SPB.4: Characterization of Be+D samples produced at different temperatures – examples of results

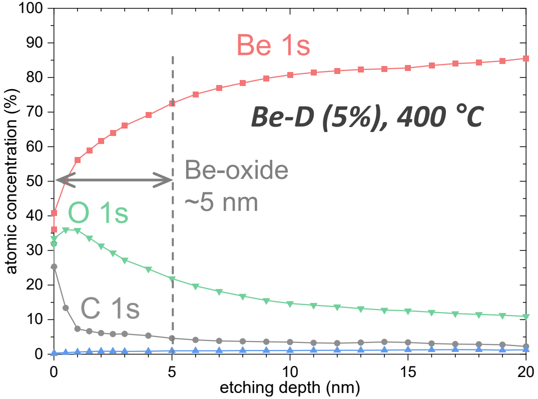
Main research results in 2022:

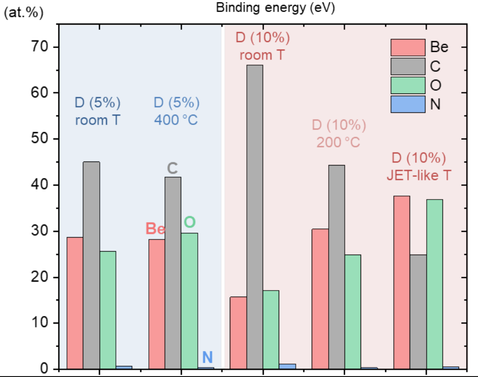
- Characterization of the Be+D and Be+O+D (5-10 at.%) samples produced at 4 different temperatures – SEM, EDX, XRD, XPS, **TDS, RBS, NRA**
  - ✓ The surface **depth profiles for the light elements, however, are quite similar**
  - ✓ Increased surface temperature seems also lead to **increased O and Be concentrations** on the surface (but only observed for one series of samples)
  - ✓ Generally: BeO thickness ~5 nm, N present as nitrides in subsurface region (1-2 at.%), C as contamination and as carbide in subsurface region (~3-6 at.%)

XPS survey spectra (C, O, Be, N)









Deliverable: *PWIE.SPB.4.T002.D005, D006; PWIE.SPB.3.T002.D007*
Status: *completed*
Facilities: 3 + 3 days accelerator (IST, NCSRD)

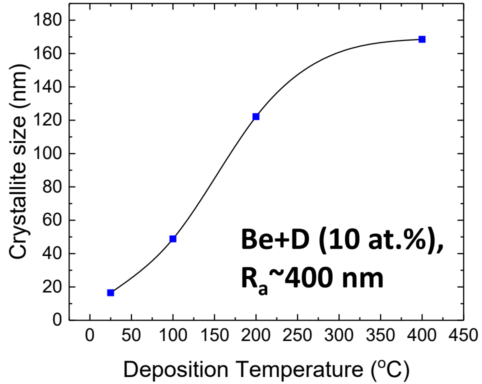
Human Resources: 2 PM + 4 PM + 3 PM
Involved RU: *IST, JSI, NCSRD*
Linked WP or TSVV: *None*

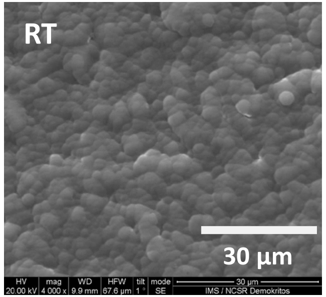
E. Alves (IST), M. Panjan et al. (JSI), K. Mergia (NCSRD)

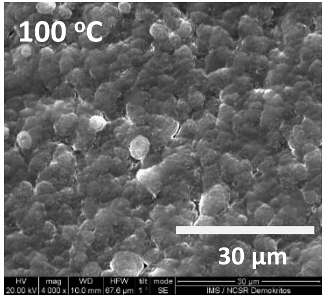
SPB.4: Characterization of Be+D samples produced at different temperatures – examples of results

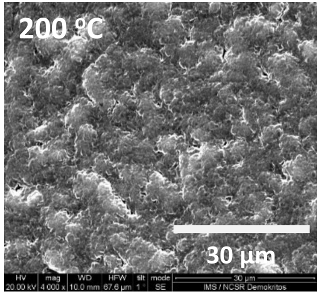
Main research results in 2022:

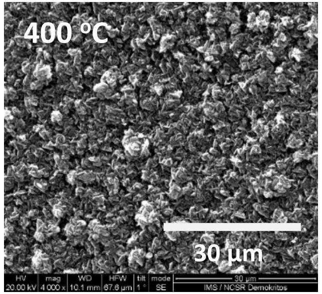
- Characterization of the Be+D and Be+O+D (5-10 at.%) samples produced at 4 different temperatures – SEM, EDX, XRD, XPS, **TDS, RBS, NRA**
  - ✓ Increasing deposition temperature **increases both the roughness and the crystallite size** but decreases the lattice constant
  - ✓ Increasing deposition temperature also **changes the surface texture** and makes it more enhanced towards [100] and [101] directions
  - ✓ **Decrease of D content** as the deposition temperature increases



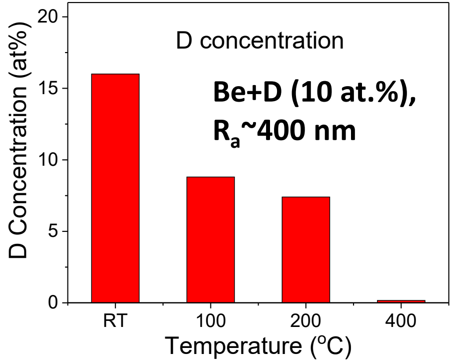








Be+D (10 at.%), R_a~400 nm



Deliverable: *PWIE.SPB.4.T002.D005, D006; PWIE.SPB.3.T002.D007*
Status: *completed*
Facilities: 3 + 3 days accelerator (IST, NCSRD)

Human Resources: 2 PM + 4 PM + 3 PM
Involved RU: *IST, JSI, NCSRD*
Linked WP or TSVV: *None*

E. Alves (IST), M. Panjan et al. (JSI), K. Mergia (NCSRD)

SP B.5 – Production of metallic dust in toroidal devices –plans for 2023

SPB.5: Overview of activities

- SP B.5 aims **assessing the amount of dust that will be produced in toroidal devices** during their normal and off-normal experimental operations
  - ✓ Consists of ongoing activities on the role of hypervelocity dust impacts on PFCs and characterization of laboratory-made W and Be dust – previously under SP B.1
  - ✓ New activities on **reviewing the present understanding of dust amounts, production, and characteristics** on AUG and WEST (MPG) as well as remobilization of dust on AUG and MAGNUM-PSI (VR)
- Details of the activities **to be defined in a separate meeting** – main points to be considered
  - ✓ Ensure that the dust applied in **laboratory experiments would be representative for fusion-reactor conditions**
  - ✓ Putting all the data available from present devices together to see **if extrapolations can be made for metallic dust generation in DEMO** – or if there are gaps that would call for new experimental activities in >2024