LINEAR PLASMA DEVICE CAPABILITIES FOR W SOURCE STUDIES

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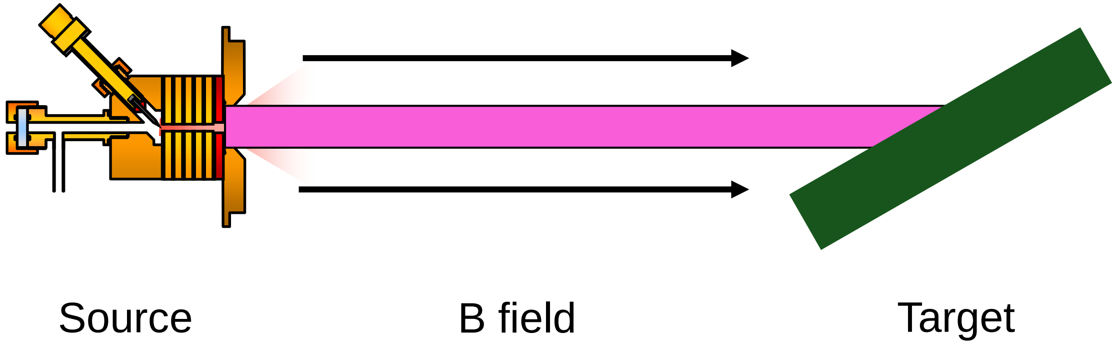
Why Linear Plasma Devices for W source studies?

Representative conditions with

- Fine control of parameters
- Good diagnostic coverage and access
- Rapid testing cycle
- Easy target exchange



Talk Overview

- Comparison EUROfusion linear plasma devices
- Example contributions to W erosion studies
  - Gym
  - PSI-2
  - Magnum-PSI
- UPP and BiGyM
- Cross machine studies

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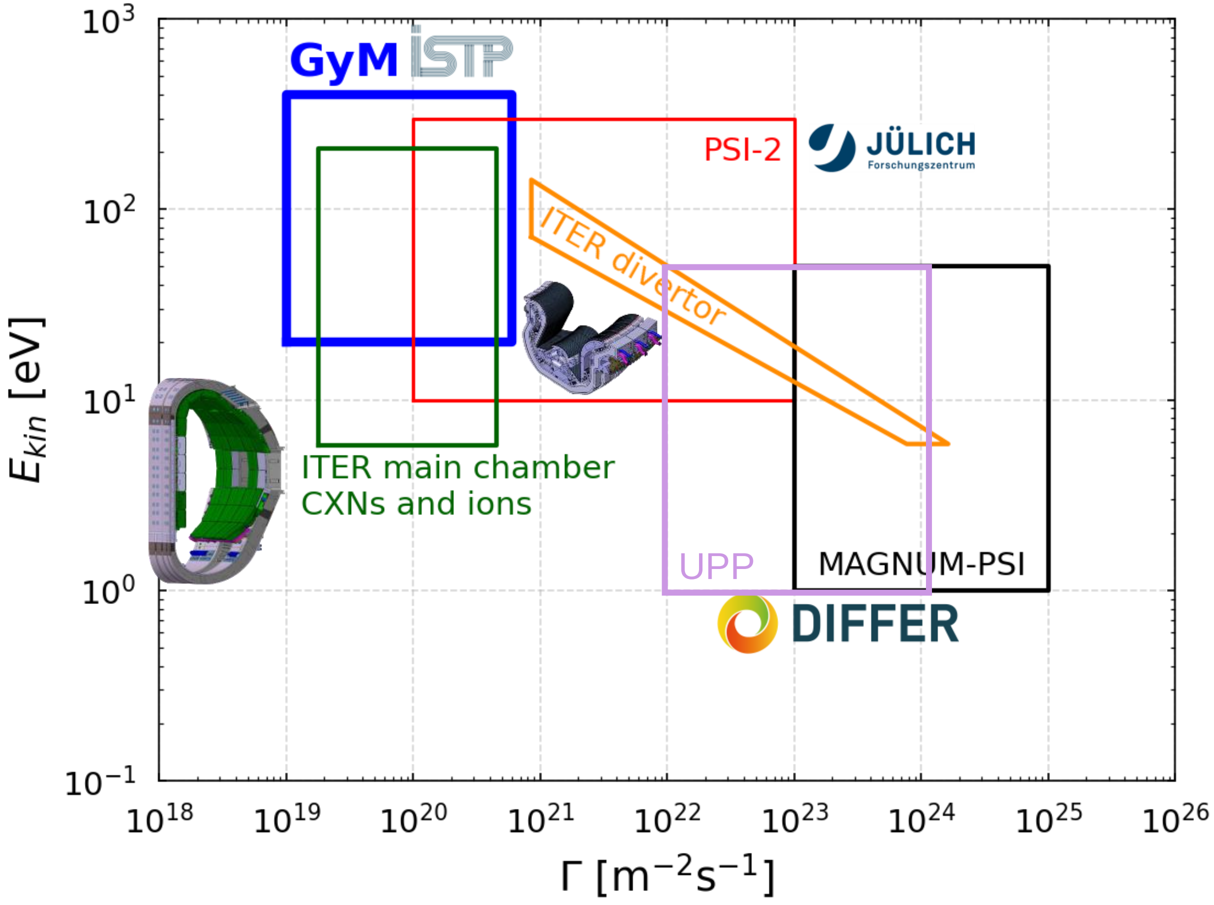
EUROfusion linear plasma devices

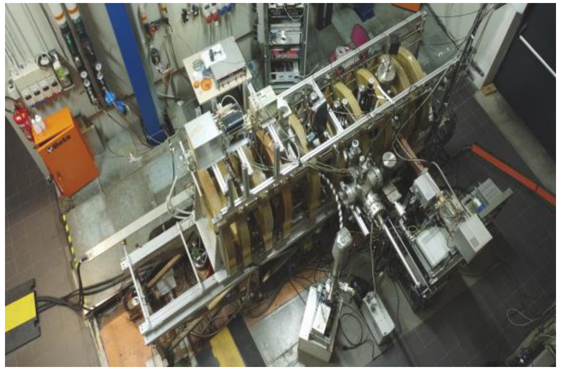


Four main linear plasma devices in EUROfusion cover the conditions expected in

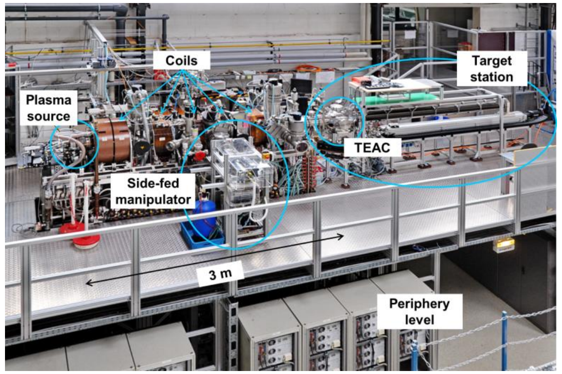
- First wall (Gym, PSI-2)
- Outer divertor (PSI-2, UPP)
- Divertor strikepoints (UPP, Magnum-PSI)

Parameter comparison

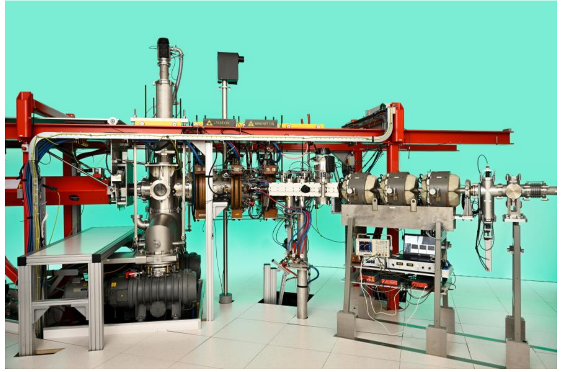
Device	n_e (m^{-3})	T_e (eV)	T_i (eV)	Γ (m^{-2} s^{-1})	$Φ_{pl}$ (mm)	E_{ion} (eV)	B (T)
Gym	~10^{17}	3-15	0.1	10^{19-21}	~200	20-400	0.13
PSI-2	~10^{16-19}	1-40	0.5-5	10^{20-23}	~60	10-300	0.1
UPP	~10^{18-20}	0.2-3	0.2-3	10^{22-24}	10-20	1-70	0.16
Magnum-PSI	~10^{19-21}	0.5-5	0.5-5	10^{23-25}	10-20	1-70	2.5



