Erosion behavior of boron-based nanostructured materials exposed to fusion-relevant deuterium plasma

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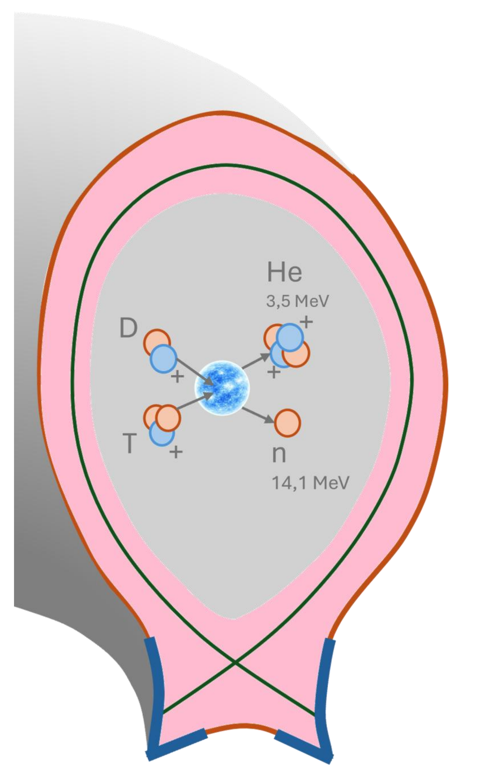
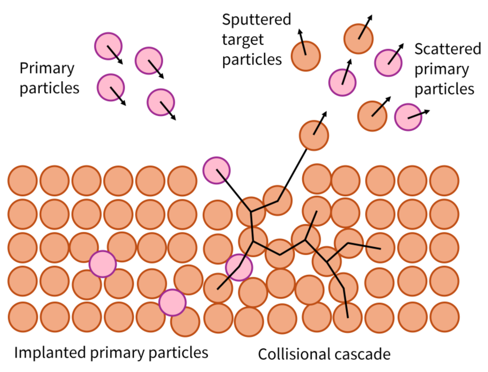
Introduction and Objectives



In **tokamaks**, fusion reactions happen in the core, where the high temperature plasma is confined. Particles **escape the confinement** and reach the **plasma facing components (PFCs)**, namely the **first-wall** and the **divertor**.

Plasma-Wall Interaction (PWI) phenomena represent one of the **main concerns** for future reactors.

- **PFCs erosion** → **transport** of eroded particles into the plasma → **degradation** of confinement **performances** → **redeposition** on PFCs → influence on **lifetime and operational reliability** of PFCs [1].
- **Tungsten (W)** → **main** PFCs material of **ITER**.
- **Boron (B)** → **boronization** to generate thin **B layer on W PFCs** to act as **oxygen** (O) **getter** and obtain **better confinement performances** [2].



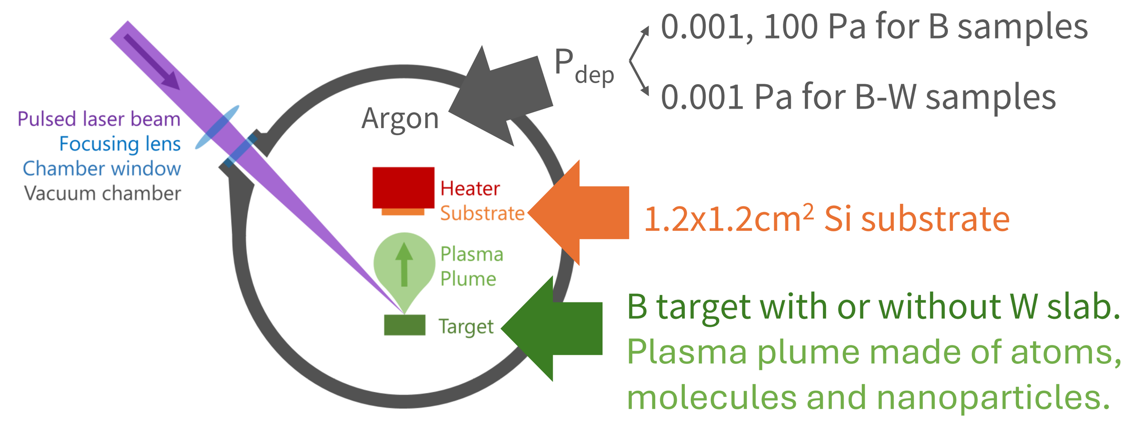
Understanding the behavior of **boron-containing materials** in **fusion-relevant conditions** is crucial to **correctly manage PWI in future reactors**.

