SP B.1: PWI studies in GyM

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G. Alberti, L. Bana, D. Dellasega, M. Passoni

Beneficiary: ENEA

Linked Third Parties: ISTP-CNR Milano and Politecnico di Milano

Consiglio Nazionale delle Ricerche

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Acknowledgements

- GyM Team
  [A. Uccello, et al., Front. Phys. **11** (2023) 1108175]

- F. Mombelli, C. Tuccari, D. Vavassori

- M. Rasinski, J. Romazanov

- Eduard Grigore

PWI studies in GyM

PWIE.SPB.1.D002

- Role of **topography** in sputtering process of W by GyM He plasma
- Role of **morphology** in sputtering process of W by GyM He plasma

Focus of this talk

Linked PWIE-SPs

Sample production

PWIE-SP B.4
Reference coatings for ITER and DEMO

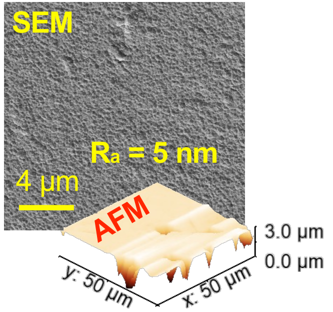
Modelling

PWIE-SP D.3.D002
ERO2.0 simulations of dynamic morphology studies in GyM. ERO2.0 simulations of the transport of sputtered material in GyM including the sample holder. (…)

Role of topography in sputtering process of W by GyM He plasma

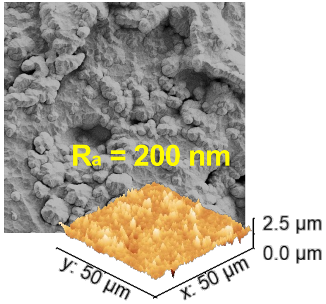
Samples from **SP B.4** ▶ *compact 500 nm-thick* W coatings deposited by **HiPIMS** on graphite and silicon substrates w/ different texturing and R_a + polished bulk W, as reference

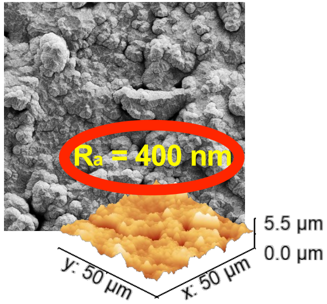
W film / polished Gr

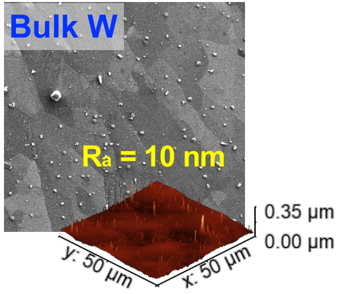


W films / **Gr w/ irregular surface**

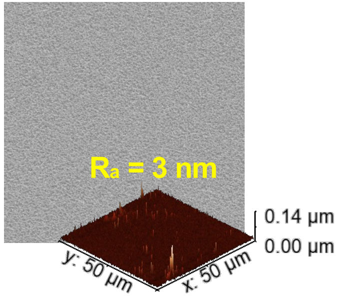
Plasma etching





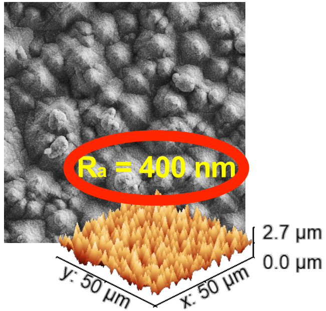


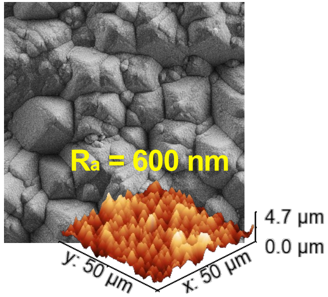
W film / flat Si

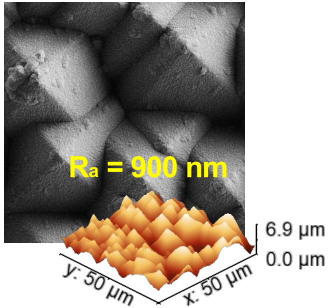


W films / **Si w/ pyramids**

Chemical etching







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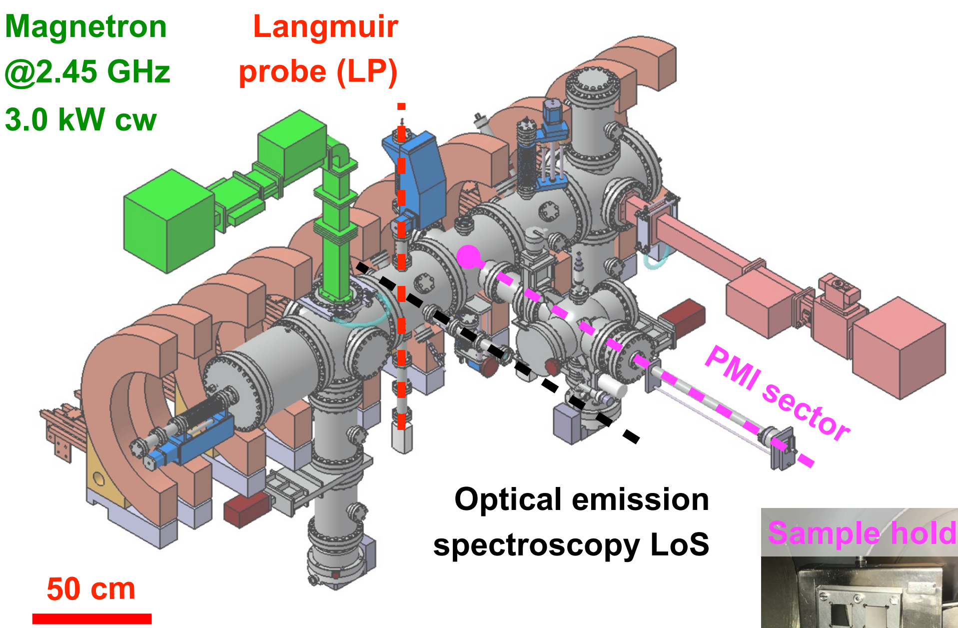
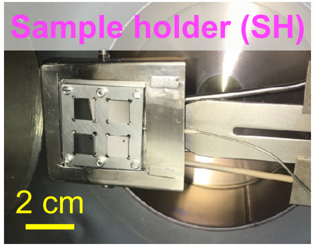
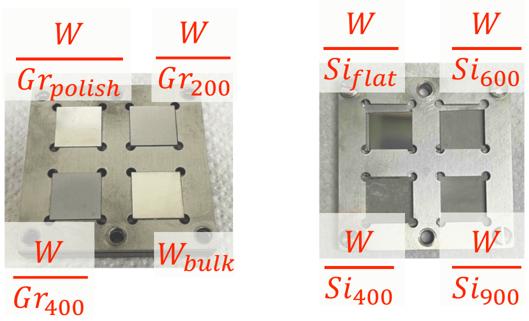




Data for benchmarking with
ERO2.0 modelling - **SP D.3**

[A. Uccello, et al., Front. Phys. **11** (2023) 1108175]



E_{He^+} [eV]		
30	✗	✓
80	✗	✓
150	✓	✓
200	✓	✓
250	✓	✓
350	✓	✓

6e20 He^+ m^{-2} · 2 hours → 4e24 He^+ m^{-2}

T_{SH} < 450 °C

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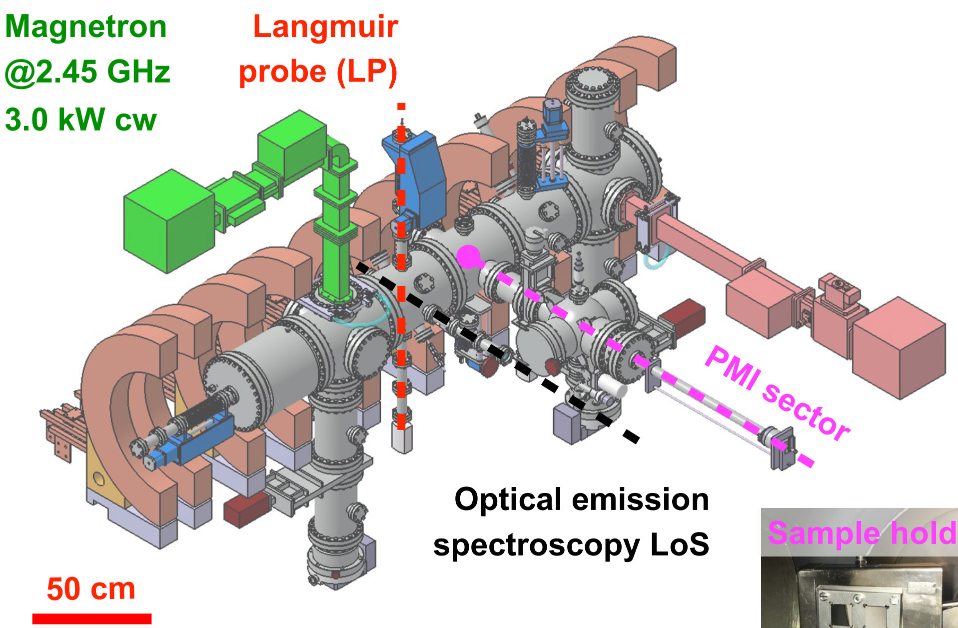

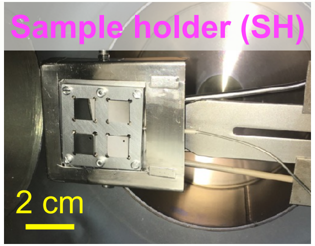

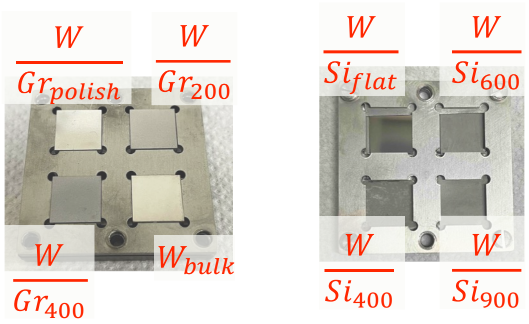

Data for benchmarking with
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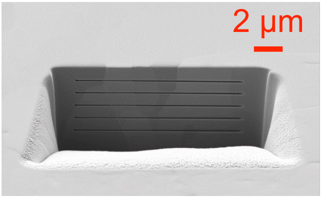
Before and after exposures

Net erosion

- Mass loss
- FIB marking, W_{bulk} →



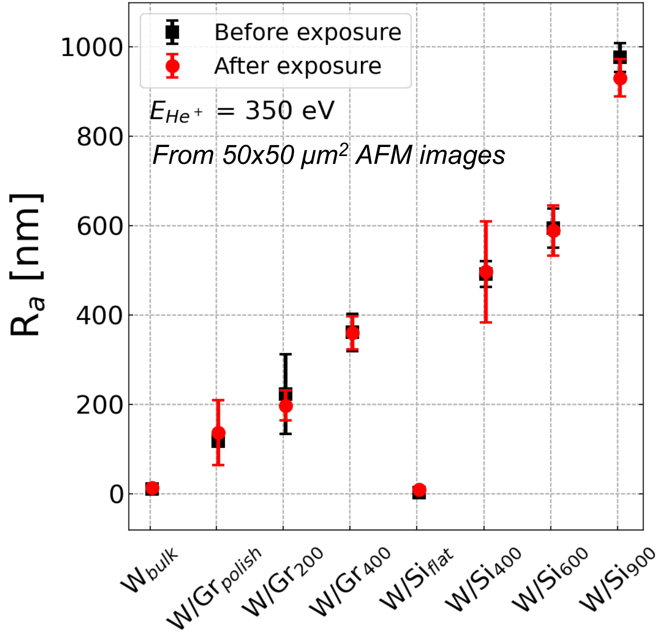
Topography → AFM

Morphology+composition → SEM+EDXS

[A. Uccello, et al., Front. Phys. **11** (2023) 1108175]