GyM



PSI-2



UPP

Magnum-PSI

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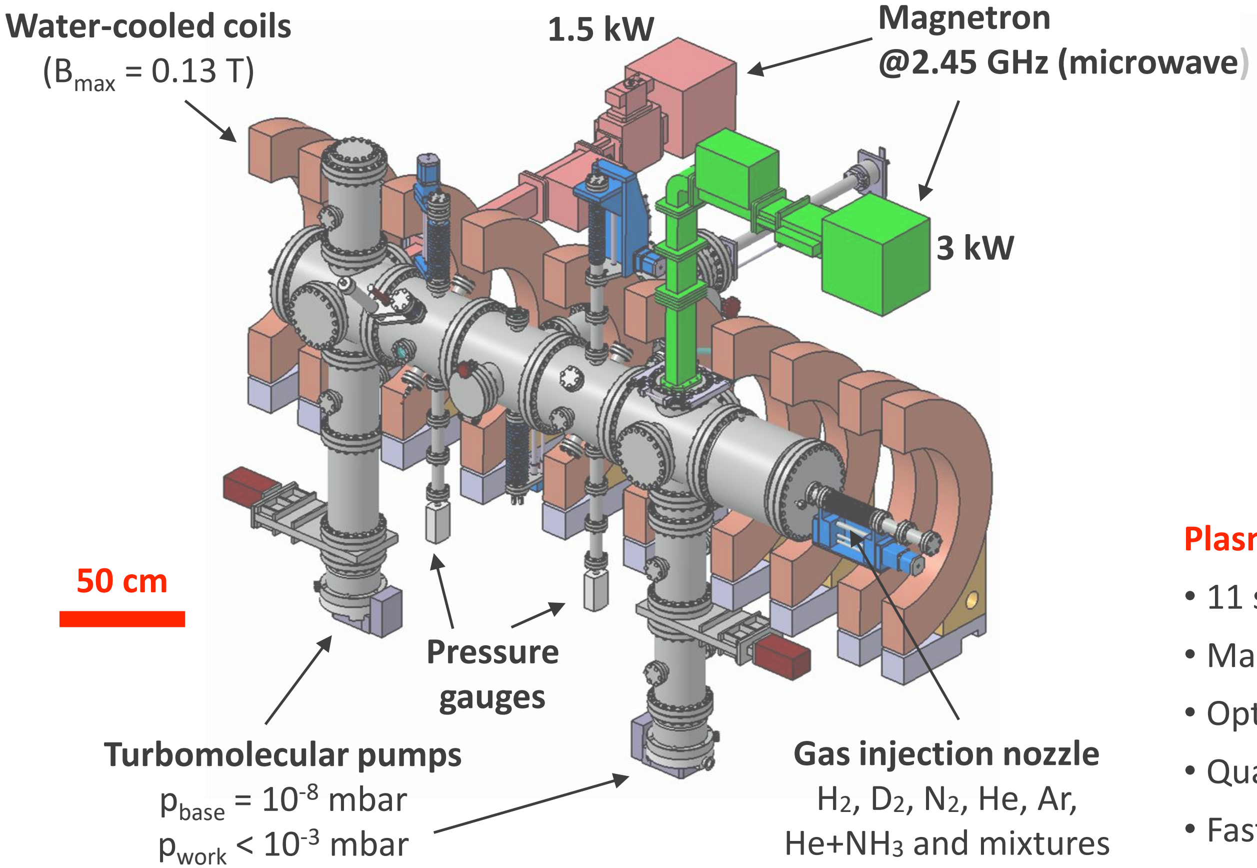
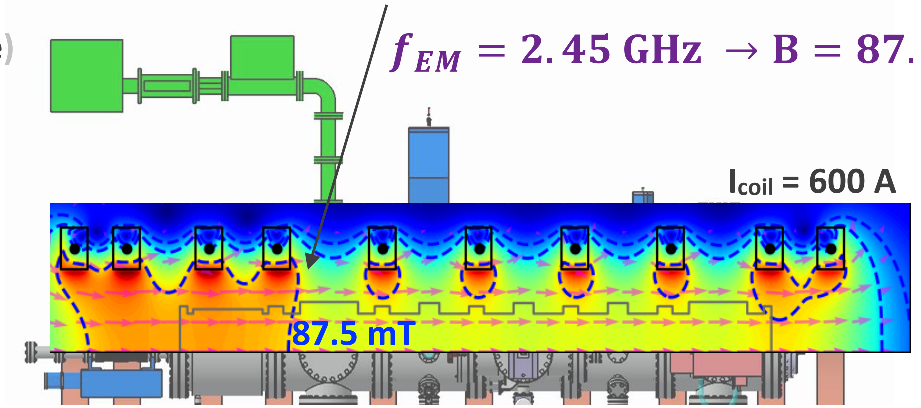
GyM overview and diagnostics



Electron cyclotron resonance heating $f_{EM} = \dfrac{e \cdot B}{2\pi m_e} \equiv f_{EC}$

$f_{EM} = 2.45\ \text{GHz} \rightarrow \text{B} = 87.5\ \text{mT}$



Plasma/Neutral gas diagnostics

- 11 single Langmuir probes (LPs)
- Mach probes
- Optical emission spectroscopy
- Quadrupole mass spectrometry
- Fast camera (shared with SPC-EPFL)

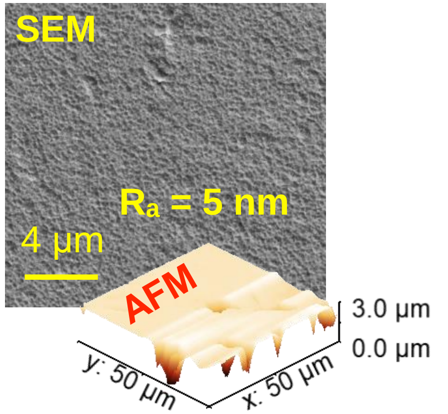
Role of topography in sputtering process of W by GyM He plasma