Aims of this study:

- Produce materials **representing possible B and B-W redeposits** forming on tokamaks first wall.
- Investigate the impact of **first-wall relevant** deuterium (D) plasma **on nanostructured B and B-W** materials in the **GyM** linear plasma device [3].
- The **erosion phenomena**, **morphological evolution** and **W enrichment** are studied as a function of **particle energy and fluence**.

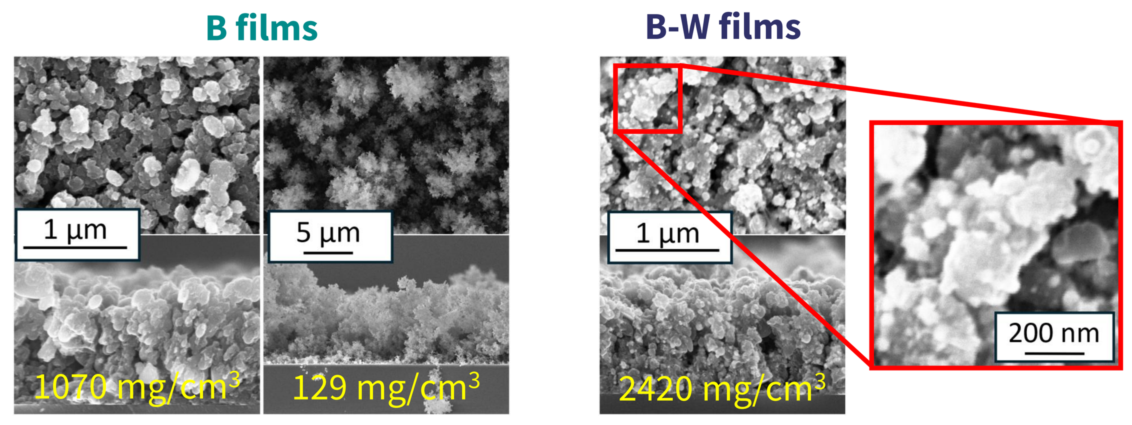
Materials Production and Exposure to Plasma

B and B-W films produced exploiting **femtosecond Pulsed Laser Deposition (fs-PLD)[4].**



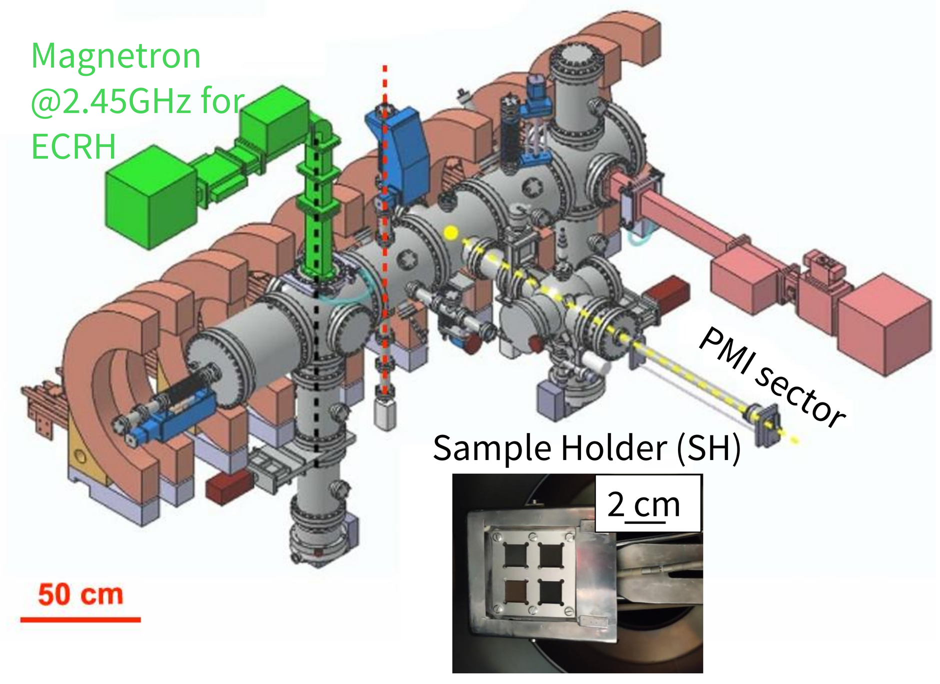
λ (nm)	T (fs)	E (mJ)	F (mJ/cm^2)	RR (Hz)
800	80	3.8	110	1000