Topography and morphology changes

Samples topography did not significantly change after exposures

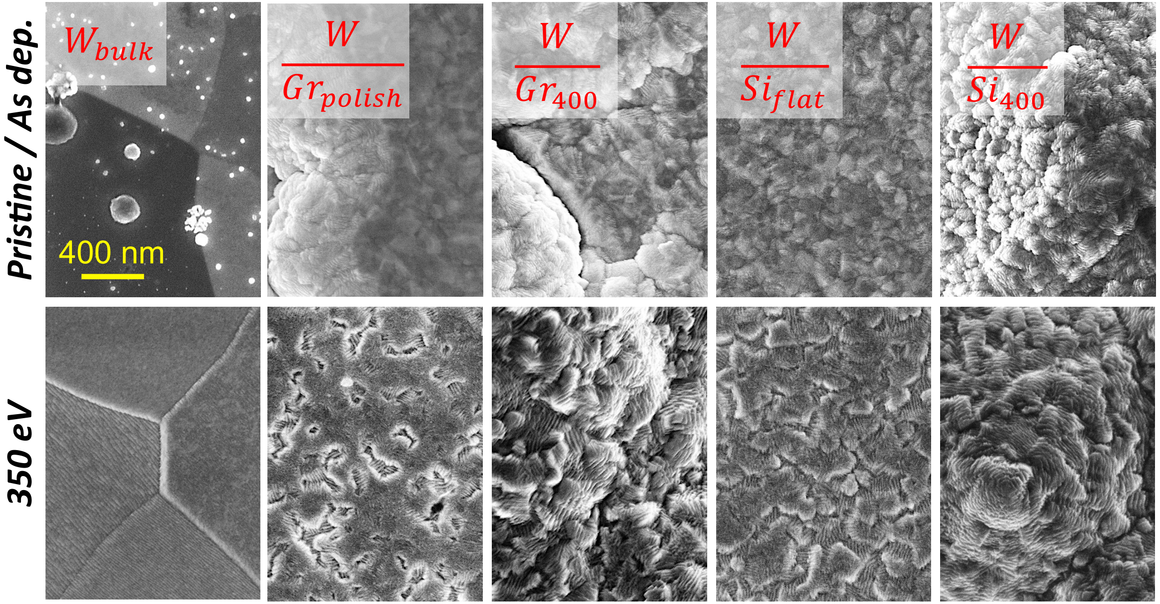


$E_{He^+} \geq 250\ eV$

→ W_{bulk} → nanostructures of [1]

→ W/Si & W/Gr: undulations w/ narrow interval

W films → preferential growth direction → [110]



Topography and morphology modifications at nm-scale

→ determination of quasi-static sputtering yield Y

→ single time step ERO2.0 simulations

[1] R. Sakamoto, et al., Nucl. Fusion **57** (2017) 016040

Topography and morphology changes

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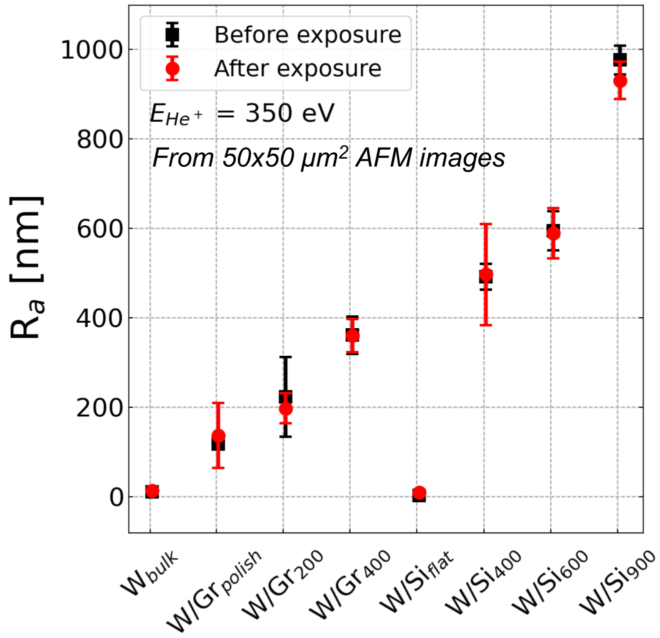

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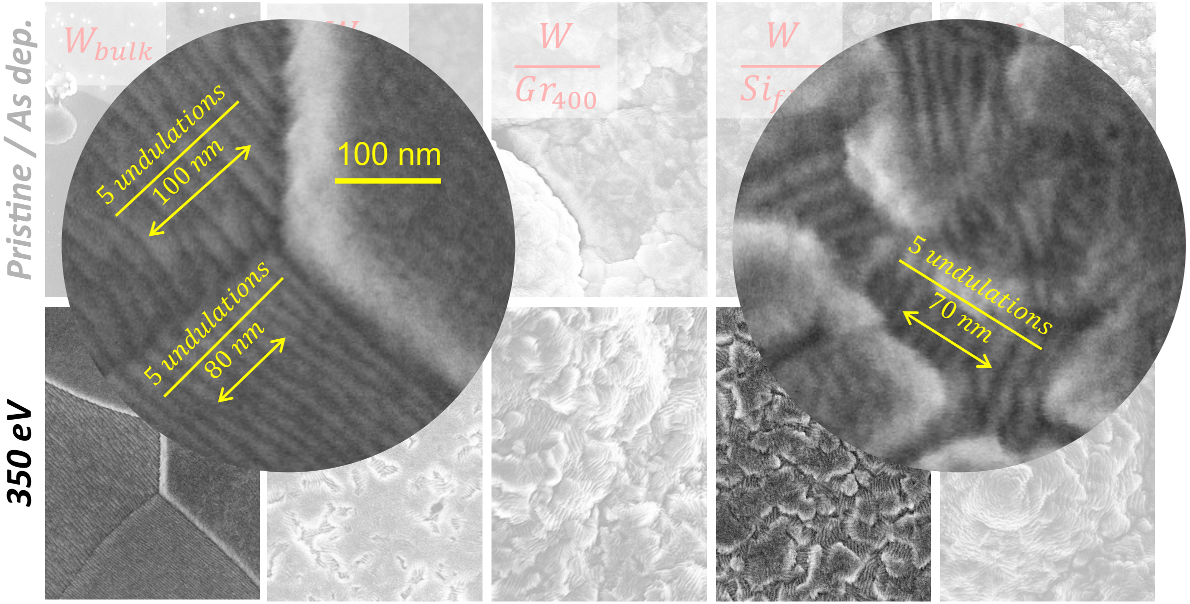

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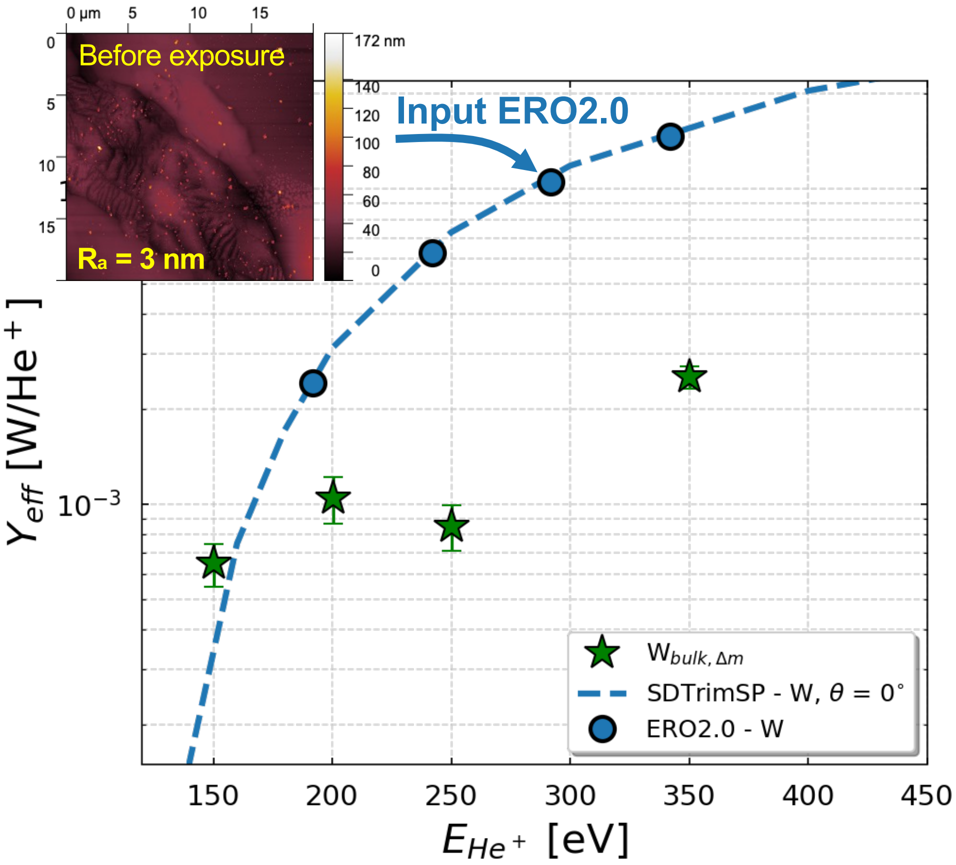
W_{bulk} Y_{eff} from mass loss data (Δm)



Energy and angular distributions of sputtered particles in ERO2.0 from SDTrimSP (amorphous W)

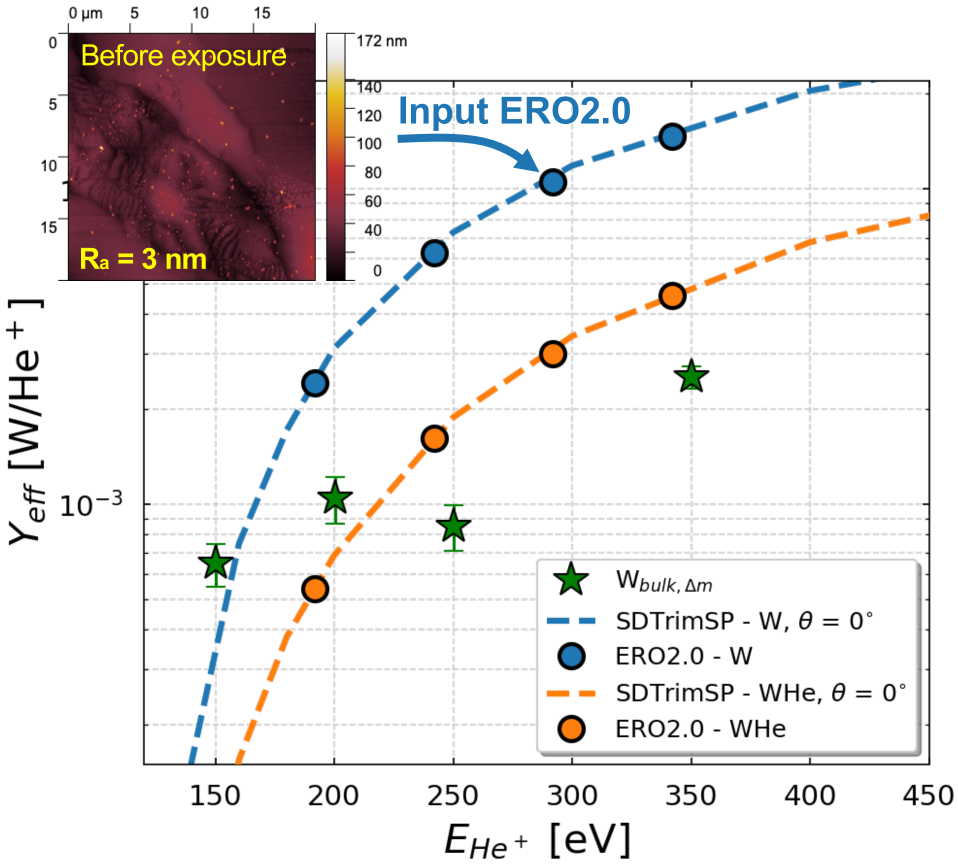
- R_a low → $Y_{eff,ERO} \simeq Y_{SDTrimSP}$

$Y_{eff,\Delta m}$ < $Y_{SDTrimSP}$ (& $Y_{eff,ERO}$) as observed in other LPDs

- He atoms on surface, from incoming flux (dynamic retention), shield W lattice atoms reducing their sputtering probability [2]

[2] R.P. Doerner, Scripta Materialia **143** (2018) 137-41

W_{bulk} Y_{eff} from mass loss data (Δm)



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as observed in other LPDs

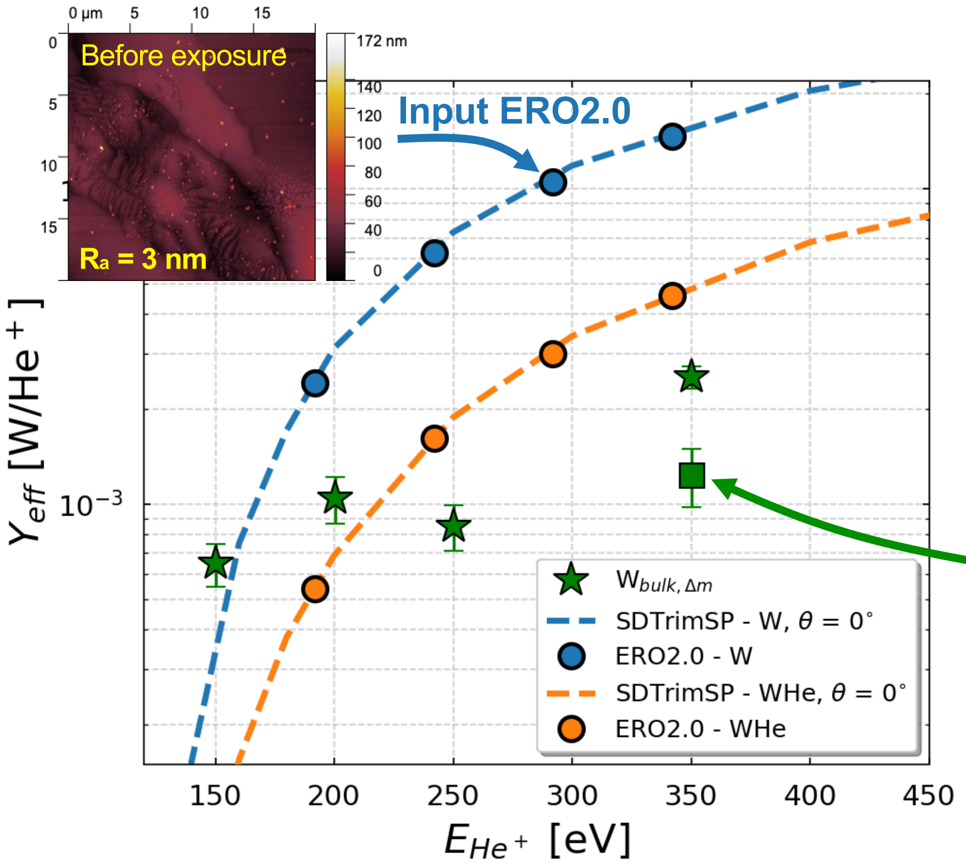
- He atoms on surface, from incoming flux (dynamic retention), shield W lattice atoms reducing their sputtering probability [2]