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

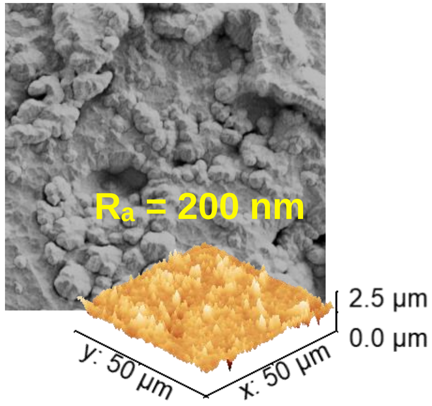
polished Gr

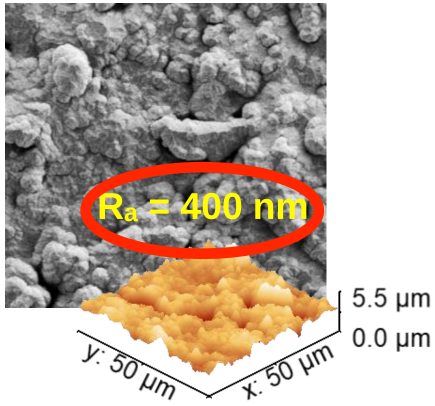


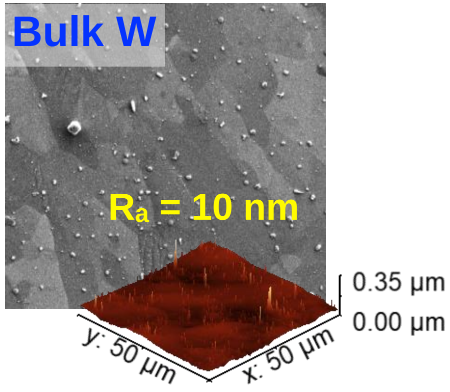
W films

Gr w/ irregular surface

Plasma etching

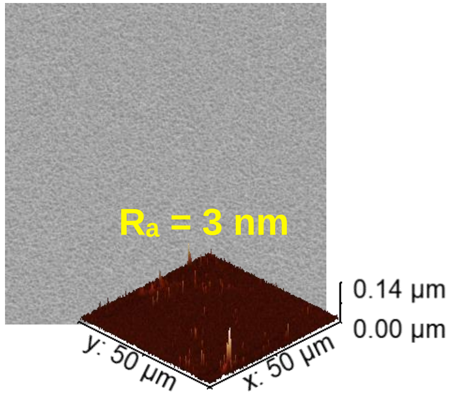






W film

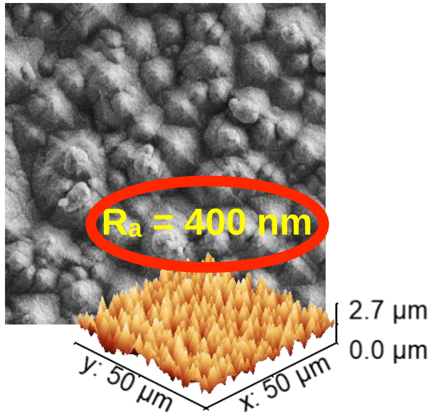
flat Si

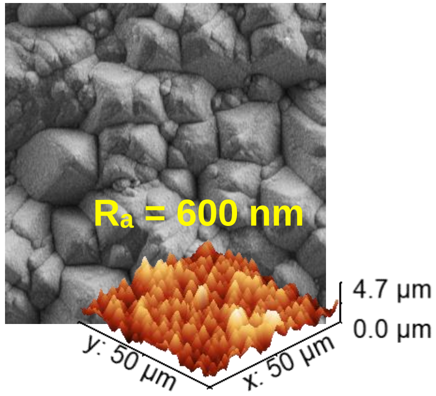


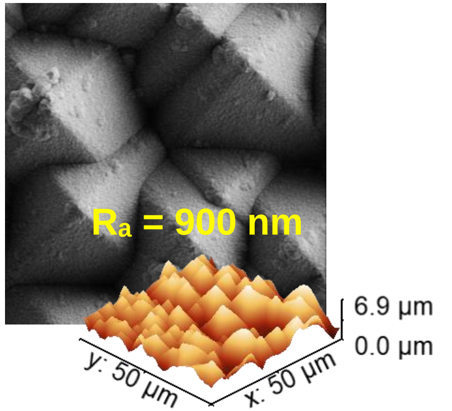
W films

Si w/ pyramids

Chemical etching

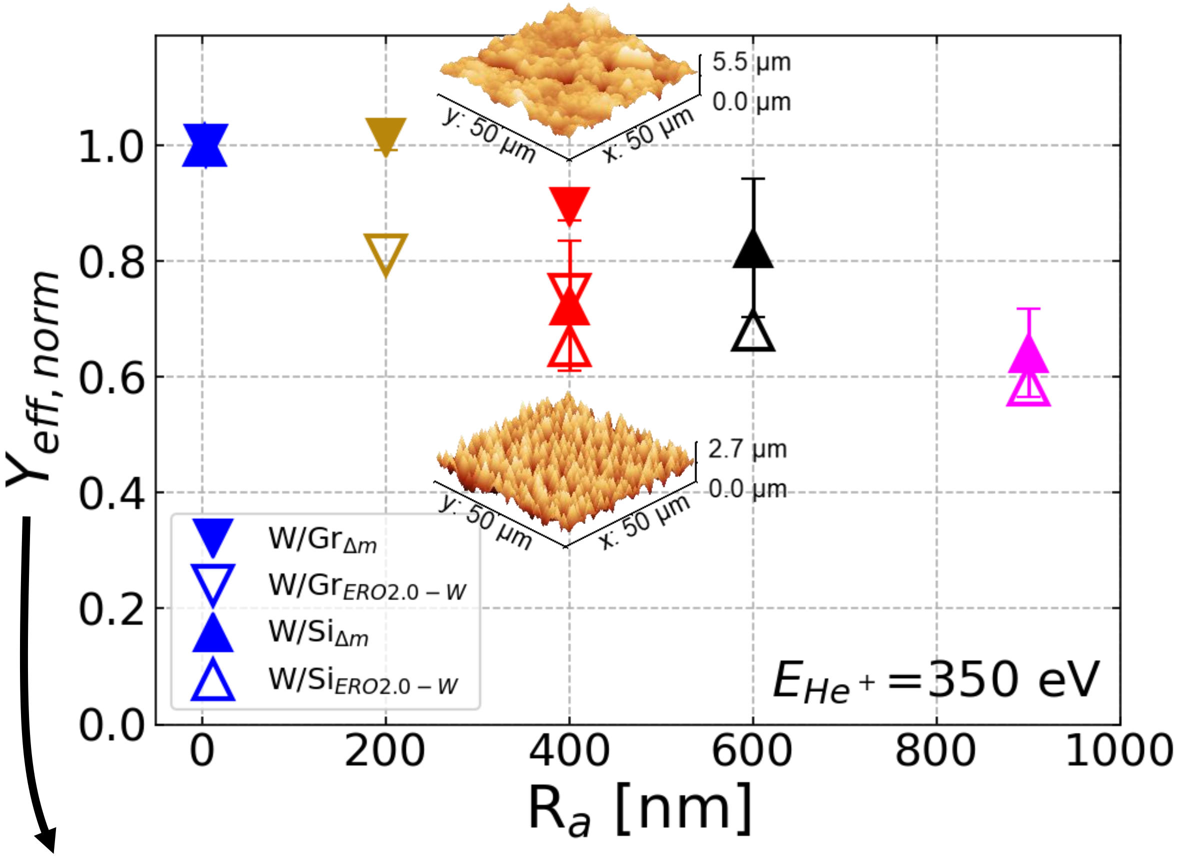


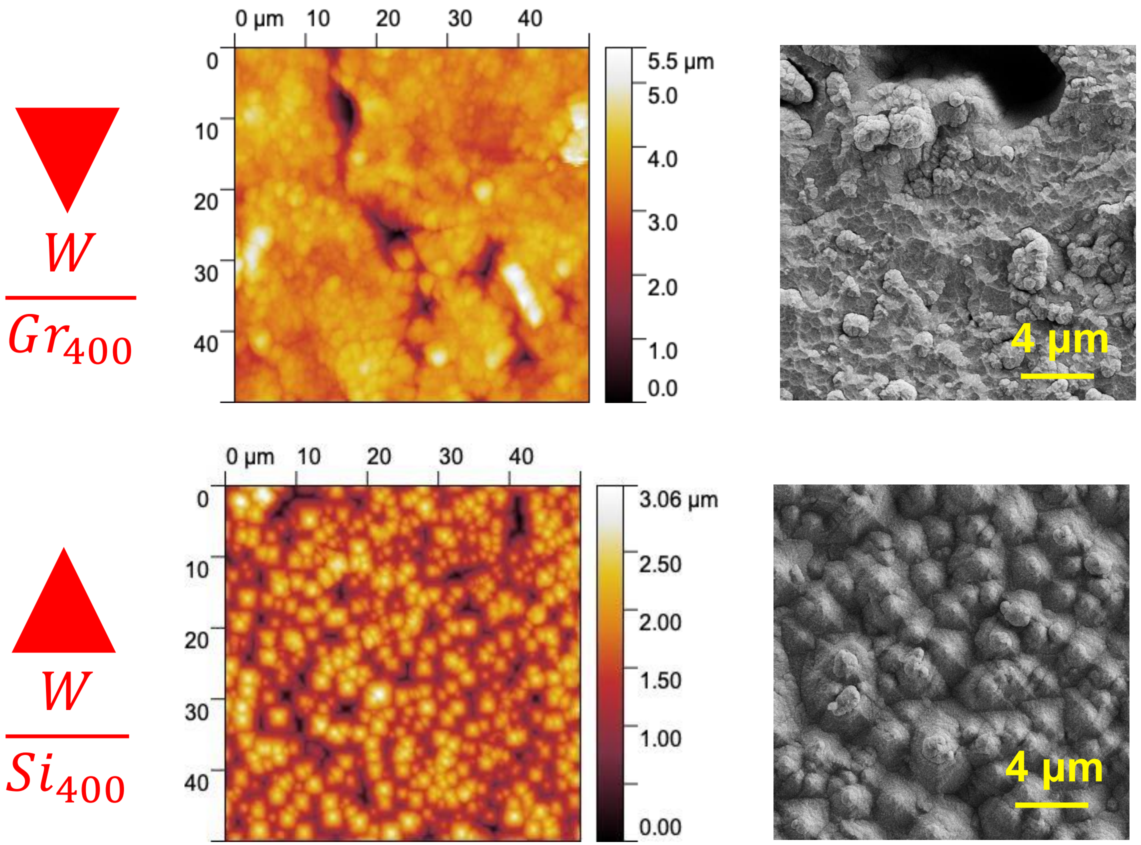




Unveil role of topography in sputtering of W by GyM He plasma

Average roughness, R_a ✗





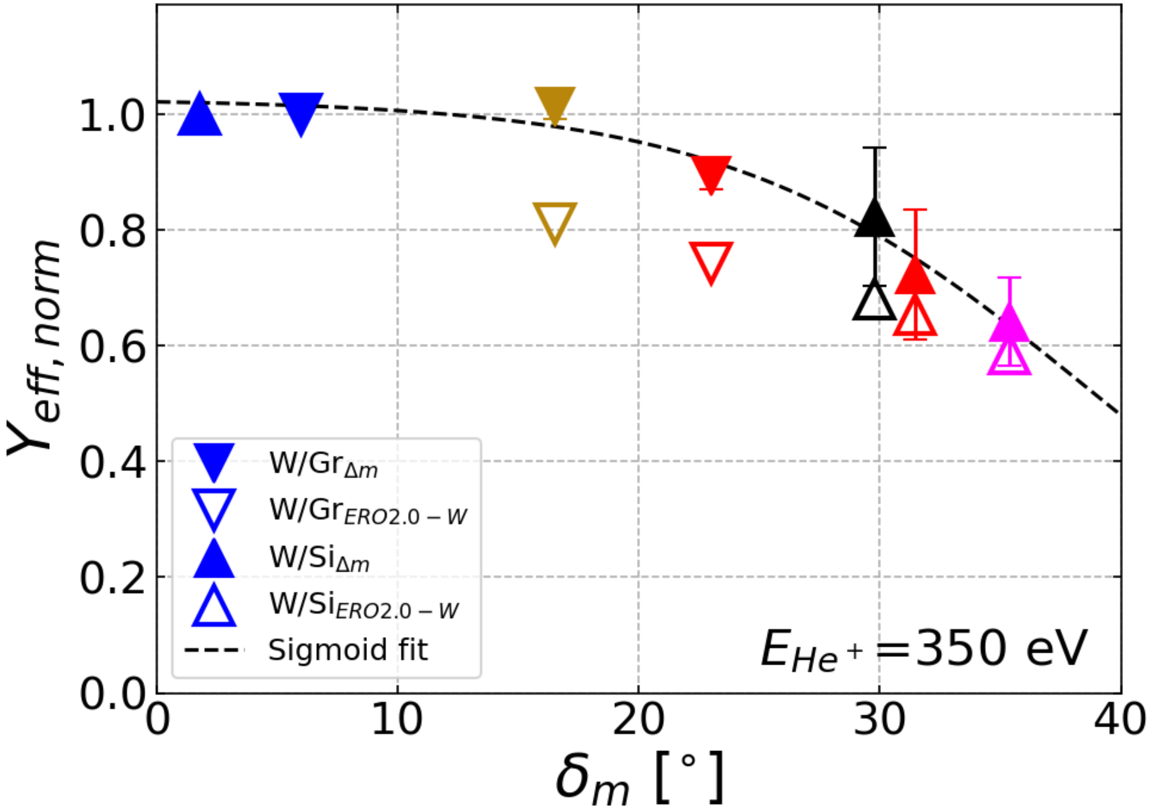
Same R_a, but different texturing

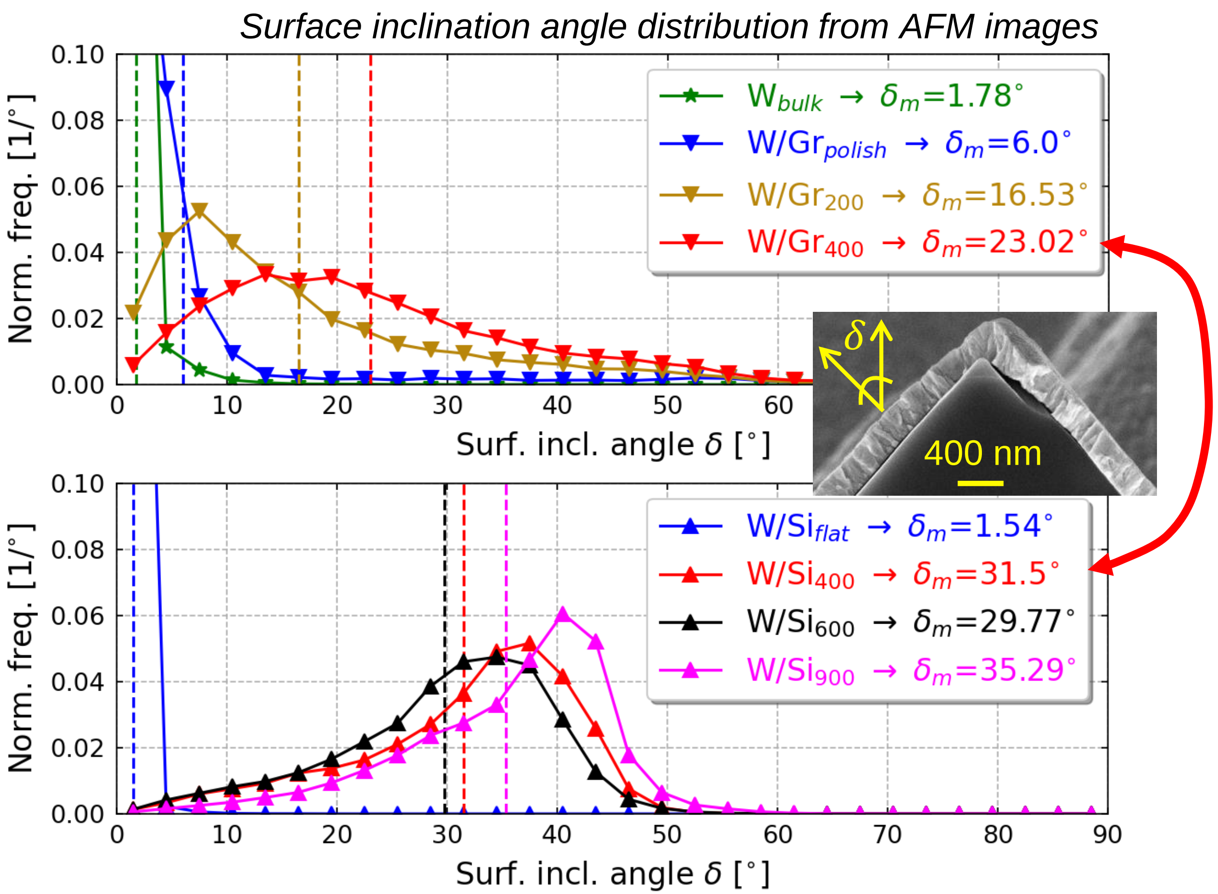
Y$_{eff}$ normalized at $Y_{eff,\Delta m,W/Gr_{polish}}$ for **W/Gr** and at $Y_{eff,\Delta m,W/Si_{flat}}$ for **W/Si**