- **Scanning Electron Microscopy** (**SEM**) and **Energy Dispersive X-ray Spectroscopy** (**EDXS**) → morphology, thickness (th) and composition.
- **EDDIE** software [5] → Mass thickness (σ) and density (ρ) thanks to the relation $\rho = \sigma \cdot th$.



- **B samples**: increasing P_{dep}, morphology evolves from **nanoparticles (NPs)** aggregated to **tree-like clusters** → **ρ ↓, th ↑**.
- **B-W films** → **W spherical NPs** decorated by B. W concentration ~**5%**.
- **B** and **B-W samples**: O concentration constant and **<10%.**

The samples were exposed to first-wall relevant D plasma in the **GyM linear plasma device**



Plasma parameters during exposure retrieved from **Langmuir probe**:

- $\Gamma = 3.85 \cdot 10^{20} \frac{ions}{m^2 s}$
- $T_e = 7.8\ eV$
- $n_e = 3 \cdot 10^{16} m^{-3}$
- $U_{plasma} = 23\ eV$
- **Negative bias** was applied to the sample holder to adjust **impinging ion energy** according to: $\mathbf{E_{ion}=q(|U_{bias}|+U_{plasma})}$.

Two series of experiments were performed, varying the **fluence (Φ)** and the energy of the **impinging ions (E_{ion})** alternatively:

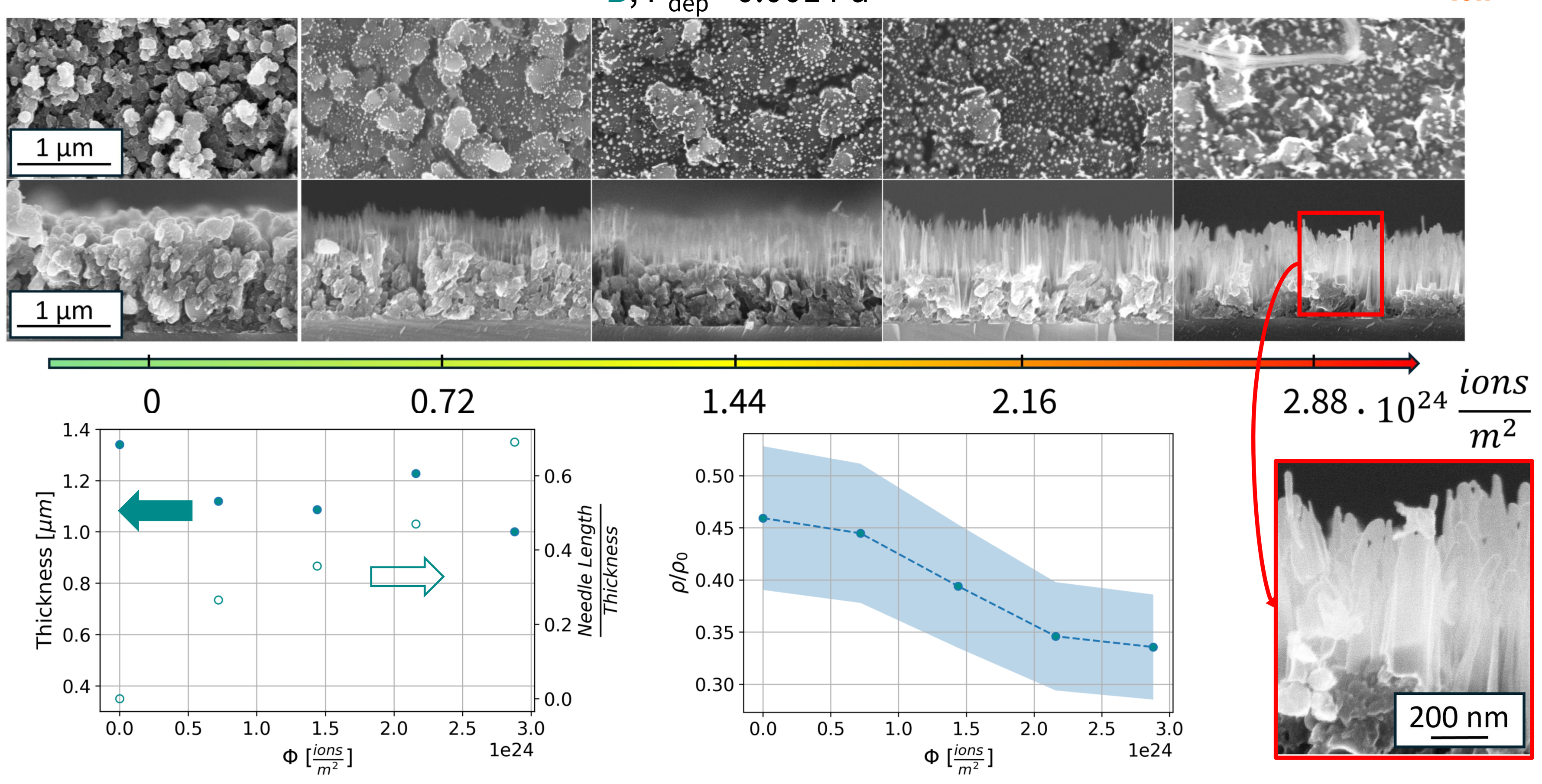
Fixed	Varying
$E_{ion} = 223\ eV$	$\Phi = 0.72 \div 2.88 \cdot 10^{24} \frac{ions}{m^2}$
$\Phi = 2.88 \cdot 10^{24} \frac{ions}{m^2}$	$E_{ion} = 43 \div 223\ eV$