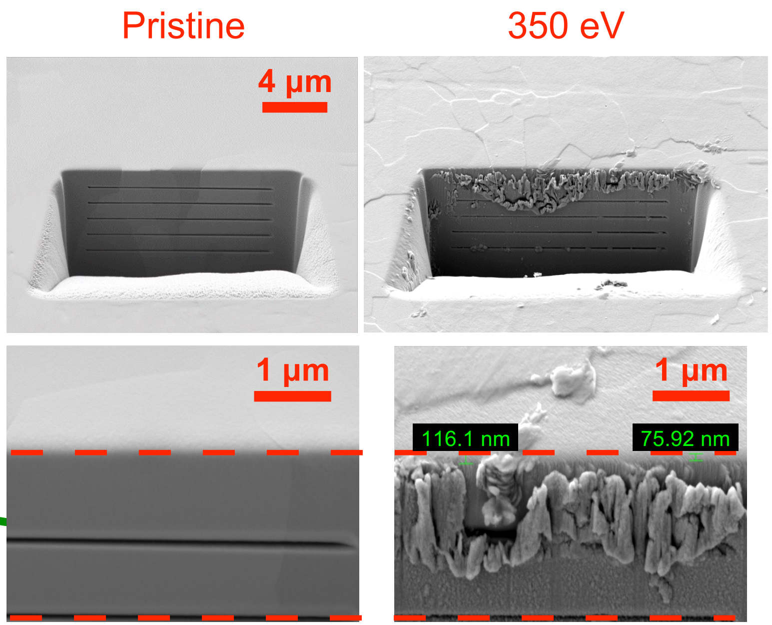
SDTrimSP for 50%W-50%He surface

- $E_{He^+} \geq 250\ eV$, **2·$Y_{eff,\Delta m}$ ≃ $Y_{SDTrimSP}$** (& **$Y_{eff,ERO}$**)

[2] R.P. Doerner, Scripta Materialia **143** (2018) 137-41

W_{bulk} global Y_{eff} from Δm and local Y_{eff} from thickness loss (Δs)



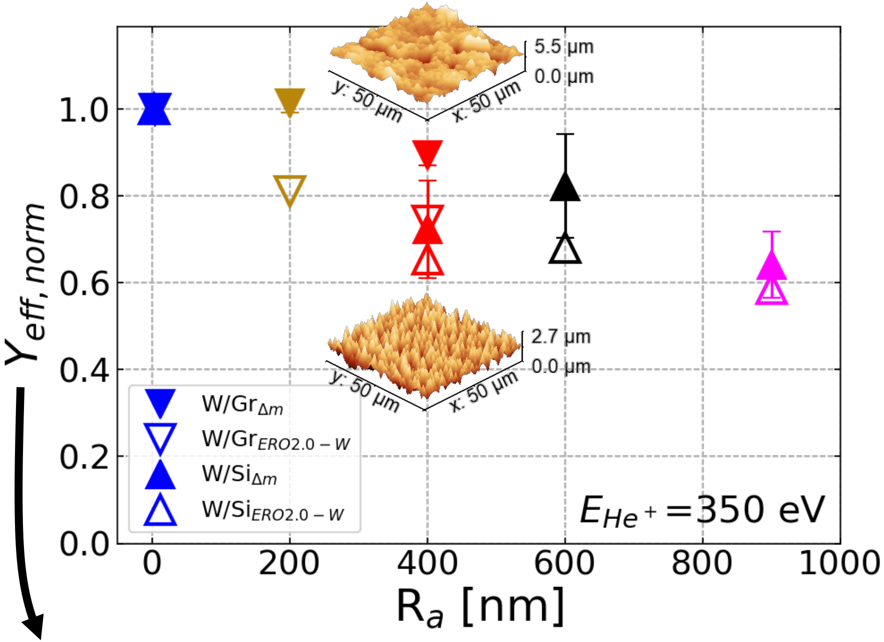


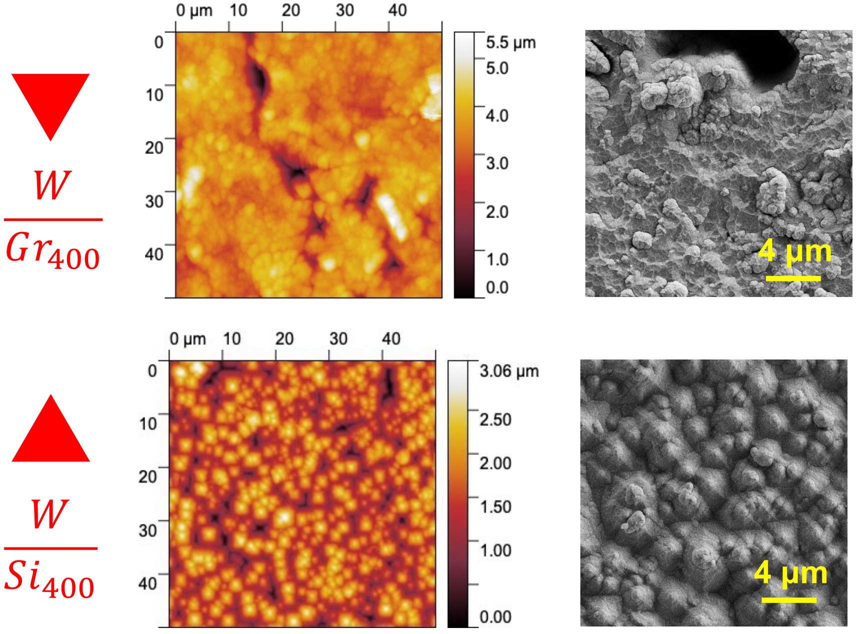
$Y_{eff,\Delta m} \neq Y_{eff,\Delta s}$ → crystal orientation dependence of sputtering [3]

[2] R.P. Doerner, Scripta Materialia **143** (2018) 137-41
[3] K. Schlueter, et al., Phys. Rev. Lett. **125** (2020) 225502

Unveil role of topography in sputtering of W by GyM He plasma

Average roughness, R_a ✗





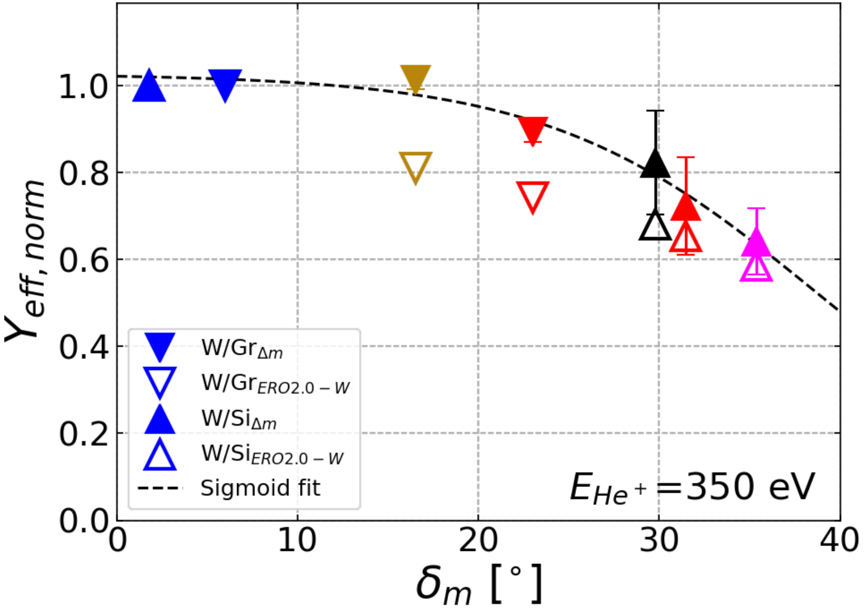
Same R_a, but different texturing

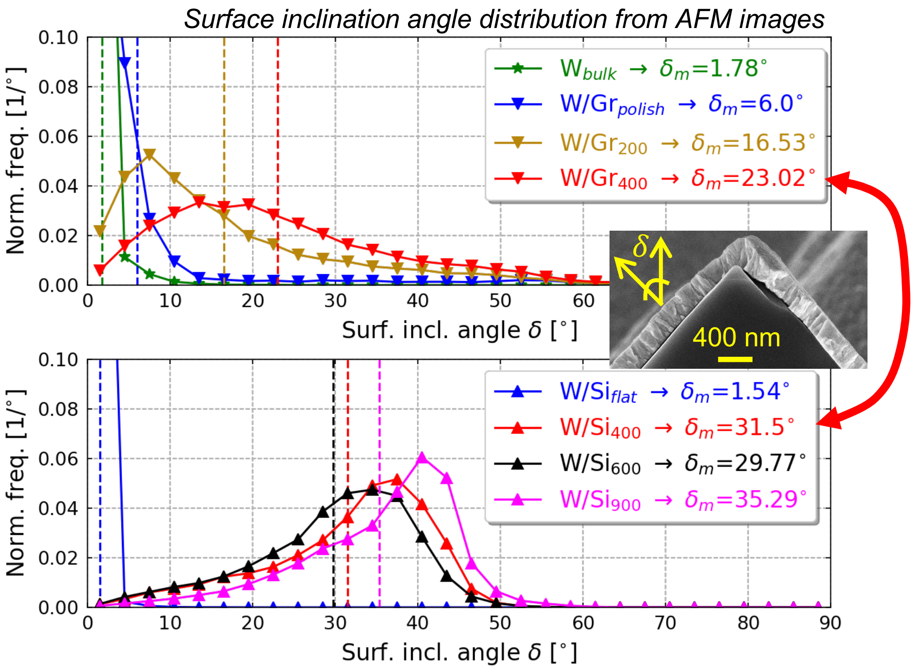
Y_{eff} normalized at $Y_{eff,\Delta m,W/Gr_{polish}}$ for W/Gr and at $Y_{eff,\Delta m,W/Si_{flat}}$ for W/Si

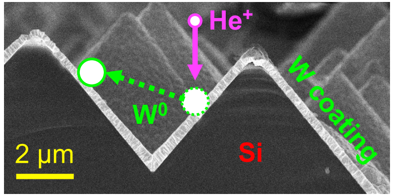
Need another **parameter** to represent surface topography

Unveil role of topography in sputtering of W by GyM He plasma

Mean surface inclination angle, δ_m [4] ✓







- Despite very different topography, $Y_{eff,norm}$ (δ_m) well fitted by sigmoid function
- **ERO2.0** → $Y_{eff,norm}(\delta_m)$ decreases due to increase of fraction of sputtered W atoms deposited at neighbouring surface

[4] C. Cupak, et al., Appl. Surf. Sci. **570** (2021) 151204

PWI studies in GyM

PWIE.SPB.1.D002

- Role of **topography** in sputtering process of W by GyM He plasma
- Role of **morphology** in sputtering process of W by GyM He plasma

Focus of this talk

Linked PWIE-SPs

Sample production

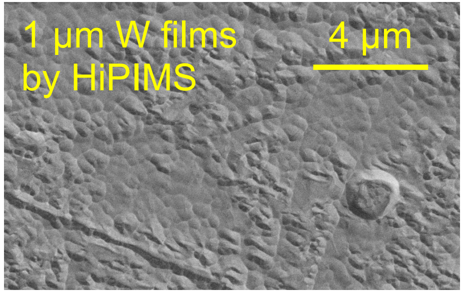
PWIE-SP B.4
Reference coatings for ITER and DEMO

Modelling

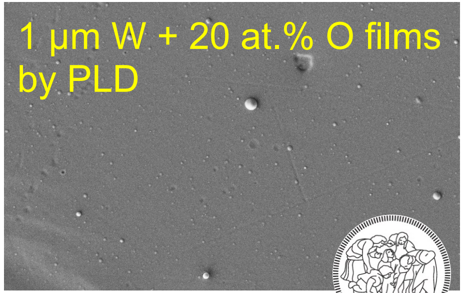
PWIE-SP D.3.D002
ERO2.0 simulations of dynamic morphology studies in GyM. ERO2.0 simulations of the transport of sputtered material in GyM including the sample holder. (…)