Need another **parameter** to represent surface topography

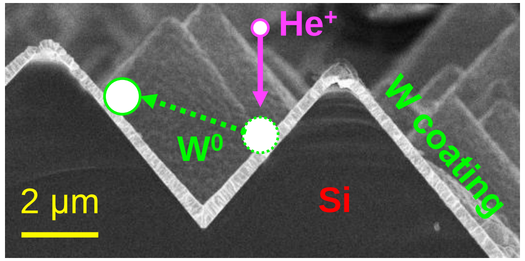
Unveil role of topography in sputtering of W by GyM He plasma

Mean surface inclination angle, δ_m [4] ✓



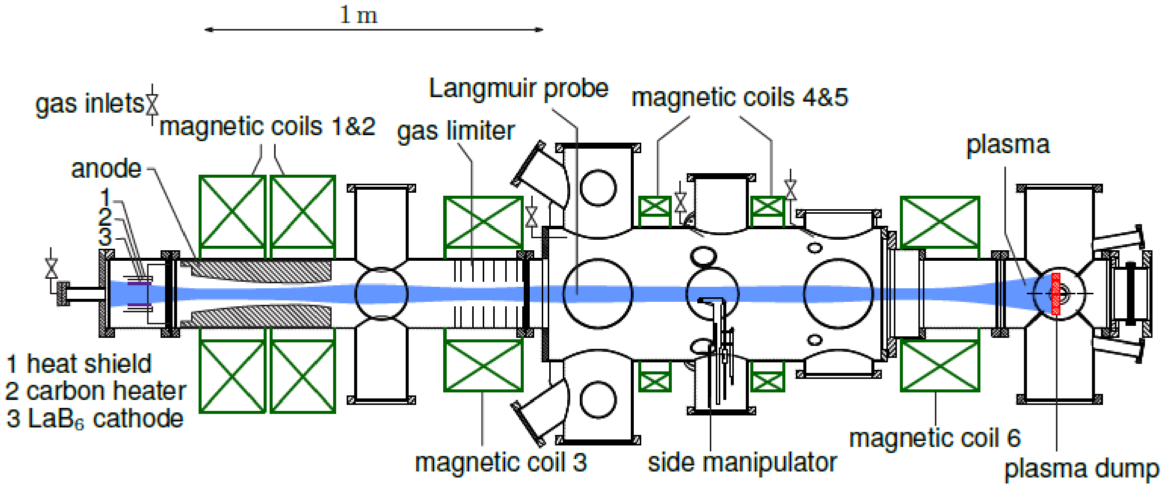


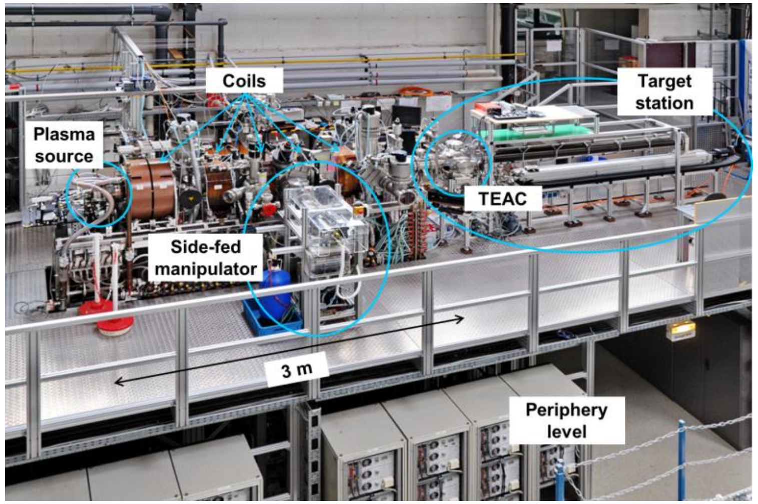
- Despite very different topography, $Y_{eff,norm}$ (δ_m) well fitted by sigmoid function
- **ERO2.0** → $Y_{eff,norm}(\delta_m)$ decreases due to increase of fraction of sputtered W atoms deposited at neighbouring surface

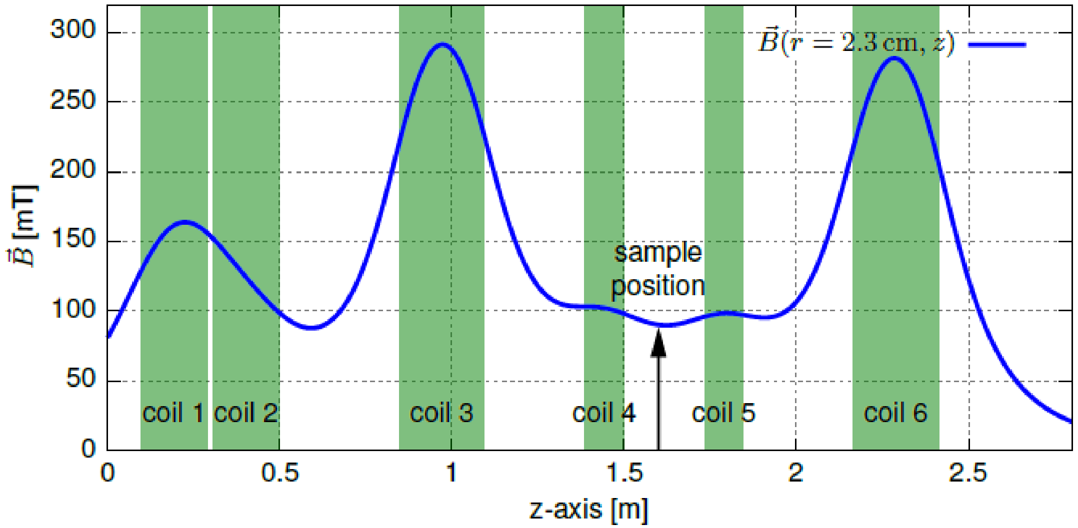


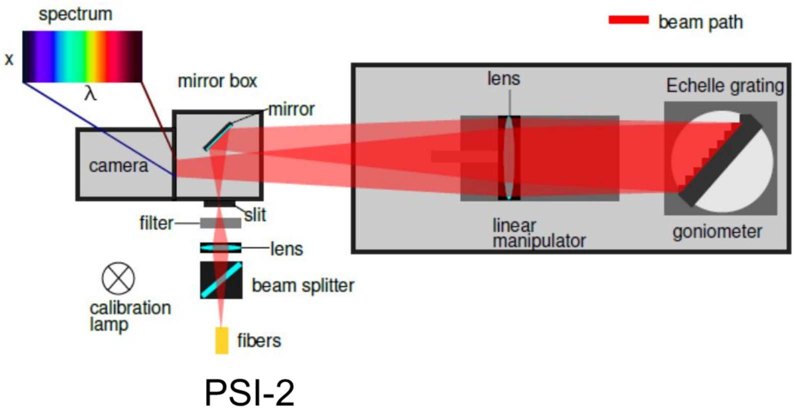
[4] C. Cupak, et al., Appl. Surf. Sci. **570** (2021) 151204