- **Microbalance** measurements → **Eroded mass** → **Sputtering Yield (Y)** i.e. Number of sputtered atoms per impinging ion.
- Sputtering → overcome binding energy → Threshold energy (E_{th}).
- During exposures, $\mathbf{T_{SH}}$**~550-650K**.

Effects of Fluence on Morphology and Composition Evolution

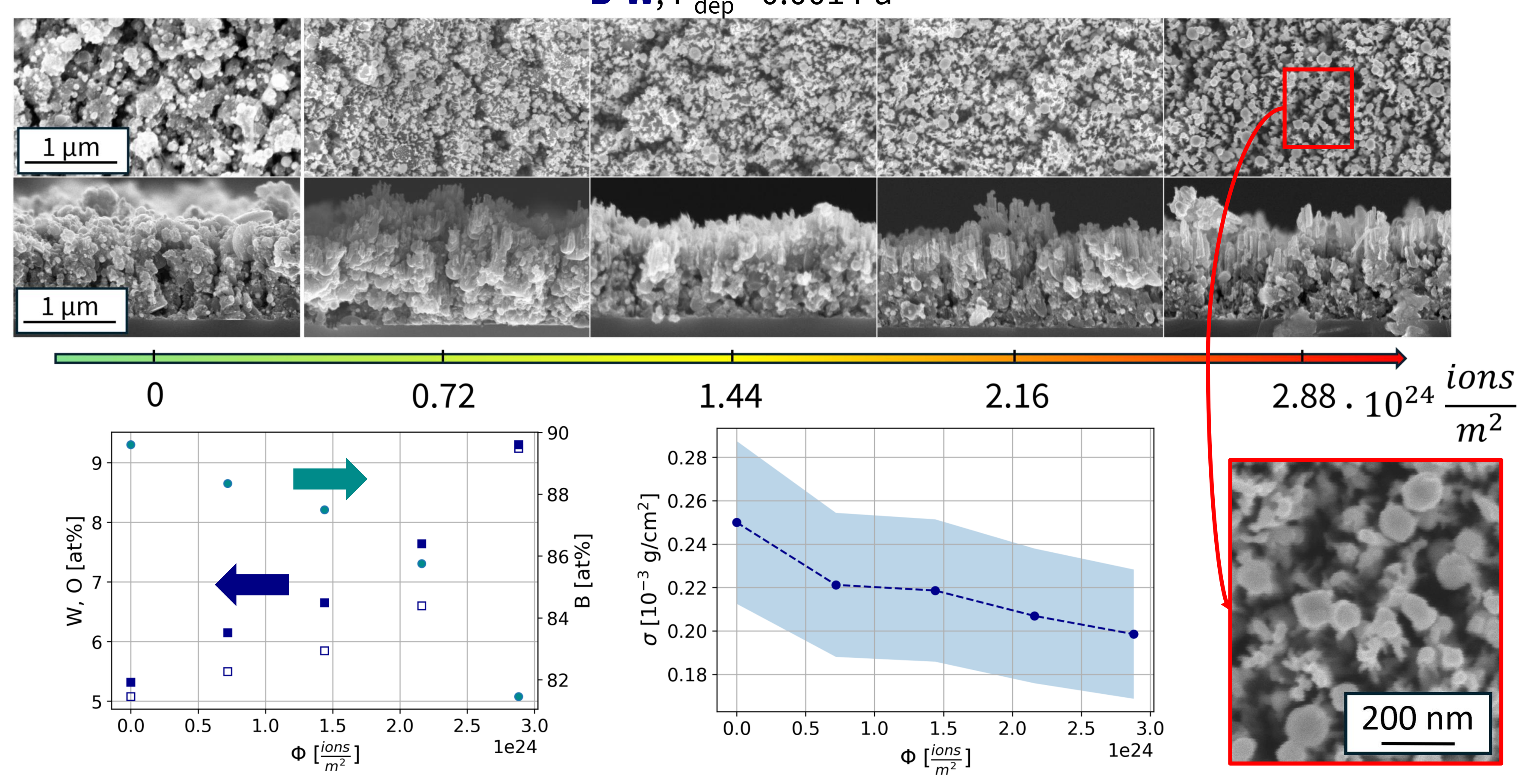
E_{ion}**=223 eV**

B, P_{dep}= 0.001 Pa



- **B erosion** → formation of thin and sparse **needle-like structures** parallel to the magnetic field.
- Their **length increases with fluence**, while the **thickness slightly decreases**.
- **Needles formation**: presence of **sputtering resistant localised phases** containing **B, O, C and D** and/or Mo atoms from SH mask [6] → **shielding of underlying B** and needle generation.
- th~const. → erosion leads to **density decrease** from **45%** to **34%** of the bulk β-R boron one (2330 mg/cm³).