Role of morphology in sputtering process of W by GyM He plasma

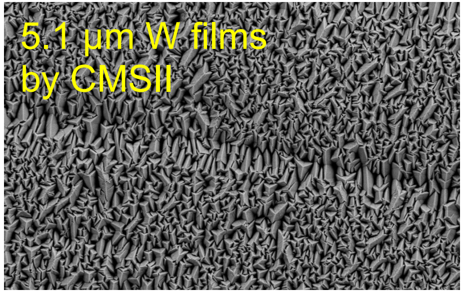
Samples from **SP B.4** ▶ *compact* nanocrystalline W and W+O coatings on **polished** Mo



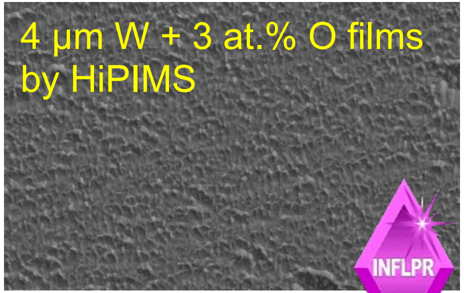
preferential growth direction → [110]



No preferential growth direction



preferential growth direction → [200]



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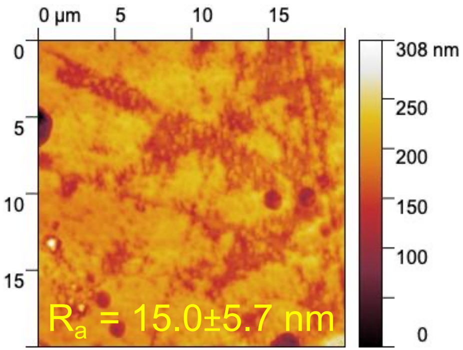

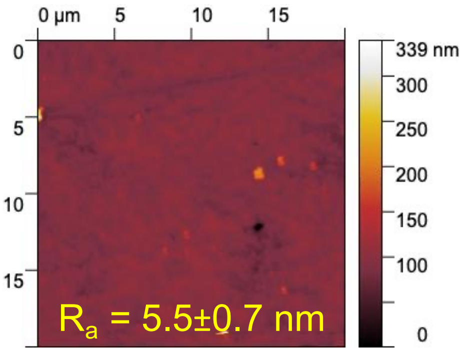

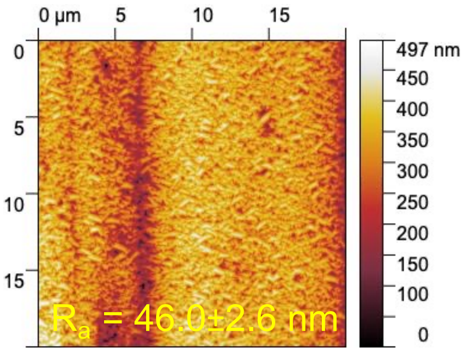

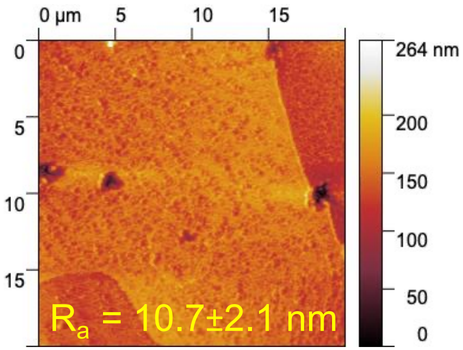

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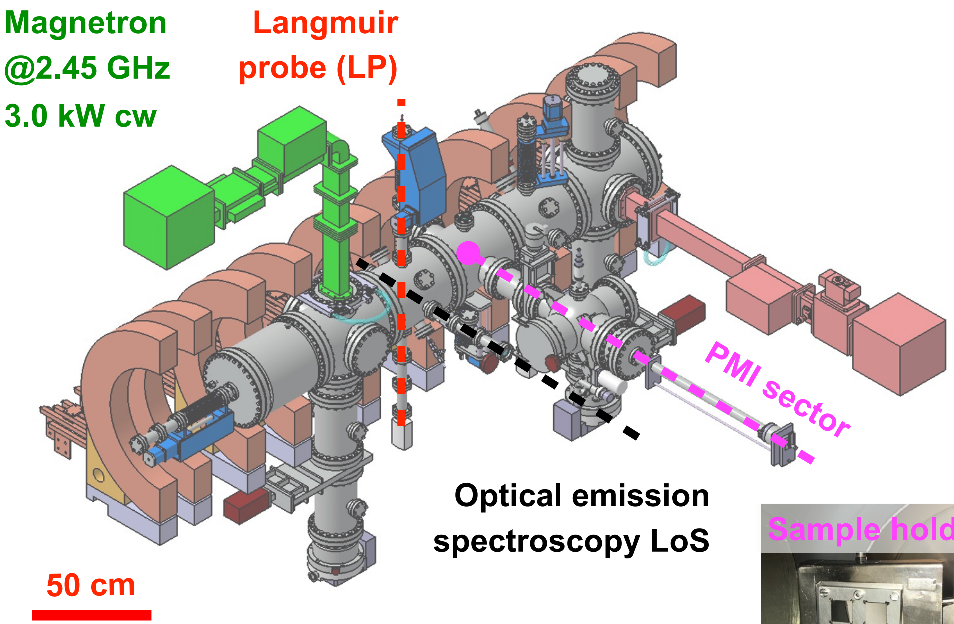
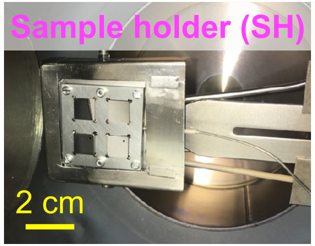
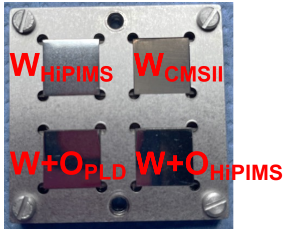




$T_{sample\text{-}holder}$ ~400-500 °C



Γ [$He^+m^{-2}s^{-1}$]	6.0e20	2.8e20
Φ [He^+m^{-2}]	4.3e24	3.6e24
E_{He^+} = 200 eV	✓	
E_{He^+} = 250eV	✓	✓
E_{He^+} = 300 eV	✓	
E_{He^+} = 350 eV	✓	

Before and after exposures

Net erosion → Mass loss

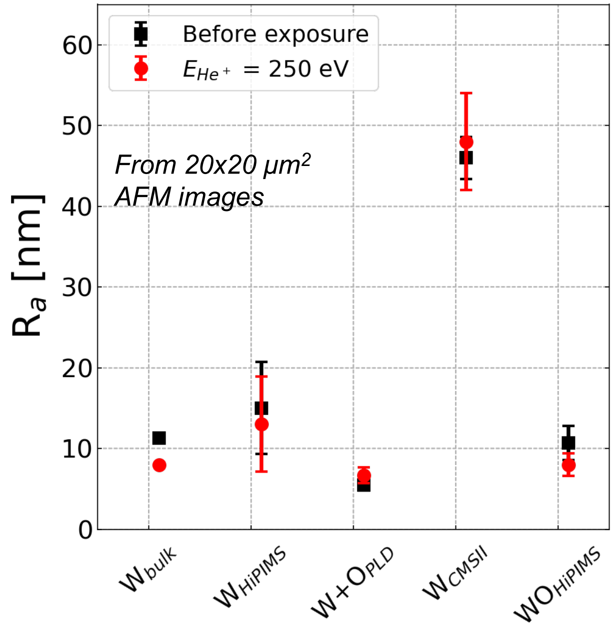
Topography → AFM

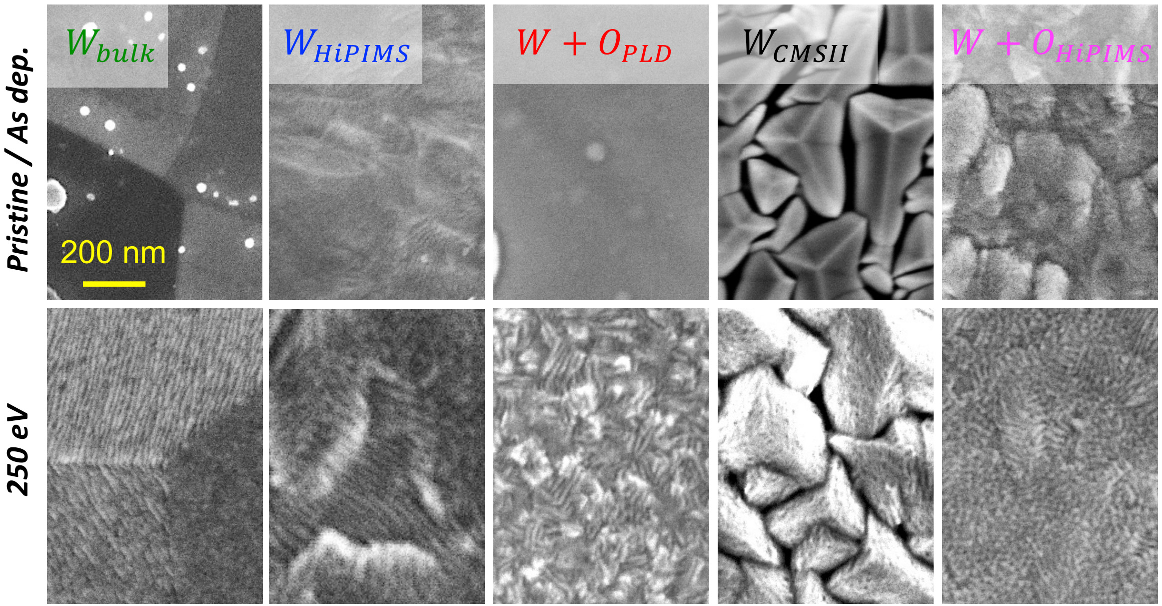
Morphology+composition → SEM+EDXS

Data for benchmarking with
ERO2.0 modelling - **SP D.3**

[A. Uccello, et al., Front. Phys. **11** (2023) 1108175]

Topography and morphology changes: $E_{He^+} = 250\ eV$





Samples topography did not change

EBSD, XRD

- $W+O_{PLD}$: grain formation ← T_{SH} ~400-500 °C enough for recrystallization [5]
- W_{HiPIMS}, $W+O_{PLD}$, $W+O_{HiPIMS}$: narrow undulations → {110} surface plane [1]
- W_{HiPIMS} & $W+O_{HiPIMS}$: jagged structure → high-index surface plane
- W_{CMSII}: top of the grains gentle smoothing

[1] R. Sakamoto, et al., Nucl. Fusion **57** (2017) 016040
[5] M. Sala, et al., Nucl. Mater. Energy **24** (2020) 100779

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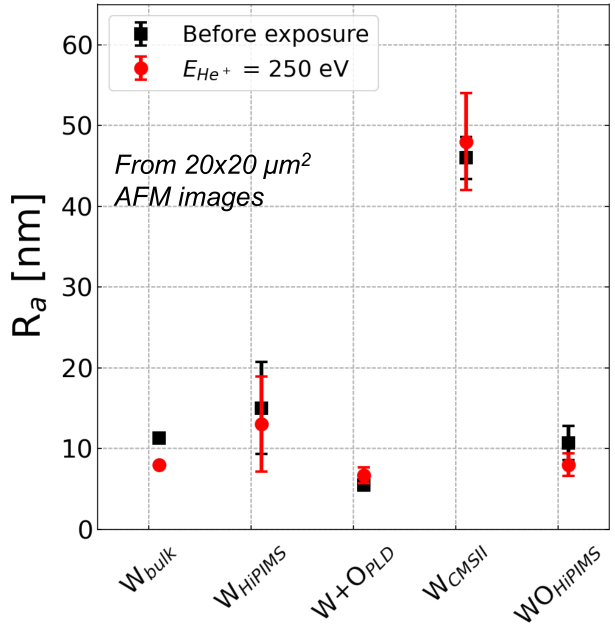