PSI-2 Overview and high-resolution spectrometer



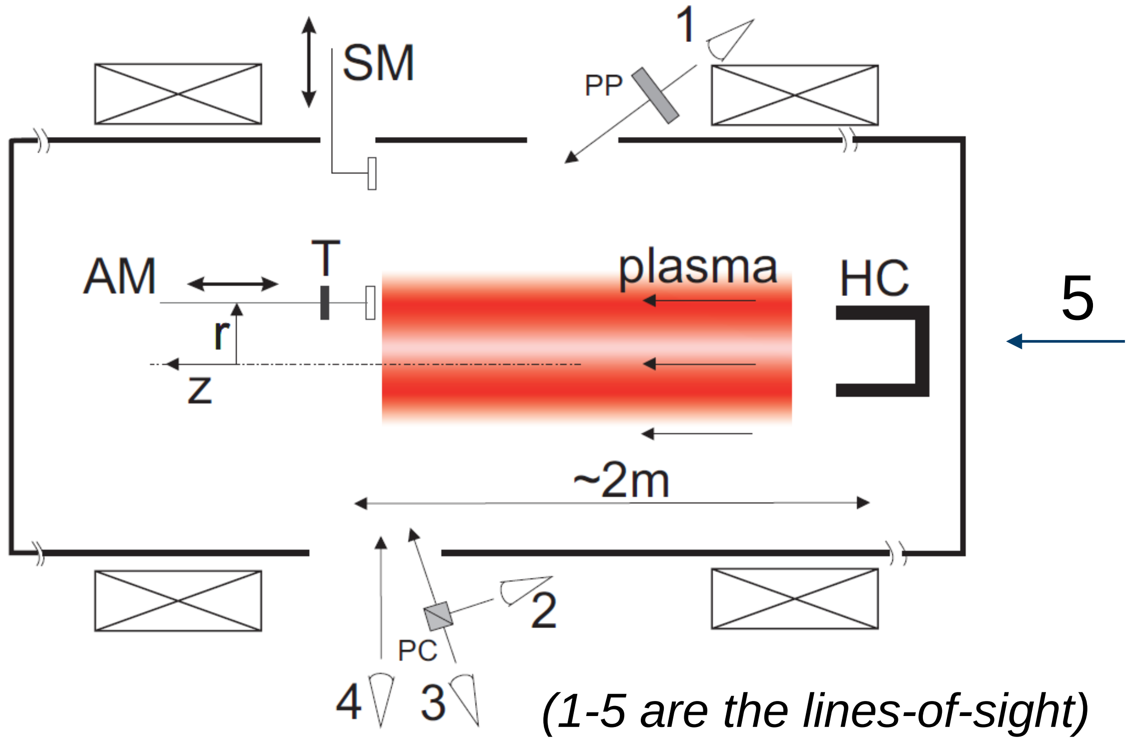




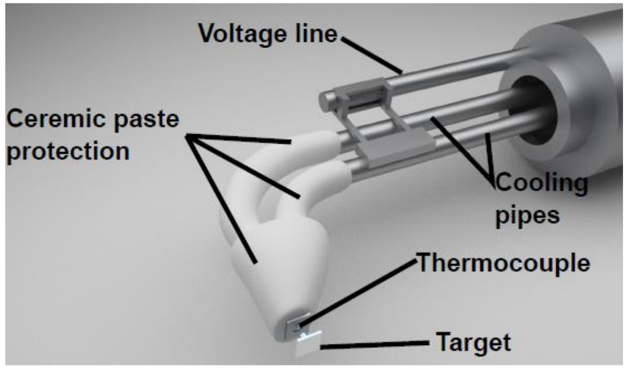


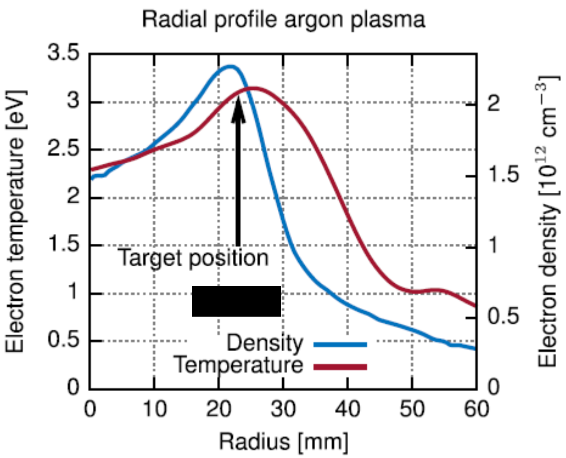
S. Ertmer , PhD thesis, **High-resolution spectroscopy studies on sputtered atoms in the linear plasma device PSI-2**
RUB Bochum, https://doi.org/10.13154/294-8580

Spectroscopic studies on W in PSI-2



(1-5 are the lines-of-sight)

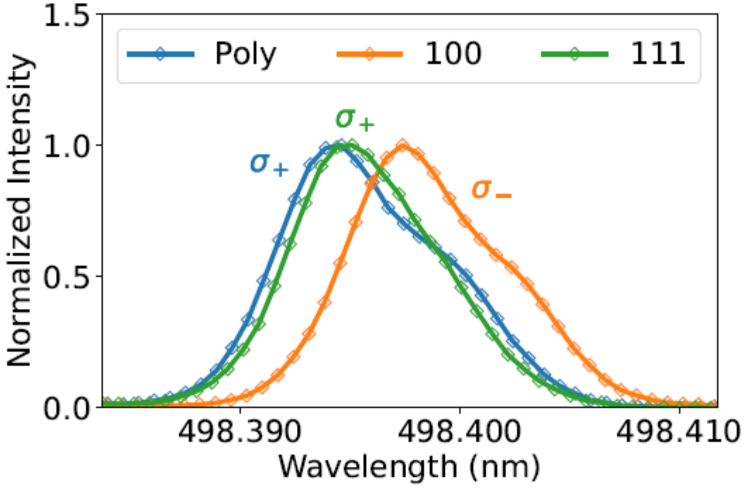




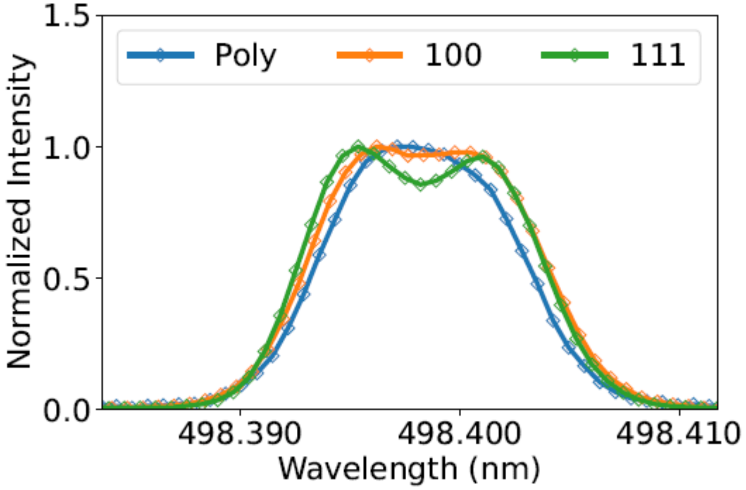
- Study of erosion and redeposition of W atoms/ ions using spectroscopy
- W targets: poly W, W (111), W (110), W (100)

Study conditions
Plasma pressure : 0.01…0.1 Pa
Electron temperature: 1..20 eV
Electron density: $10^{10}…10^{12}$ cm^{-3}
Magnetic field: 0.025…0.1 T
Ionization degree: 1-5%
Targets: 13x13mm^2

Study energy and angular distribution of sputtered W



(a) 0° LOS, 51 eV

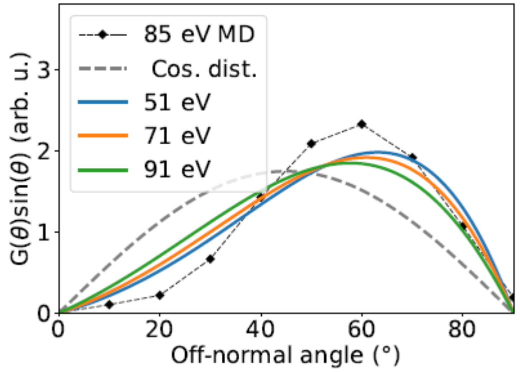


(b) 90° LOS, 51 eV

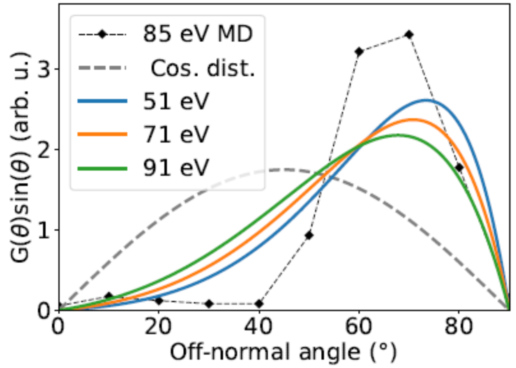
[1] Sackers M. et al, Physics of Plasma (submitted)

Example of W spectra with different structure poly-, mono (100) and (111):

- Using the Doppler emission model [2] one obtains the information on the energy/velocity (VDF) and angular distribution function (ADF) of sputtered tungsten.
- Benchmarking the codes (MD Simulation, TRIM, etc..) close to sputtering energy threshold