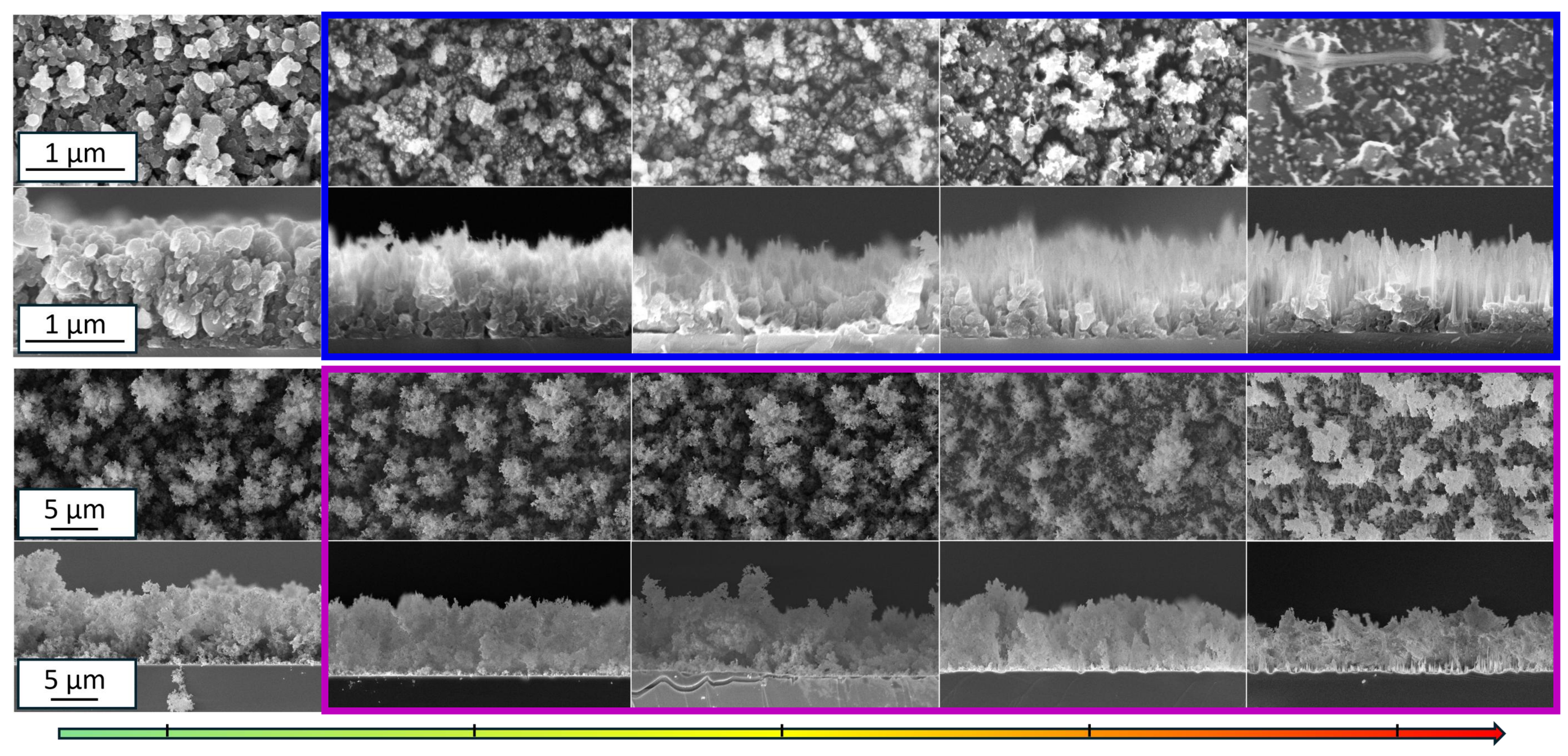
B-W, P_{dep}= 0.001 Pa



- **Spherical W NPs** still present after exposure ($\mathbf{E_{th,D\to W}}$**~**$\mathbf{E_{ion}}$), they appear **more defined** and numerous, due to the **preferential sputtering of the surrounding B** (Y_W<<Y_B) → **W enrichment** up to 10%.
- Vertical structures **shorter and larger** compared to B samples.
- O increase may be due to **W oxidation** during cooling phase after exposure at **high temperatures** (**~650 K**).
- **Erosion** is highlighted by σ **decrease.**