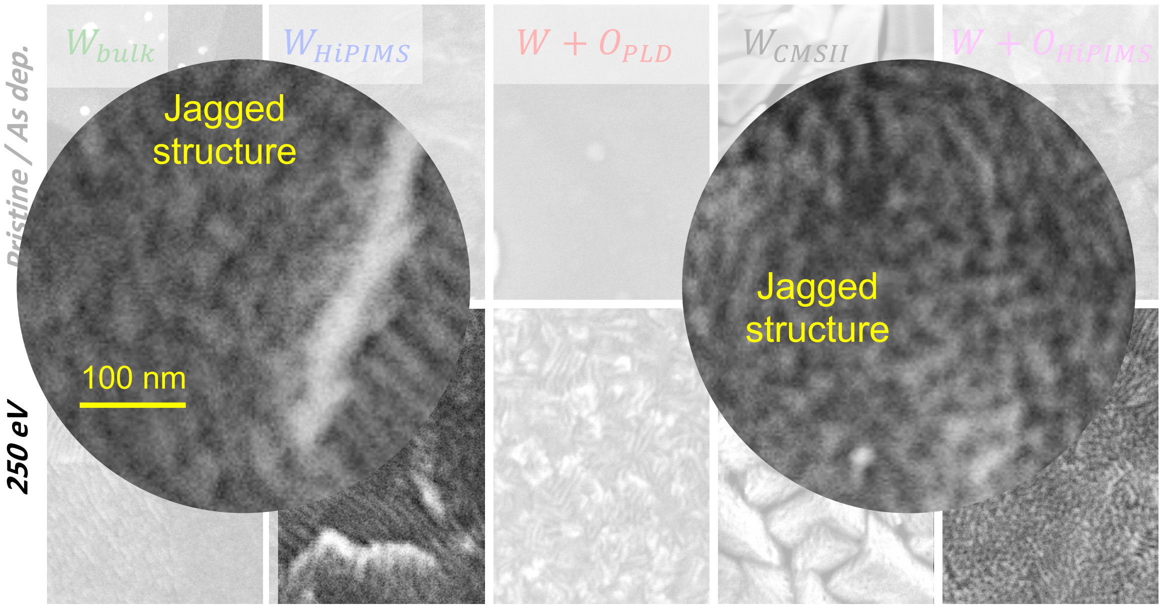

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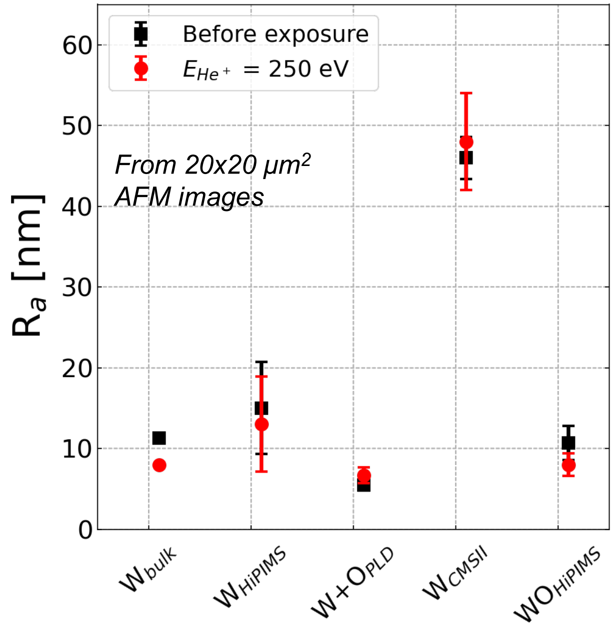

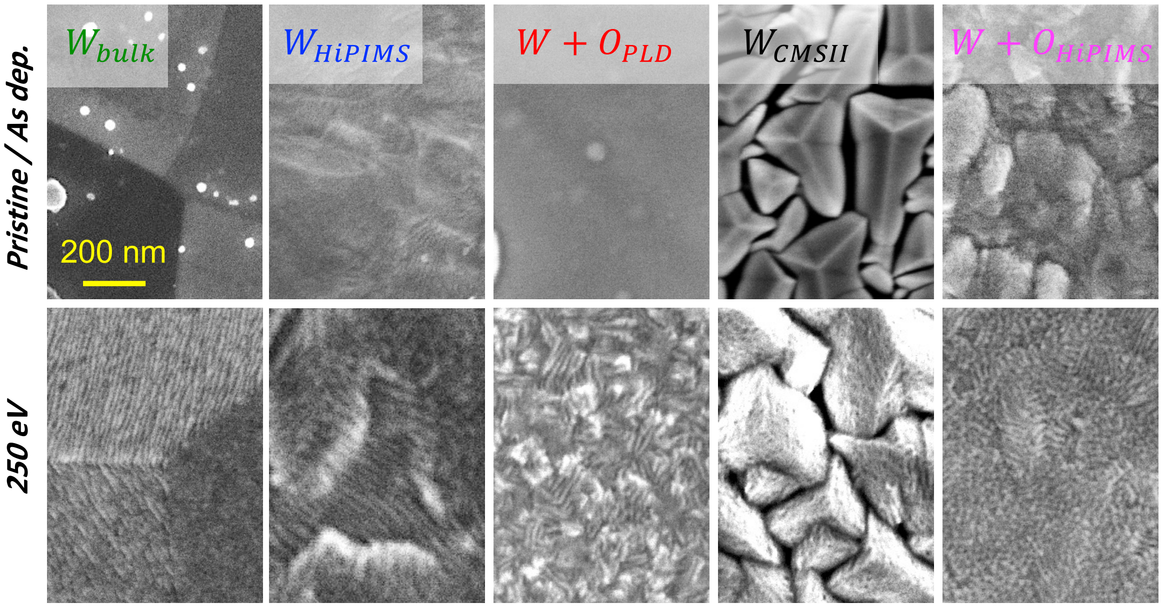

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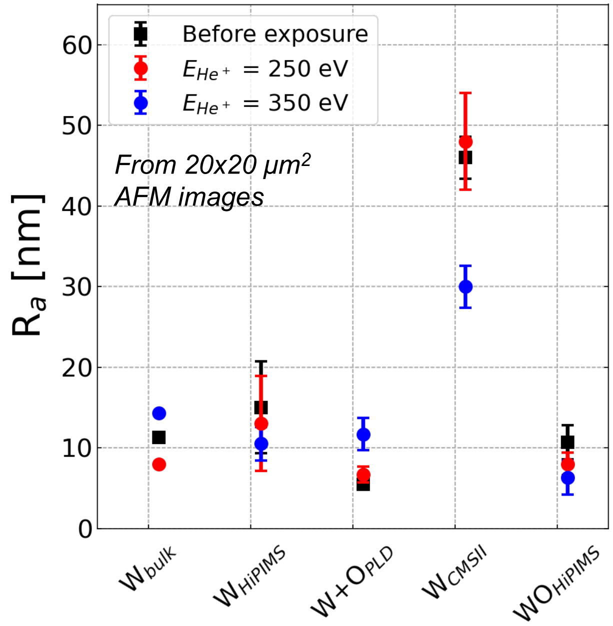
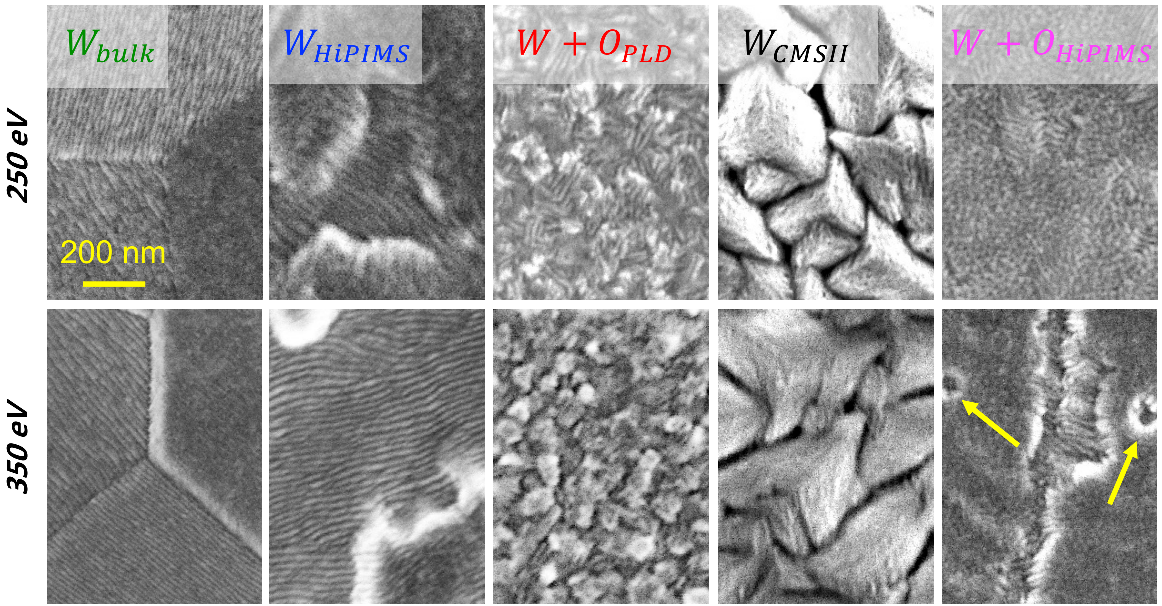
Topography and morphology changes: $E_{He^+} = 250\ eV$ vs $350\ eV$





AFM & SEM: smoothing of W_{CMSII}

EBSD, XRD

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- W_{HiPIMS} & $W+O_{HiPIMS}$: jagged structure → high-index surface plane
- $W+O_{HiPIMS}$: holes → aggregation of He bubbles

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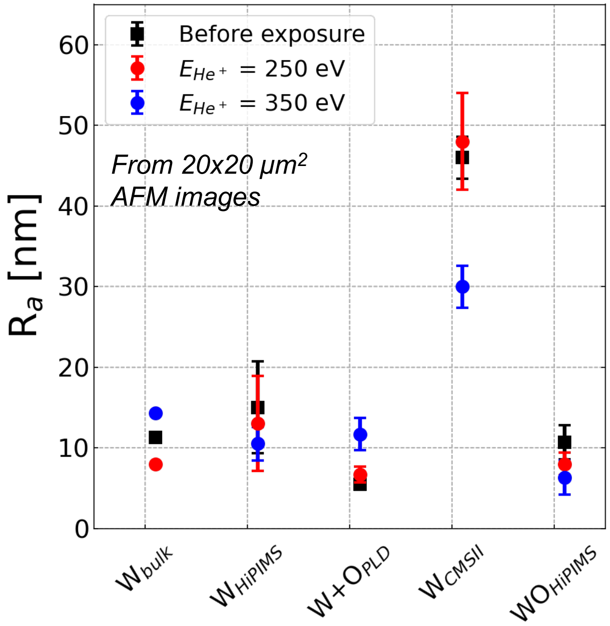
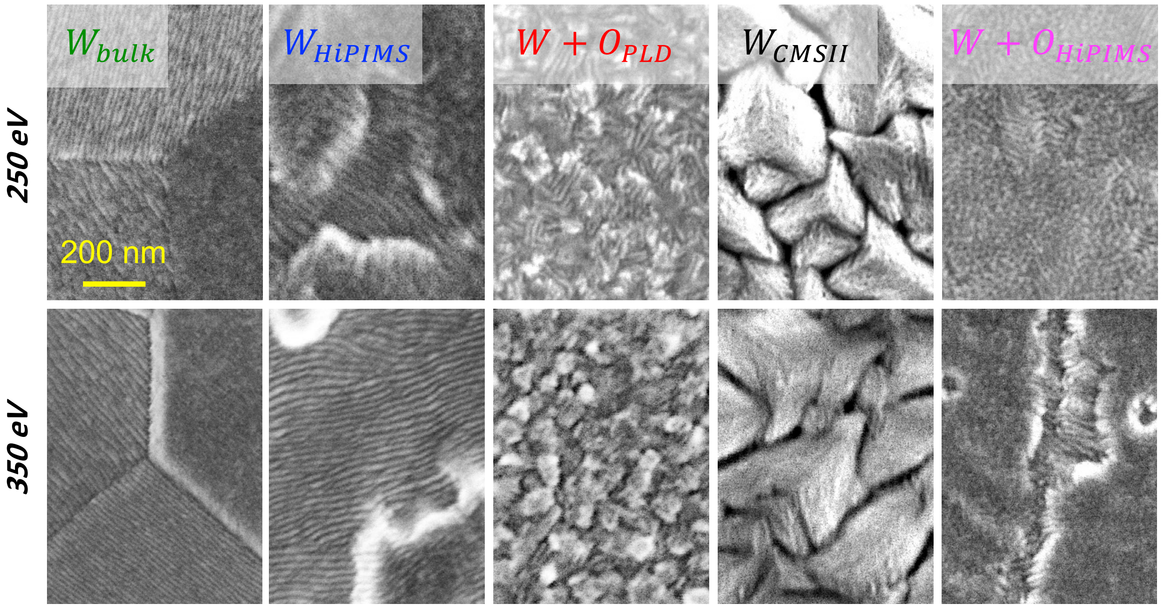
Topography and morphology changes: $E_{He^+} = 250\ eV$ vs $350\ eV$