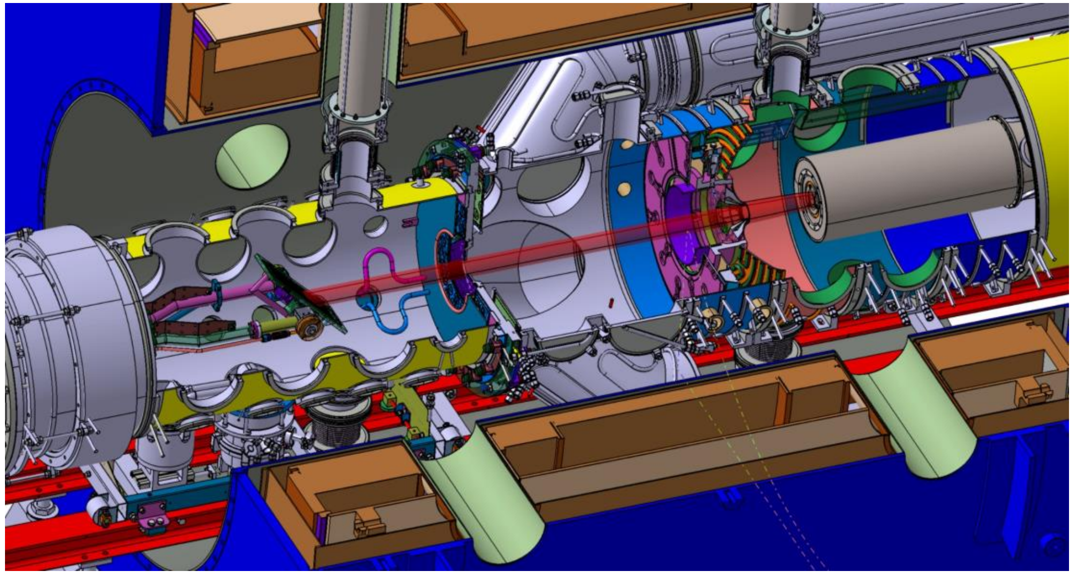
(a) W poly ADF

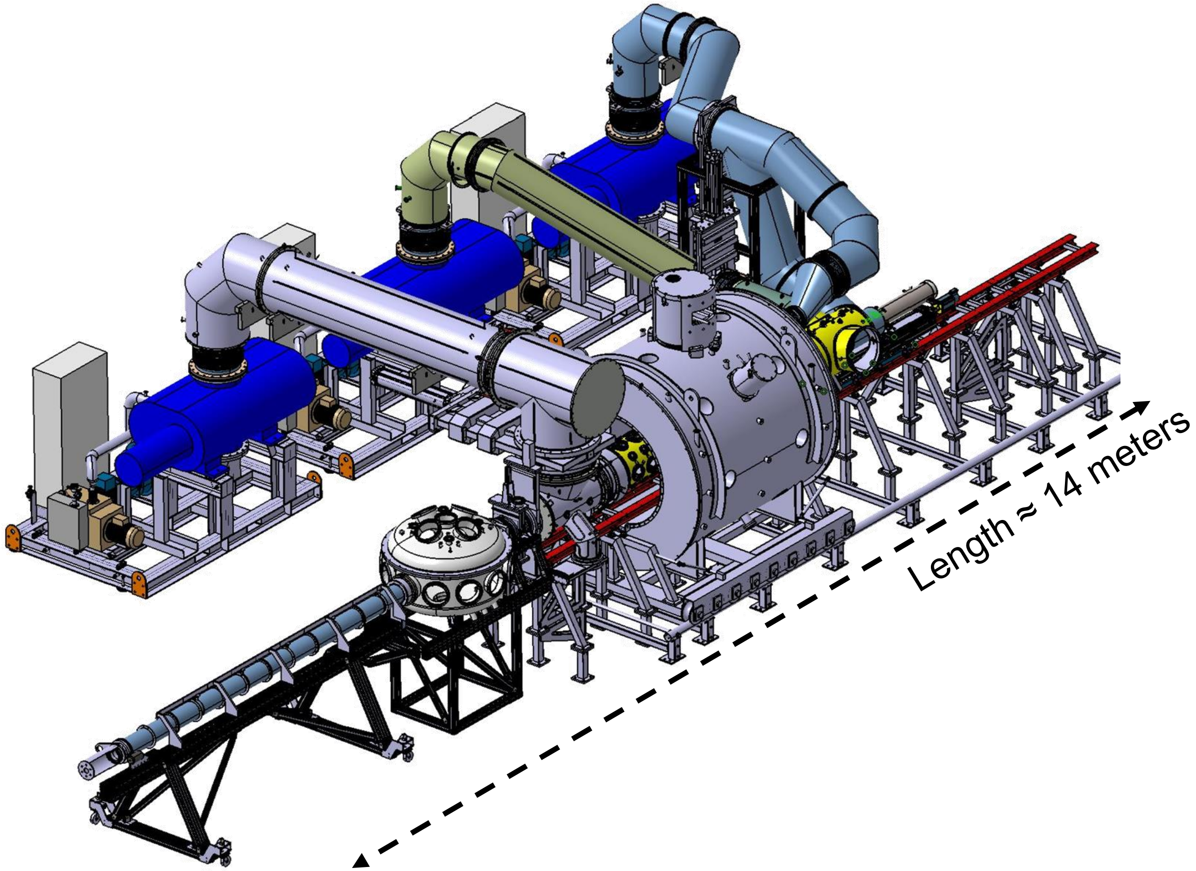


(c) W (111) ADF

[2] Sackers M. et al, Phys. Scr. 98 (2023) 115603

Magnum-PSI overview and diagnostics





During plasma exposure
Thomson scattering: T_e and n_e
Pyrometer, cooling calorimetry and fast IR camera: T_{target} and q
Optical spectroscopy (survey & high-res); RGA: species concentration
Quartz crystal microbalance: erosion monitoring
Collective Thomson scattering system: T_i, v_{plasma}
Fast visible light camera up to 1 MHz
Collective Thomson scattering system: Ti, v_{plasma}

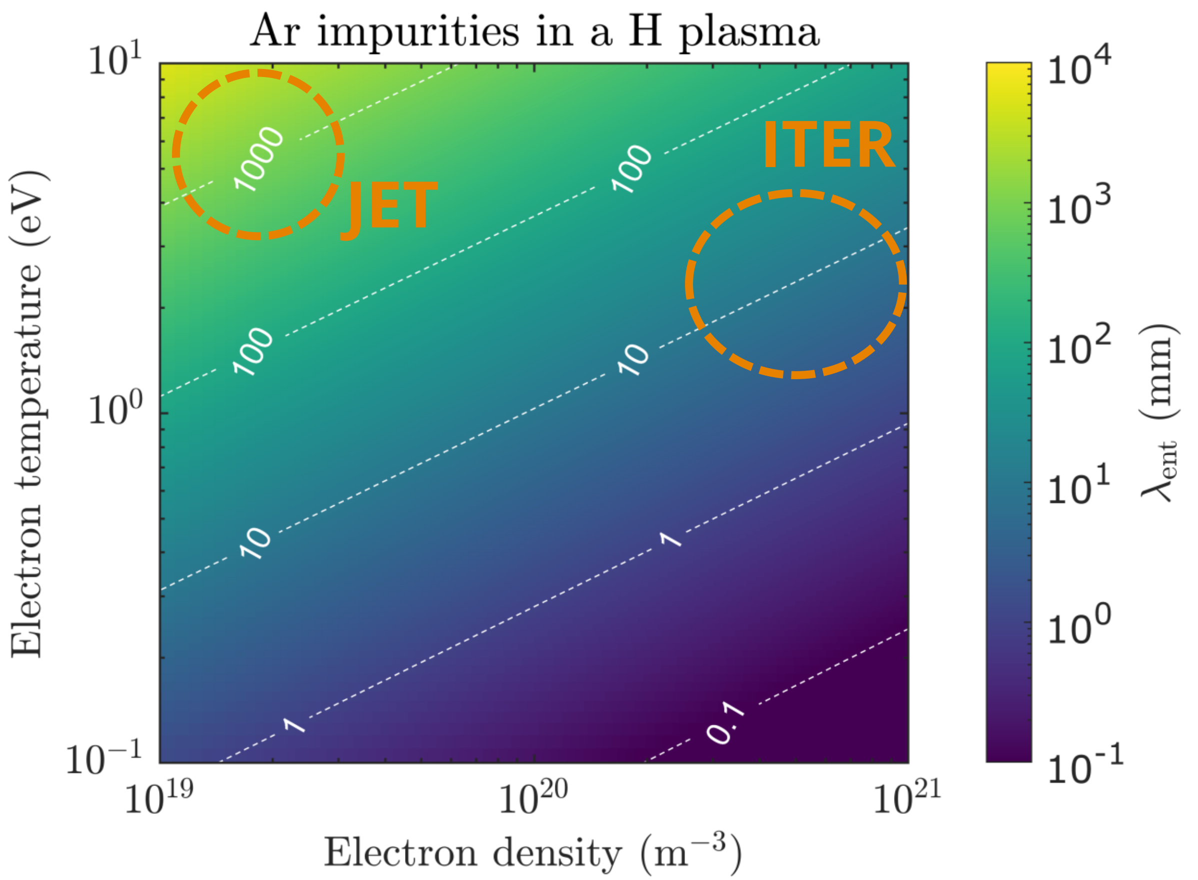
Post plasma exposure
Ion beam: Rutherford backscattering
Ion beam: Nuclear Reaction Analysis
Laser Induced Breakdown Spectroscopy

Example: W erosion entrainment and re-deposition

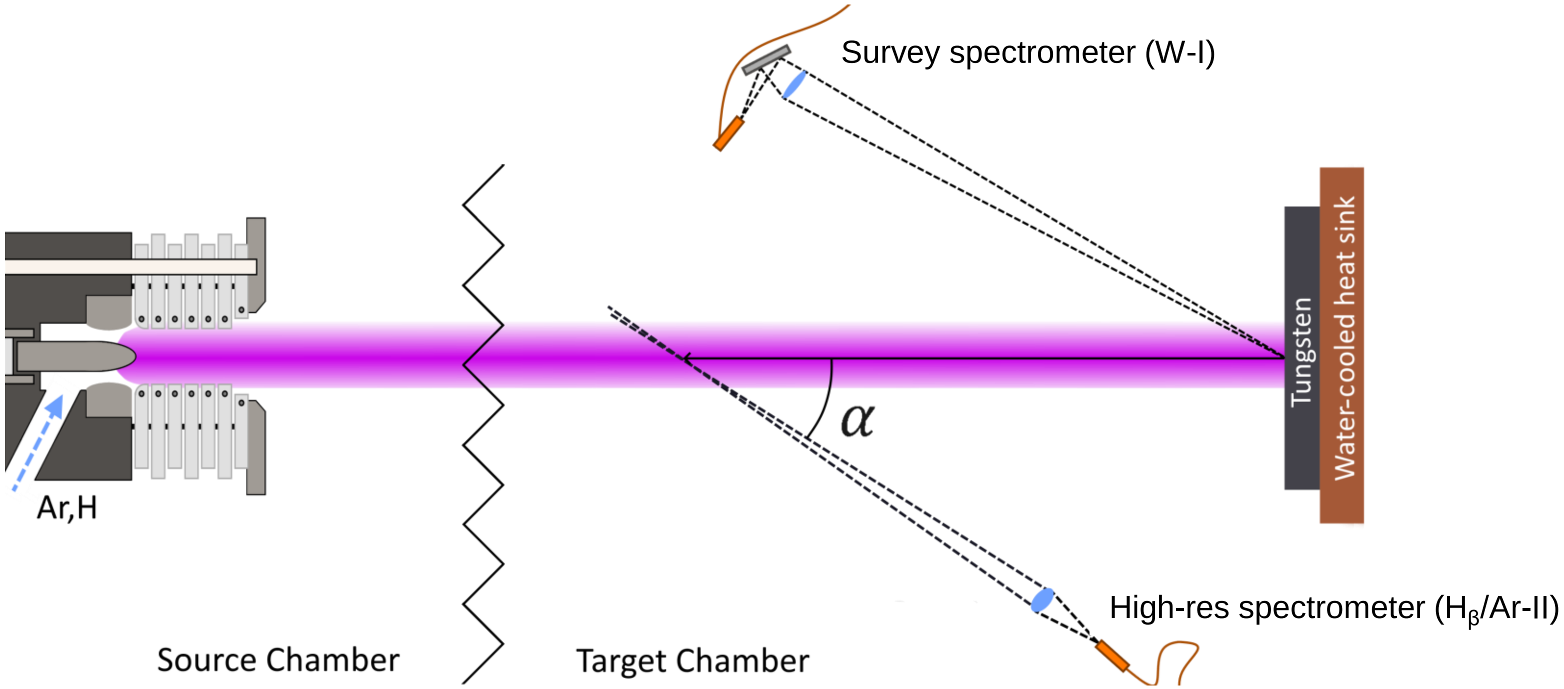
Entrainment results in higher impact energies:

$$E_i = (fM_{\text{ent}}^2 + 1.5)k_bT_e - eV_{\text{bias}}$$

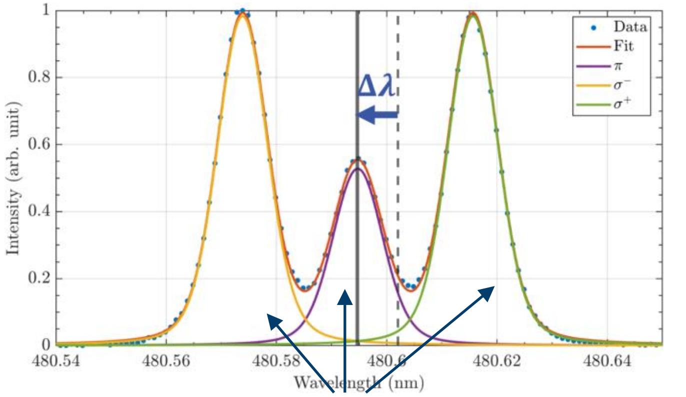
f = mass ratio between impurity & plasma species
M_{ent} = ratio impurity speed & plasma sound speed



Two methods used to measure entrainment

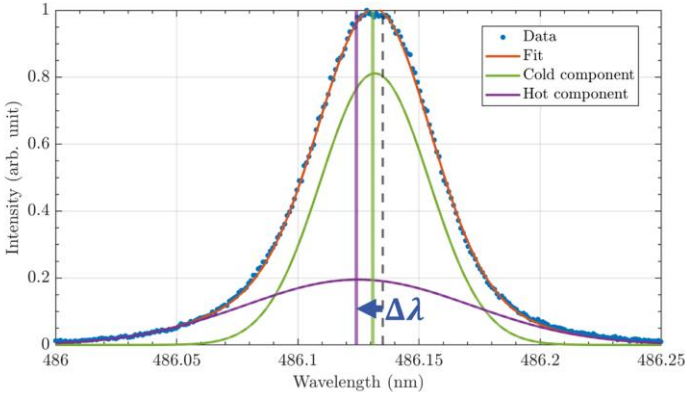


Ar^+ (480.6 nm)



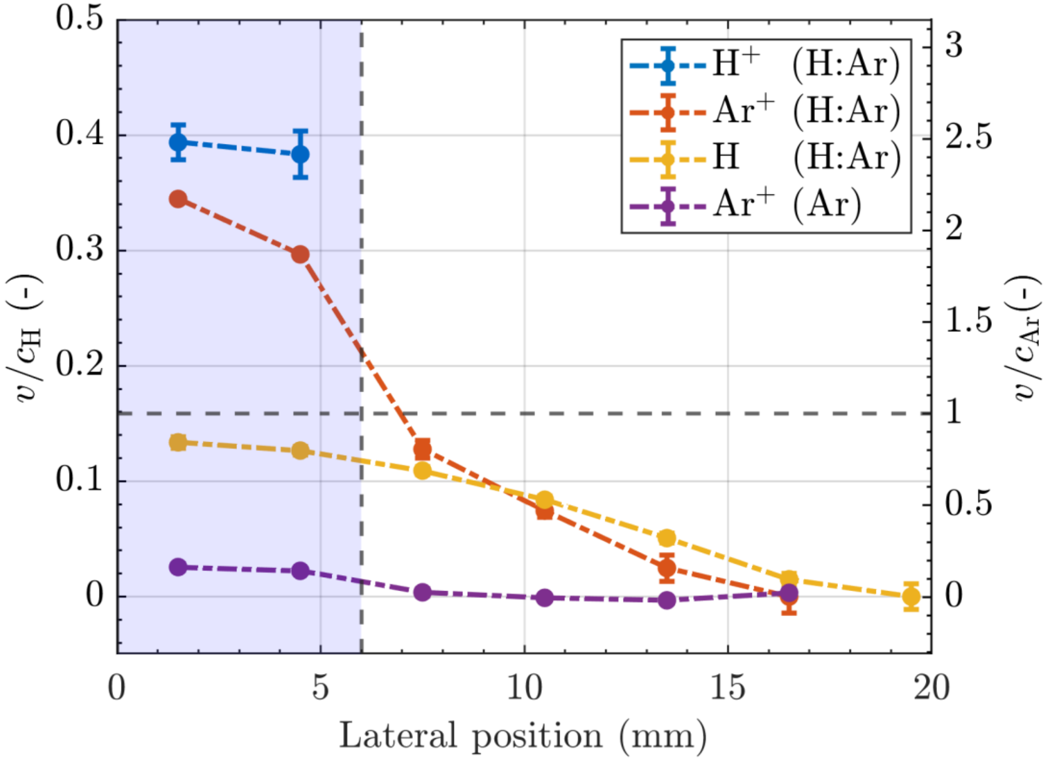
Zeeman splitting

Hβ (486.1 nm)

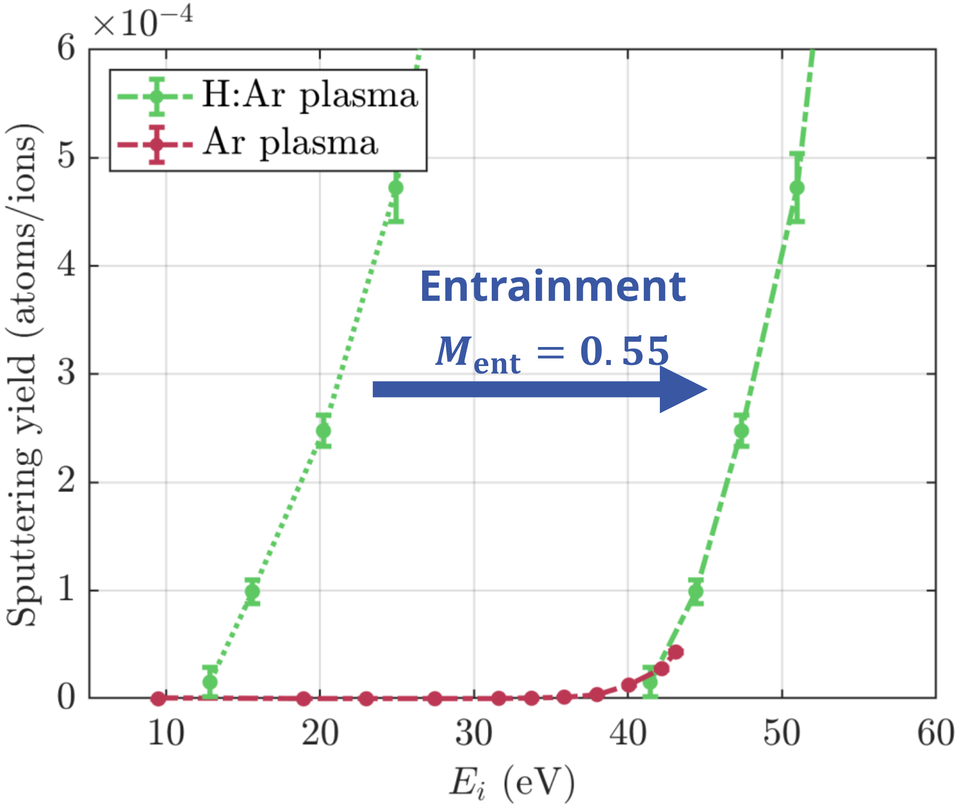


Velocities from Doppler shift

Entrainment accelerates impurities and increases sputtering



Velocity of Ar+ approaches H+ due to entrainment process



Sputtering greatly increased at low ion energies due to entrainment

Through matching to sputtering yield curve can determine M_{ent}

$$E_i = \left(f M_{ent}^2 + 1.5\right) k_b T_e - eV_{bias}$$

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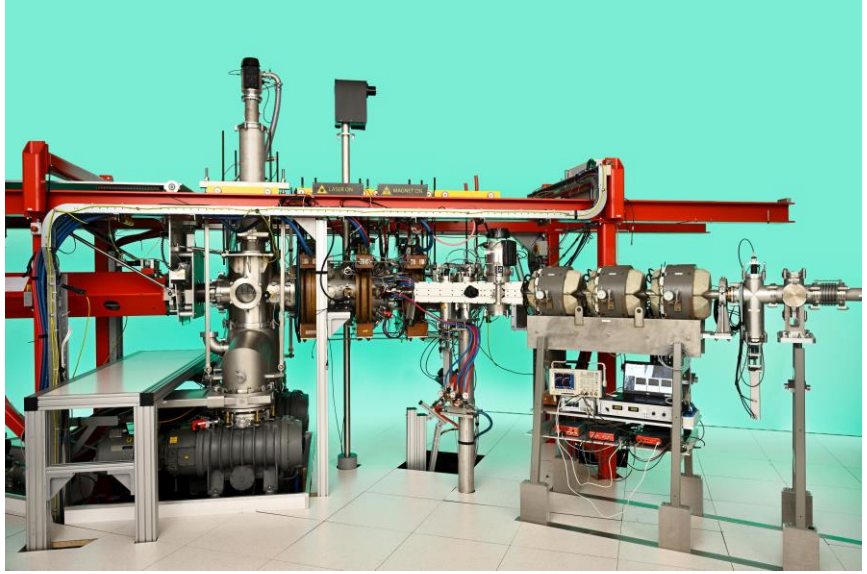
Upgraded Pilot-PSI