Effects of Ion Energy on B Morphology and Sputtering Yield

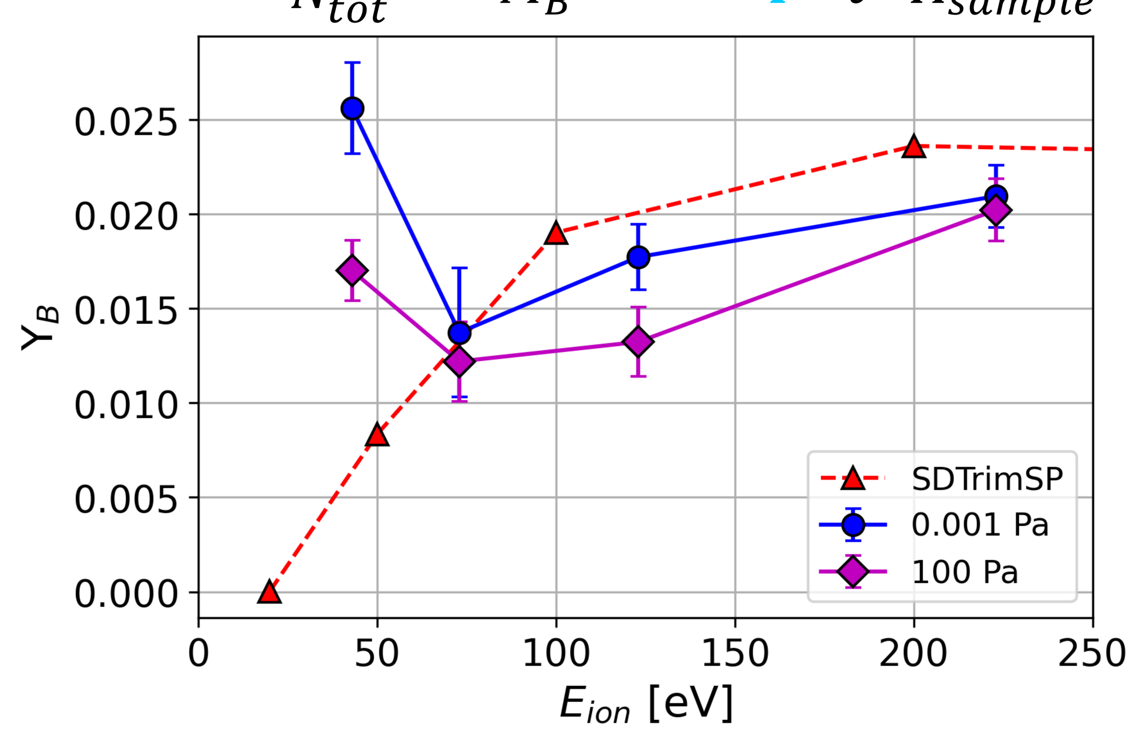
- **Increasing E_{ion}** results in needles with **larger lateral size and more sparse** distribution.
- th~const. → **ion penetration increases with E_{ion}** → **increase** in needle **relative length**.



- **Tree-like clusters** remain almost **unchanged** apart from possible **collapse** for high energies.

$\mathbf{\Phi = 2.88 \cdot 10^{24} \frac{ions}{m^2}}$

$$Y_B = \frac{N_B^S}{N_{tot}^{ion}} = \frac{\Delta m_B}{M_B} \cdot N_{av} \cdot \frac{1}{\Gamma \cdot t \cdot A_{sample}}$$



Effective sputtering yield evaluated thanks to **experimental mass loss** (Δm_B) and **particle flux** (Γ). Comparison with Binary Collision Approximation **SDTrimSP** code for bulk and flat B.

For E_{ion}≥70 eV:

- **Good agreement** (within 20%) with the model for **0.001 Pa** deposited → **low impact** of **morphological evolution** on sputtering, as needles are **thin and sparse**.
- **Lower sputtering for 100 Pa** deposited → **tree-like** morphology may enhance **re-deposition** of sputtered B due to geometrical trapping effects.

For E_{ion}=43eV (~$E_{th,D\to B}$= 23 eV):

- Y_B up to 5 times higher than model → possibly due to **ion assisted chemical erosion** at T_{SH}~550K [7].

Conclusions and Future Perspectives

- Generation of **first data** on the behavior of **nanostructured films under fusion-relevant plasma exposure**.
- Boron erosion leads to the **formation of needle-like structures**.
- For mixed B-W materials, **B preferential erosion causes W enrichment**.
- For $\mathbf{E_{ion}}$**≥70 eV, more compact** nanostructured materials show **sputtering similar to simulations**.

→

- Perform experiments at **varying exposure temperature and Eion≤43 eV** to further investigate the role of **ion assisted chemical sputtering for boron** in fusion-relevant environments.
- **Support results interpretation through PMI codes (e.g. ERO2.0)** to better understand B and W erosion.

[1] S. Brezinsek, et al. Nuclear Fusion 59, 096035 (2019)
[2] C. Martin, et al. Nuclear Materials and Energy 41, 101764 (2024)
[3] A. Uccello, et al. Frontiers in Physics 11, 1108175 (2023)
[4] D. Orecchia, et al. Small Structures 5, 2300560 (2024)
[5] A. Pazzaglia, et al., Materials Characterization 153, 92-102 (2019)
[6] D. Nishijima, et al., Nuclear Materials and Energy 18, 67-71 (2019)
[7] A. Annen and W. Jacob, Applied Physics Letters 71, 1326-1328 (1997)

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