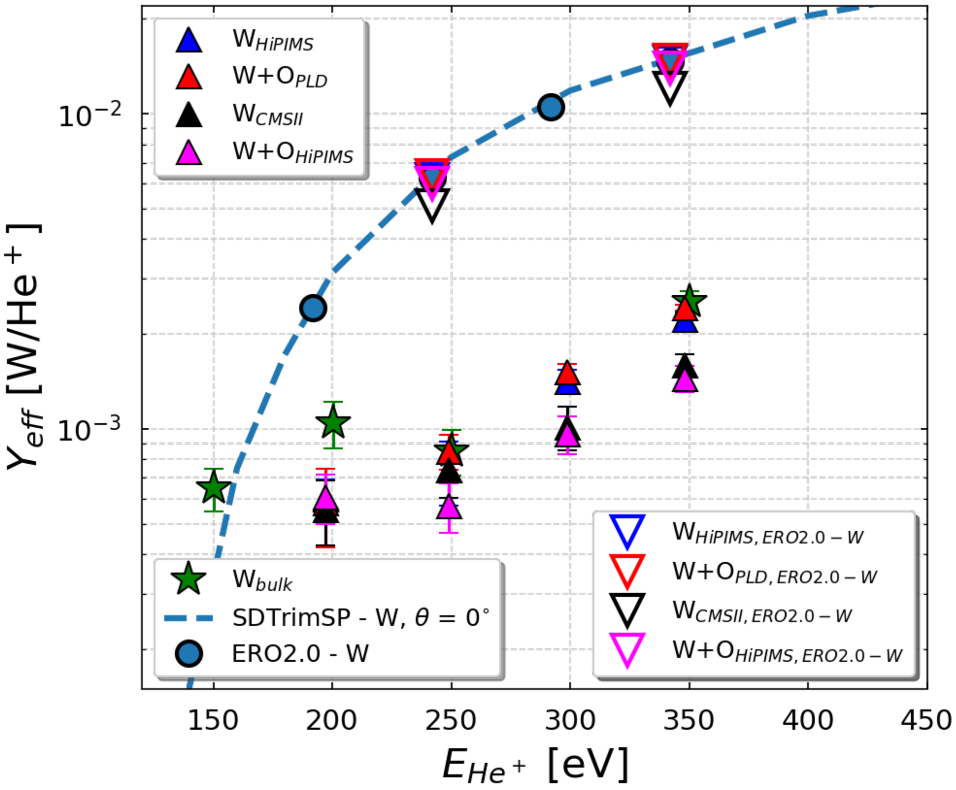
Topography and morphology modifications at nm-scale

→ determination of quasi-static sputtering yield Y

→ single time step ERO2.0 simulations

W_{bulk} Y_{eff} from mass loss data (Δm)

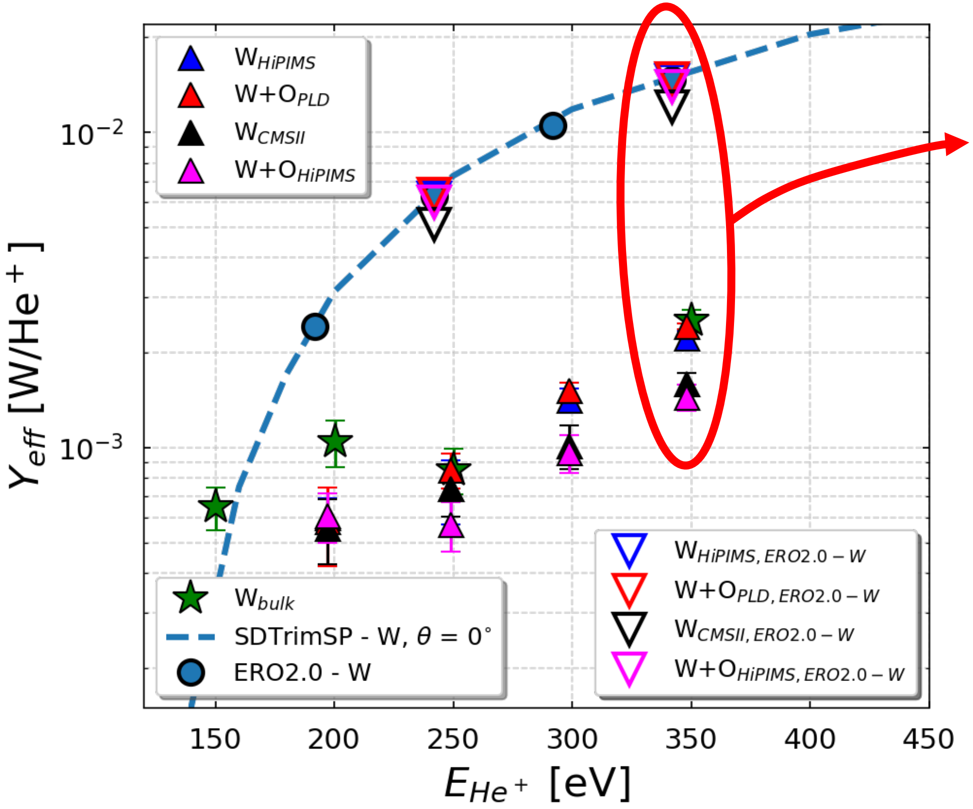
$Y_{eff,\Delta m}$ < $Y_{eff,ERO}$ W_{bulk} → He dynamic retention

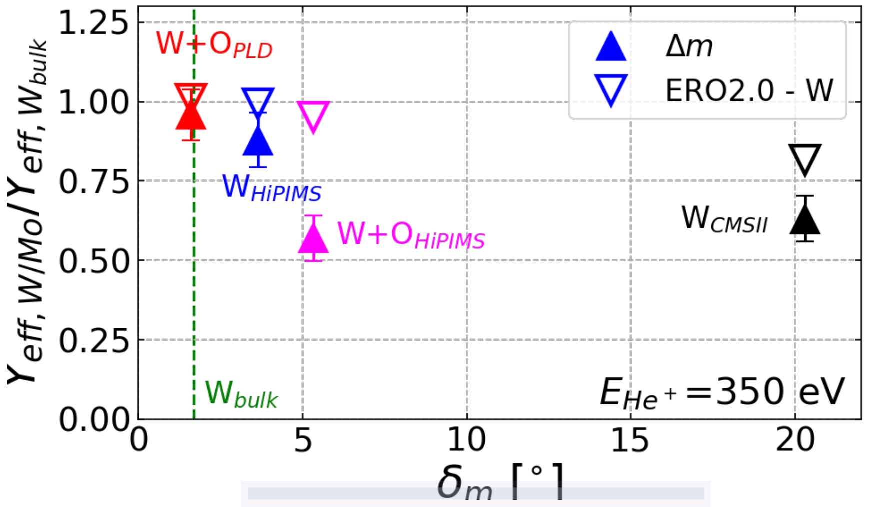


[2] R.P. Doerner, Scripta Materialia **143** (2018) 137-41

W_{bulk} Y_{eff} from mass loss data (Δm)

$Y_{eff,\Delta m}$ < $Y_{eff,ERO}$ W_{bulk} → He dynamic retention





- ERO2.0 → $\frac{Y_{eff,W/Mo}}{Y_{eff,W_{bulk}}}$ decrease w/ δ_m not enough
- $\left.\frac{Y_{eff,W/Mo}}{Y_{eff,W_{bulk}}}\right|_{\Delta m} \neq \left.\frac{Y_{eff,W/Mo}}{Y_{eff,W_{bulk}}}\right|_{ERO}$ → ≠ crystal orientation?

ERO2.0 simulations using Y(E,α) of W surface w/ ≠ orientations (110), (100), etc. from SDTrimSP

[2] R.P. Doerner, Scripta Materialia **143** (2018) 137-41

Conclusions

Compact **W coatings** deposited on **Gr** substrates with **irregular** surface and **Si** substrates with **pyramids** + polished **W**$_{\mathbf{bulk}}$

Compact **W** and **W+O coatings** with different structure at micro- and nanometer scale deposited on **polished** Mo substrates

He plasma exposure in GyM @ 4e24 He^+ m^{-2} and $E_{He^+} \lesssim 350\ eV$

$\mathbf{Y_{eff,\Delta m}} < \mathbf{Y_{SDTrimSP}}$ (& $\mathbf{Y_{eff,ERO}}$) → He dynamic retention

$$Y_{eff,norm}\Big|_{\Delta m}(\delta_m) \cong Y_{eff,norm}\Big|_{ERO}(\delta_m)$$

$$\frac{Y_{eff,W/Mo}}{Y_{eff,W_{bulk}}}\Bigg|_{\Delta m} \neq \frac{Y_{eff,W/Mo}}{Y_{eff,W_{bulk}}}\Bigg|_{ERO}$$

$\mathbf{Y_{eff,norm}(\delta_m)}$ allows to study role of topography in sputtering process of W

Role of crystal orientation in sputtering process of W?

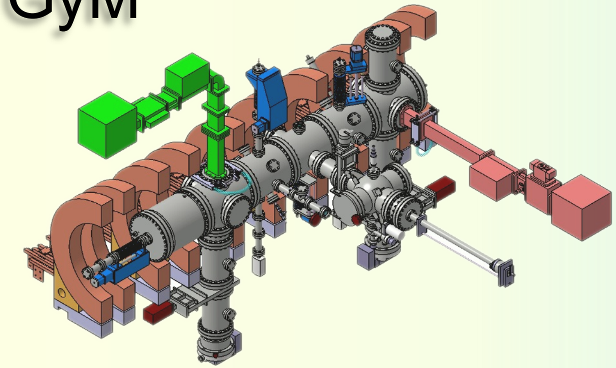
EBSD

XRD

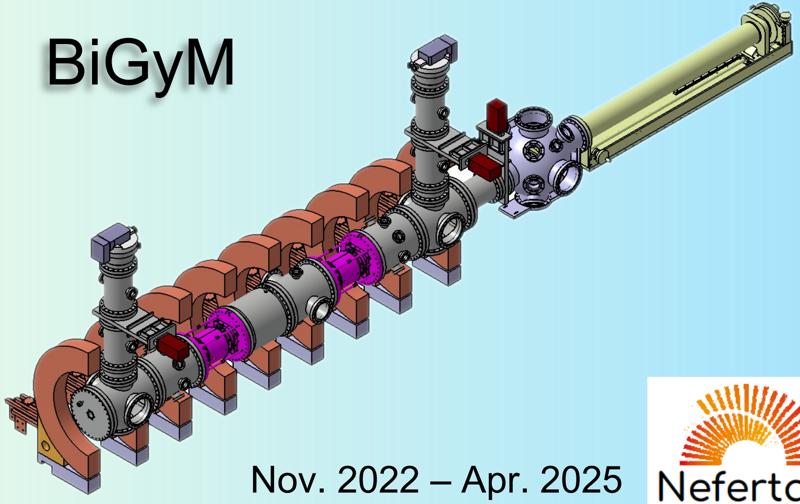
ERO2.0

Thank you!

GyM



BiGyM



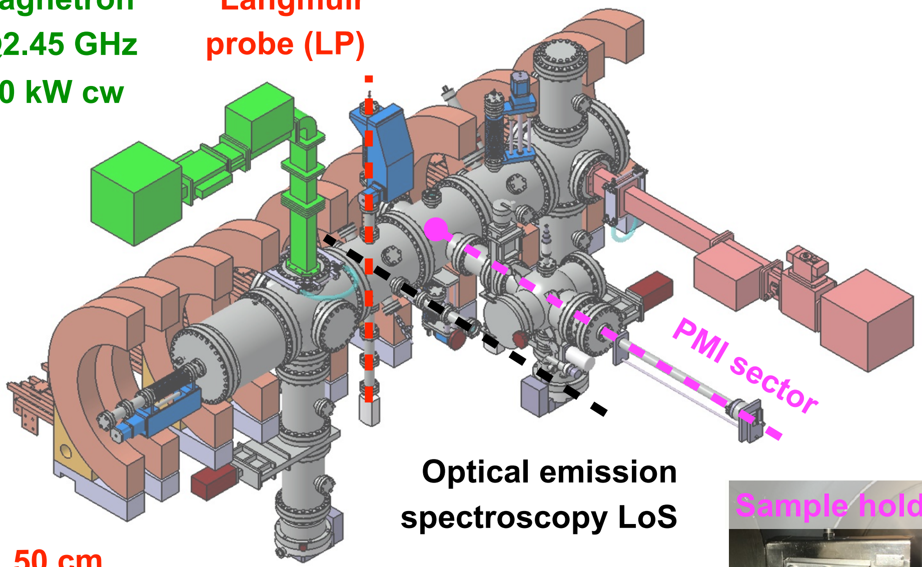
Nov. 2022 – Apr. 2025

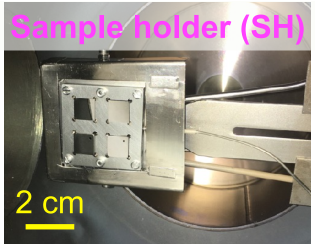
Nefertari

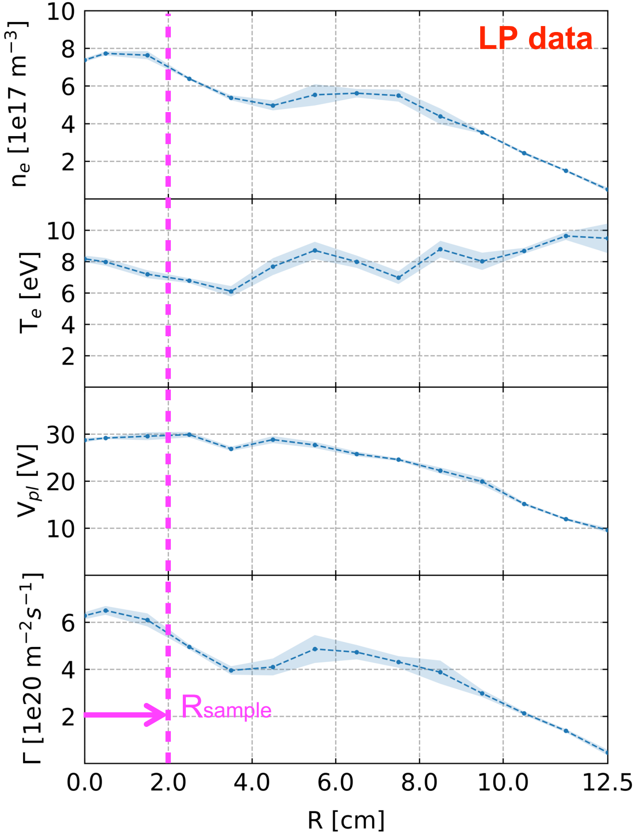
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | Consiglio Nazionale delle Ricerche | FEDERICO II

Experiment and characterisations

P_{source} = 1.2 kW, p_{work} = 10^{-3} mbar, B_{axis} = 80 mT



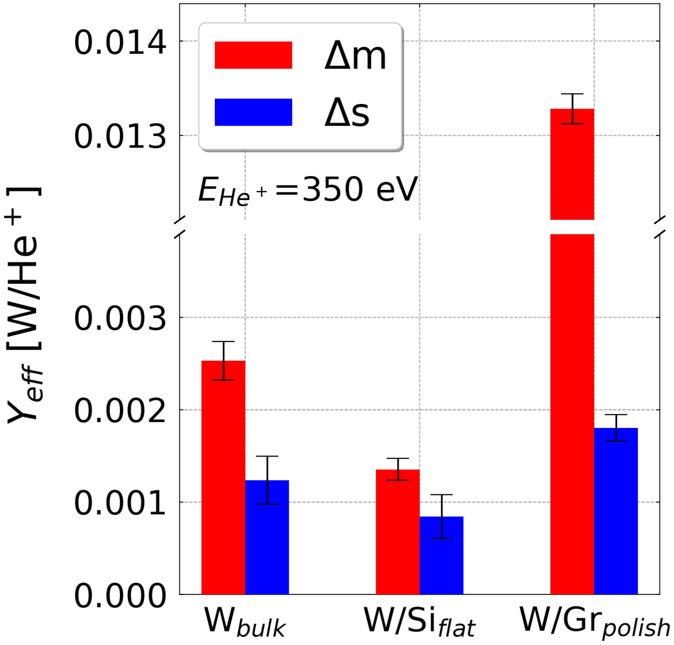


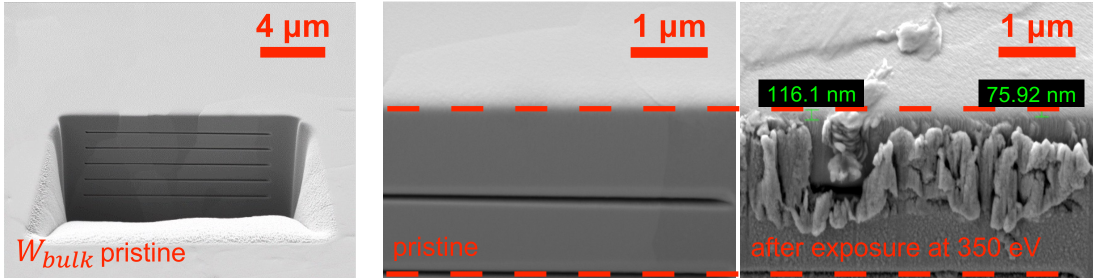


Data for benchmarking with
SOLPS-ITER modelling - **SP D.1**

[A. Uccello, et al., Front. Phys. **11** (2023) 1108175]

Global Y_{eff} from Δm and local Y_{eff} from thickness loss (Δs)

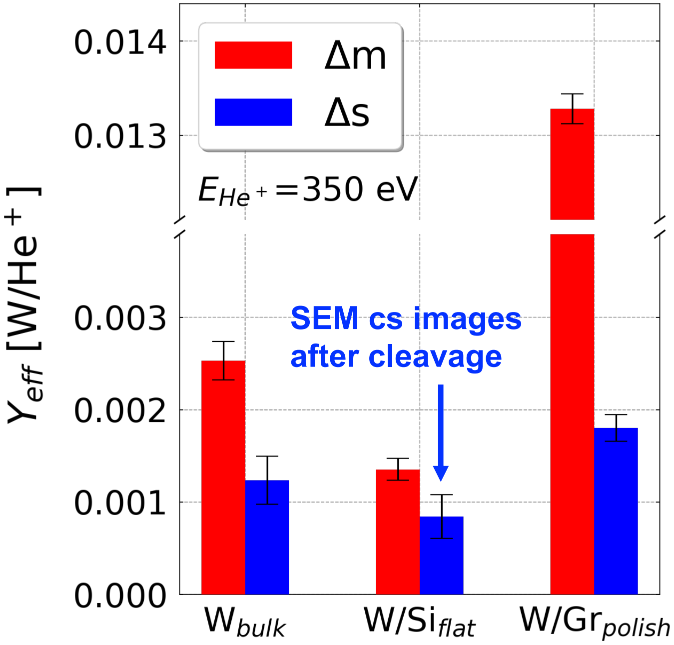


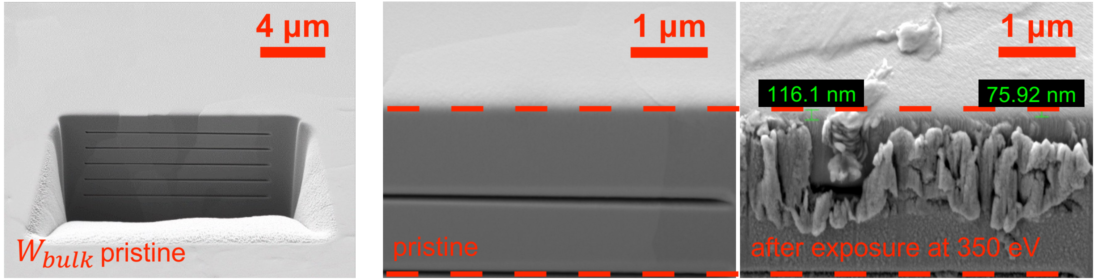


W_{bulk}: $Y_{eff,\Delta m} \neq Y_{eff,\Delta s} \rightarrow$ sputtering crystal orientation dependence [3]

[3] K. Schlueter, et al., Phys. Rev. Lett. **125** (2020) 225502

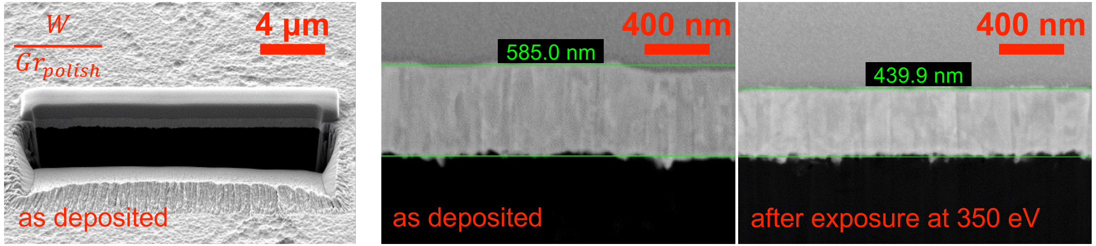
Global Y_{eff} from Δm and local Y_{eff} from thickness loss (Δs)





W_{bulk}: $Y_{eff,\Delta m} \neq Y_{eff,\Delta s}$ → sputtering crystal orientation dependence [3]

W/Si_{flat}: $Y_{eff,\Delta m} \simeq Y_{eff,\Delta s}$ → [110] W nanocrystallites

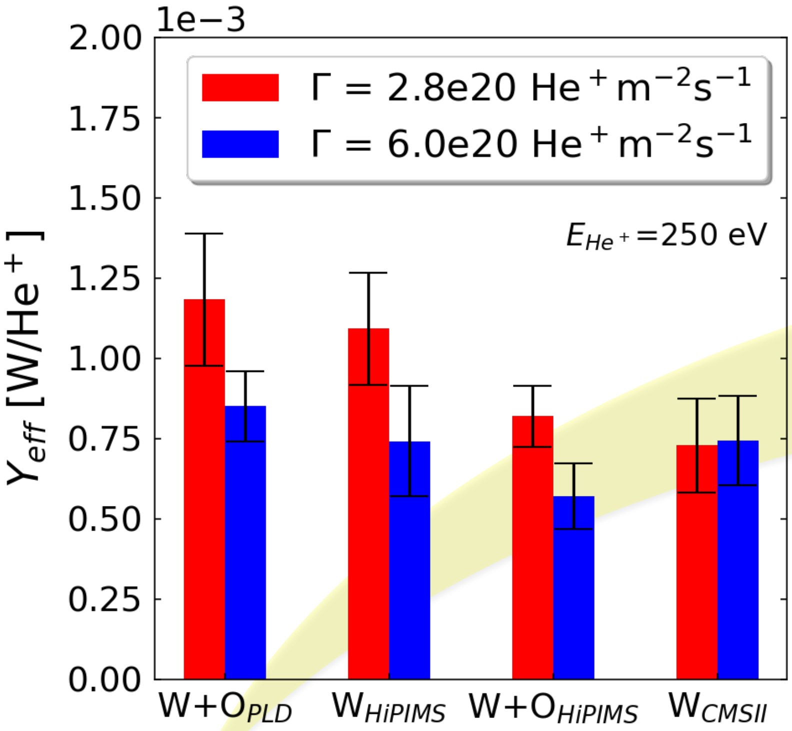


W/Gr_{polish}: $Y_{eff,\Delta m}$ → Gr outgassing, $T_{sample\text{-}holder}$ = 350-450 °C [4]

Y_{eff} normalized at $Y_{eff,\Delta m,W/Gr_{polish}}$ for W/Gr and at $Y_{eff,\Delta m,W/Si_{flat}}$ for W/Si

[3] K. Schlueter, et al., Phys. Rev. Lett. **125** (2020) 225502
[4] J. Bohdansky, et al., J. Nucl. Mater. **162-4** (1989) 861-4

Y_{eff} from Δm vs Γ



Small decrease of $Y_{eff,\Delta m}$ by increasing Γ due to larger He dynamic retention

Cross-machine experiment (in progress)

- **GyM** (Γ = 10^{19} - 10^{21} m^{-2} s^{-1})
- **PSI-2** (Γ = 10^{20} - 10^{23} m^{-2} s^{-1})
- **MAGNUM-PSI** (Γ = 10^{23} - 10^{25} m^{-2} s^{-1})

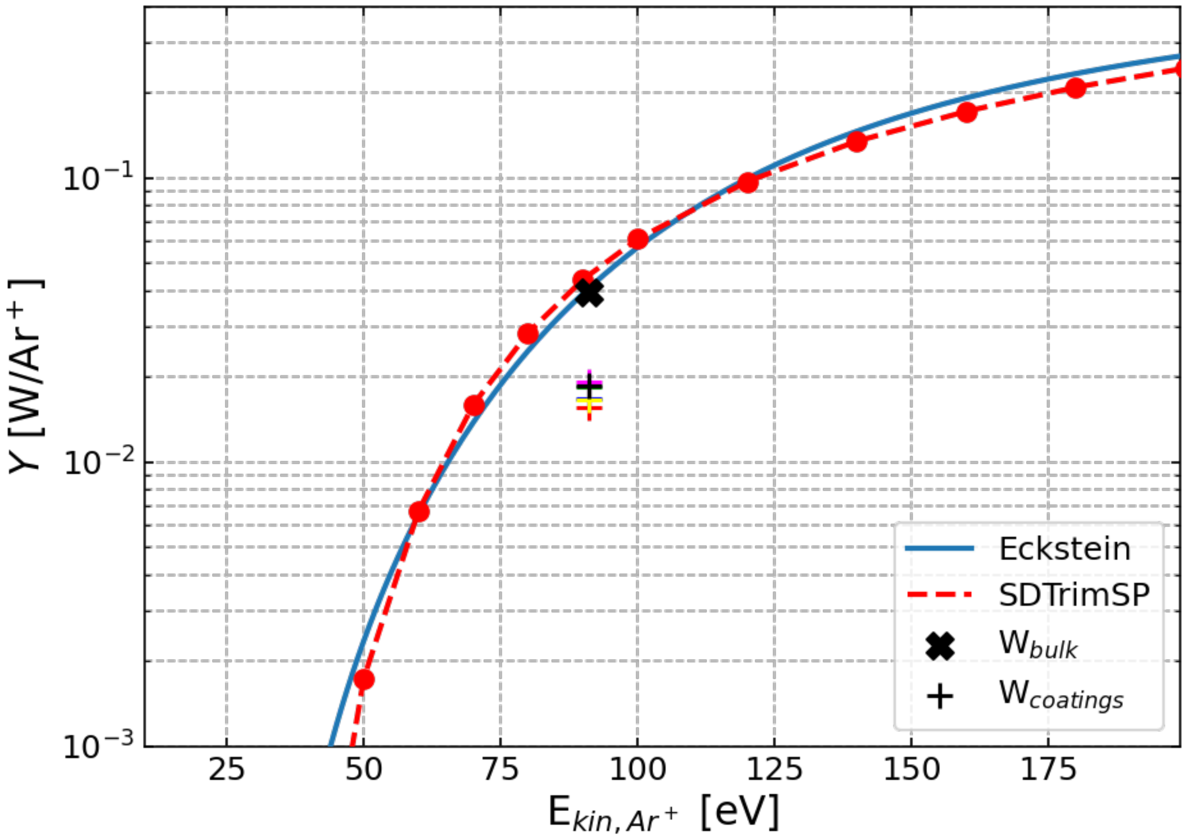
Goal: study effect of Γ on W erosion

1st campaign, exposure conditions

- **Argon** plasma
- **Ar^+ energy** = 50 eV
- **Φ** = 1.0e25 Ar^+m^{-2} (GyM: ~2 working-days)

Experiments in GyM once nanocolumnar W samples are available (scheduled for mid-Feb)

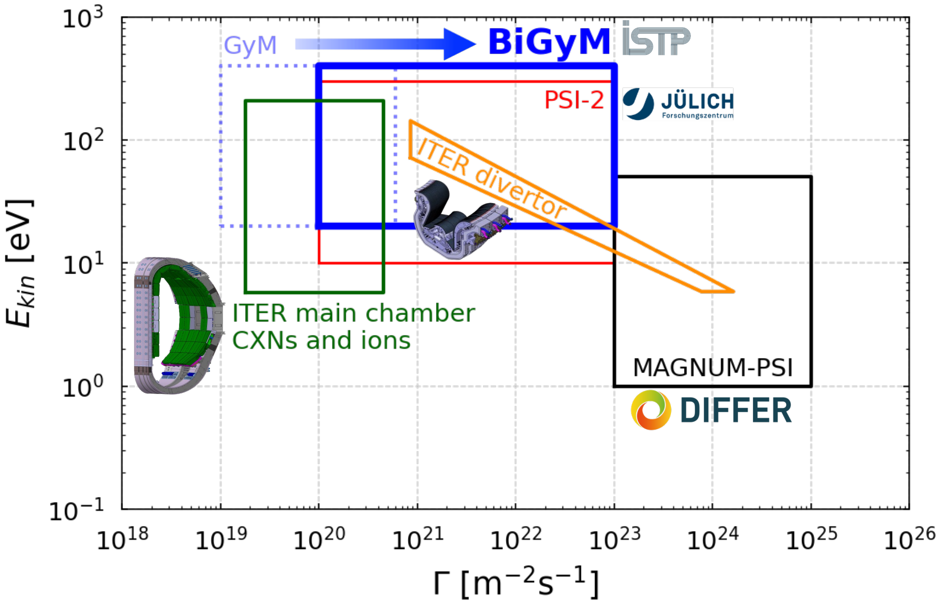
Cross machine experiment



GyM upgrade: BiGyM → Why?

Nov. 2022 – Apr. 2025
Total grant: 1.354.800,00 €

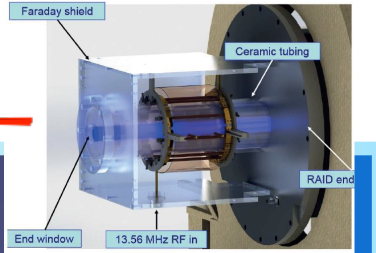
- To boost performance to study **divertor-relevant PMI**
  - Plasma-side: $n_e \leq 10^{19}$ m^{-3} and $\Gamma \leq 10^{23}$ $m^{-2}s^{-1}$
  - Material-side: $T_{sample} \leq 1500$ K
  - Diagnostics-side: hydrogen isotope retention
- To support and complement RFX-mod2 PWI program
- To contribute to educational and training of **young researches** in view of **DTT**
- To start **brand new activities** in other technological sectors, like aerospace, solar collectors and catalysis



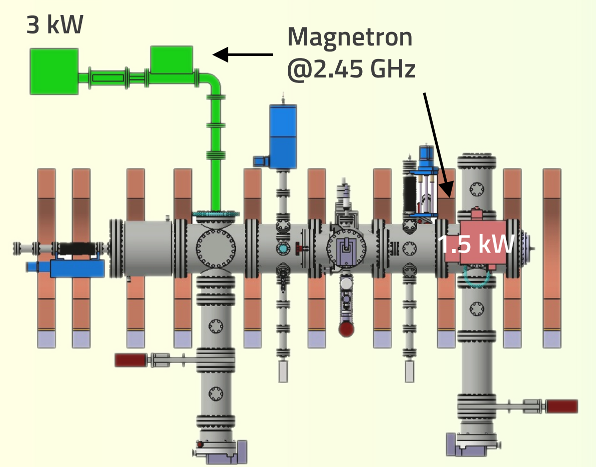
GyM upgrade: BiGyM → How?

- Hiring of **new personnel**: 2 temporary researches and 1 PhD student
- Procuring and installing **new hardware**

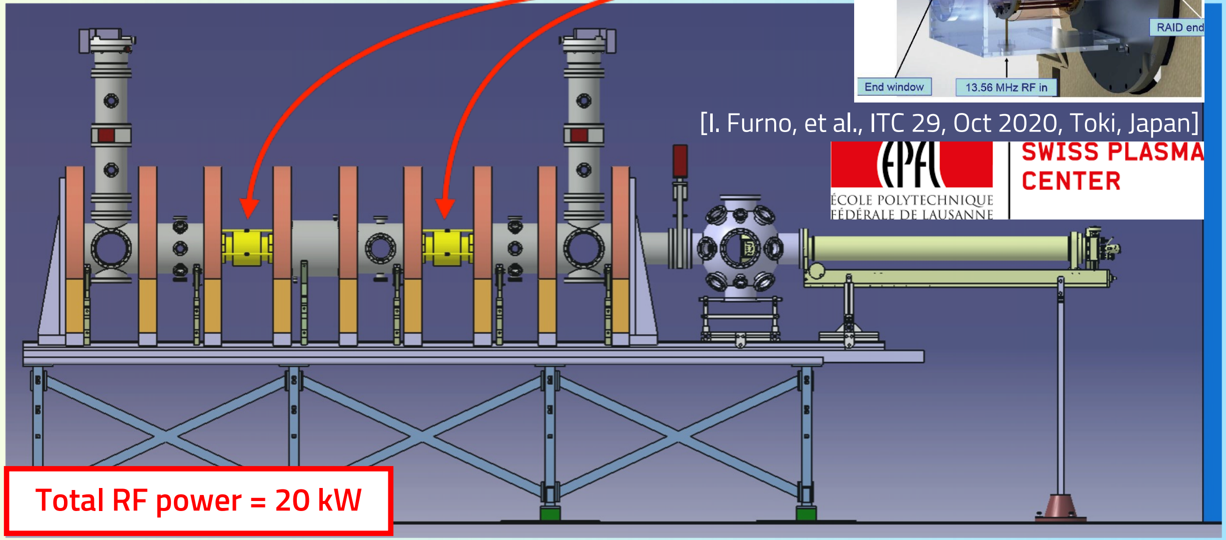
2 helicon plasma sources @13.56 MHz (radiofrequency)



[I. Furno, et al., ITC 29, Oct 2020, Toki, Japan]



Total microwave power = 4.5 kW

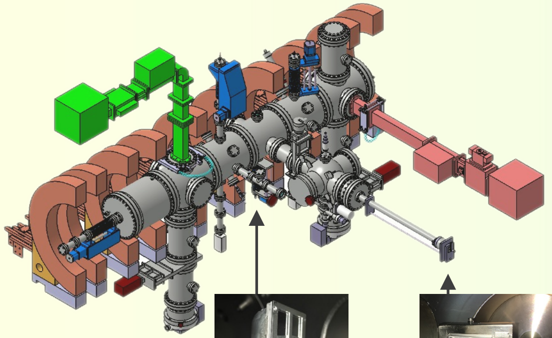


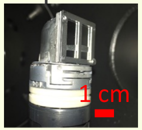
Total RF power = 20 kW

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE SWISS PLASMA CENTER

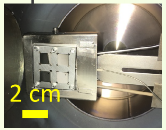
GyM upgrade: BiGyM → How?

- Hiring of **new personnel**: 2 temporary researches and 1 PhD student
- Procuring and installing **new hardware**

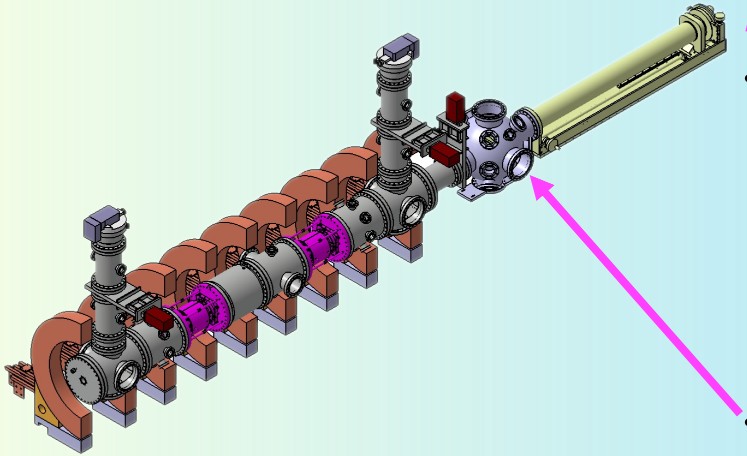




Active heating
T_{max} = 1000 K



Water-cooled



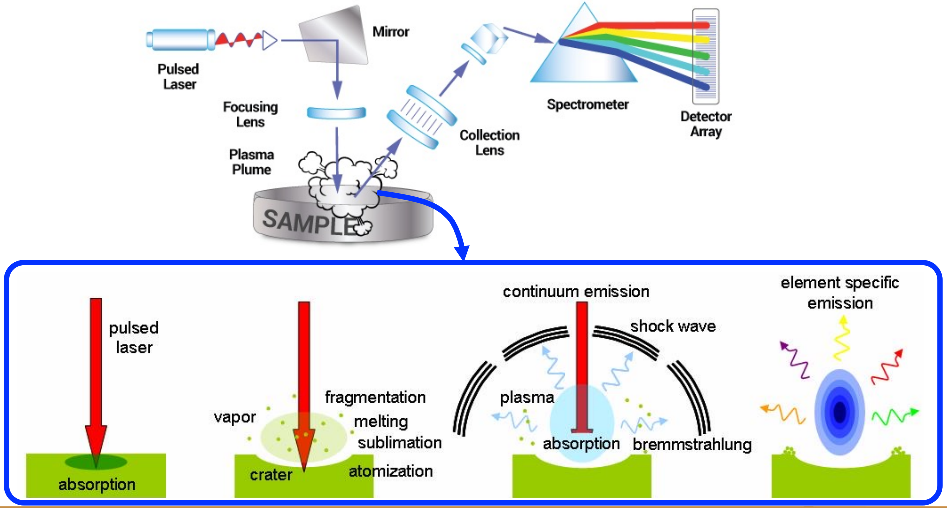
New sample exposure system

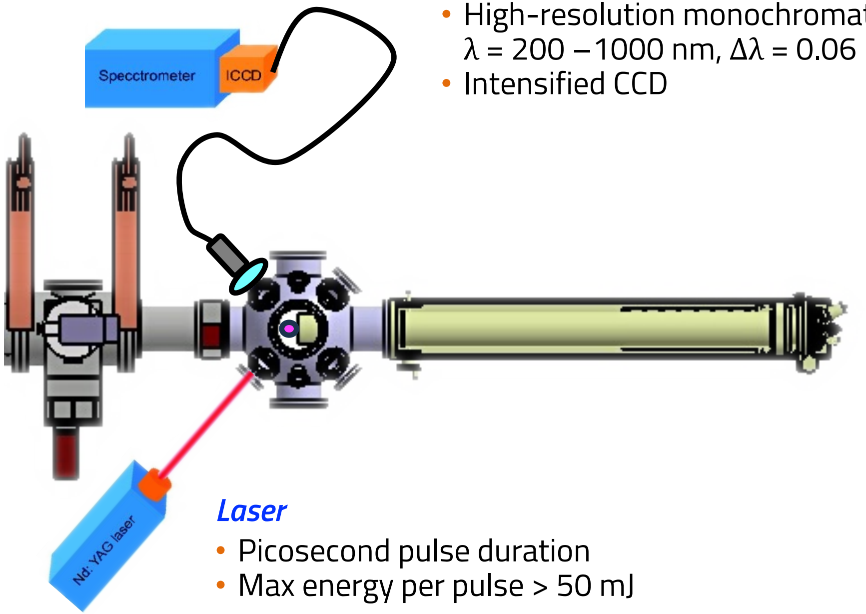
- Manipulator and sample-holder
  - ✓ **T_{sample} control 400 K - 1500 K**
  - ✓ V_{bias} ≥ -300 V
  - ✓ 1 m axial shift
  - ✓ Rotation: ±180°
  - ✓ Tilt: 90°
  - ✓ ~10x10 cm^2 sample-holder
- Sample exchange and analysis chamber Ø = 40 cm w/ ~20 ports

GyM upgrade: BiGyM → How?

- Hiring of **new personnel**: 2 temporary researches and 1 PhD student
- Procuring and installing **new hardware**

Laser-induced breakdown spectroscopy (LIBS)





Spectrometer

- High-resolution monochromator $\lambda = 200 - 1000$ nm, $\Delta\lambda = 0.06$ nm
- Intensified CCD

Laser

- Picosecond pulse duration
- Max energy per pulse > 50 mJ