UPP offers operando ion-beam analysis (operational since 2024)

Enables e.g. operando measurements of sputtering and redeposition rates, retention rates (also for B)

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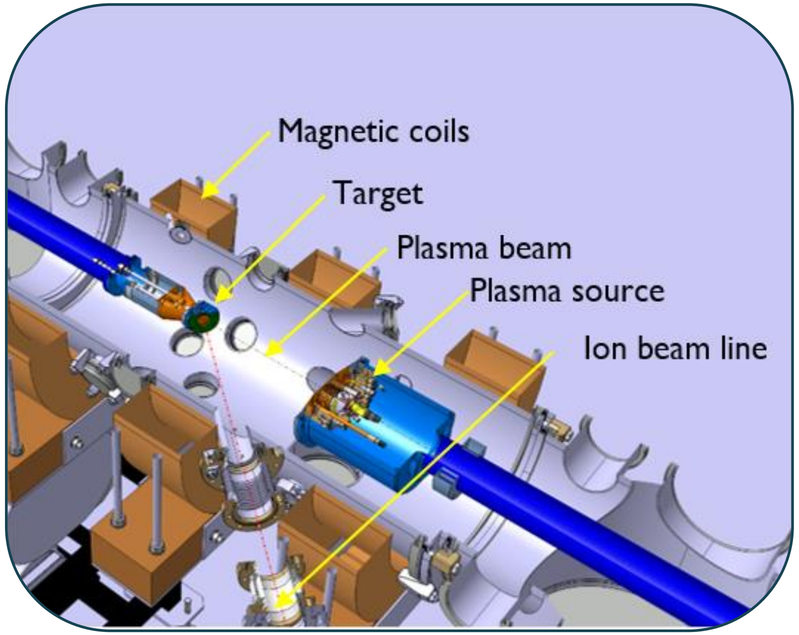
Fast visible light camera up to 1 MHz



BiGyM upgrade

GyM upgrade: BiGyM

Nov. 2022 – Oct. 2025

- 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 researchers** in view of **DTT**
- To start **brand new activities** in other technological sectors, like aerospace, solar collectors and catalysis

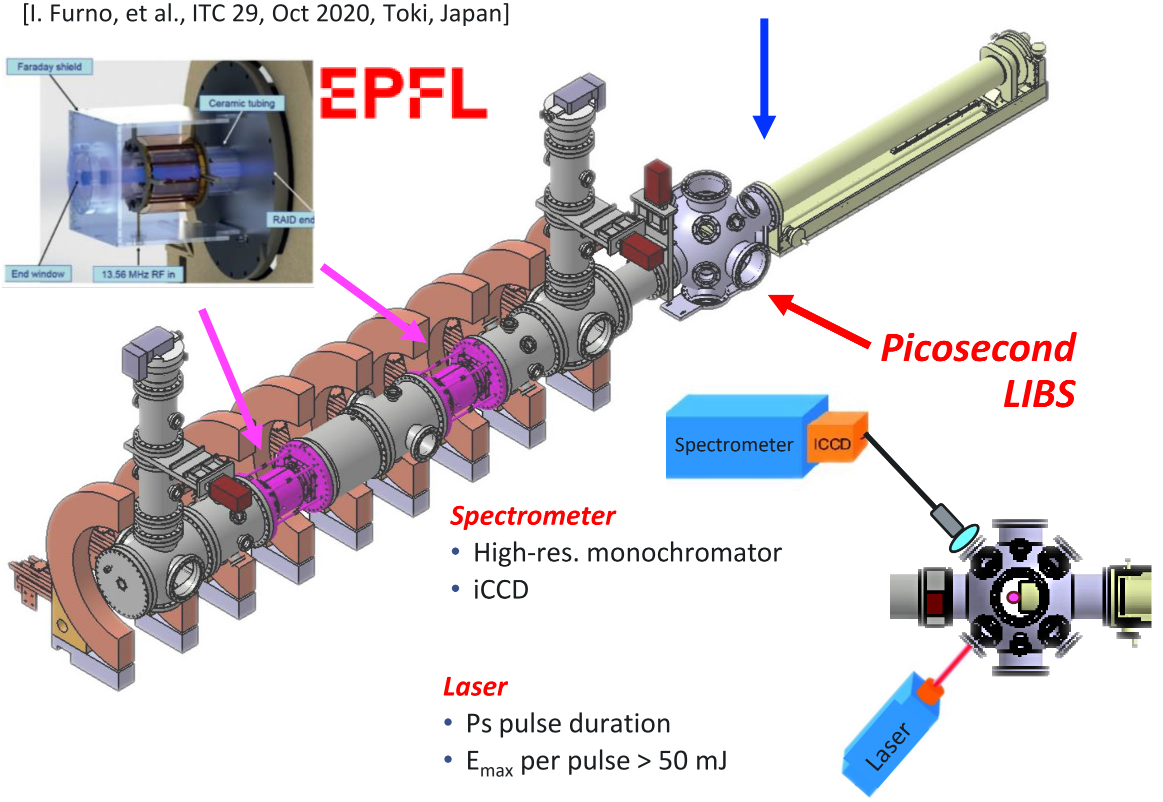
New sample exposure system

- T_{sample} control 400 K - 1500 K
- $V_{bias} \geq$ -300 V
- Rotation: ±180°, tilt: 90°

2 helicon plasma sources

@13.56 MHz,10 kW each

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



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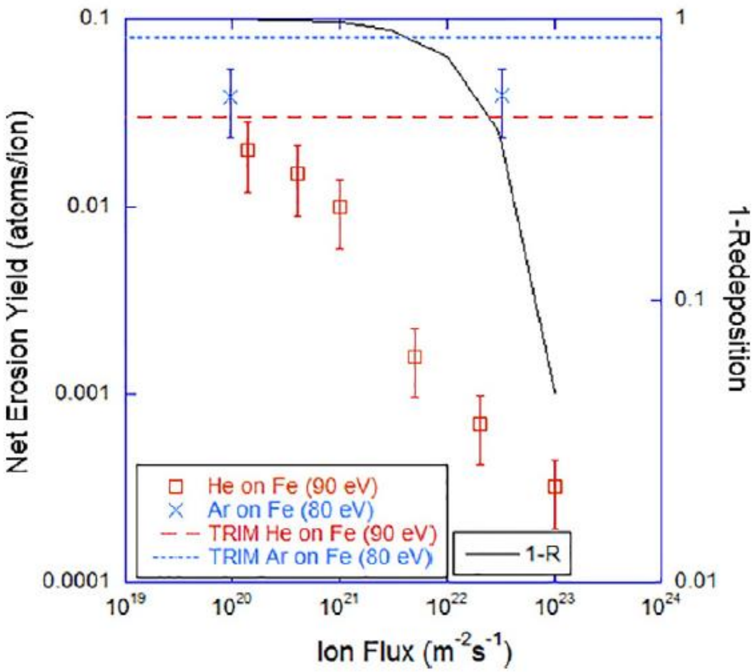
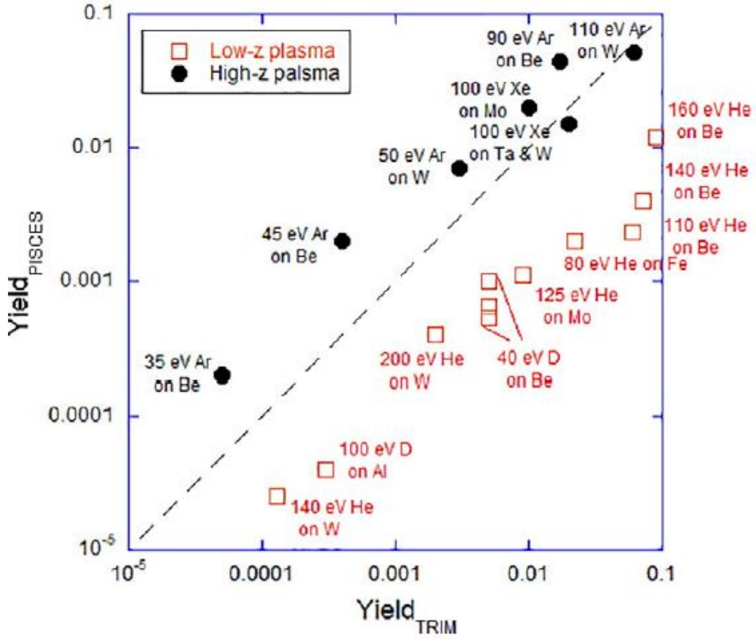
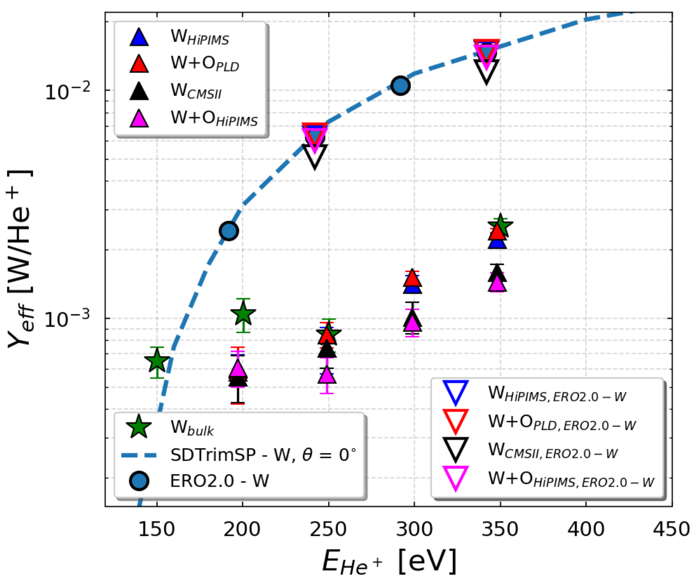
Cross machine studies







Results from PISCES show sputtering yield discrepancy between low and high Z plasmas and as a function of flux [1]

Possibly due to dynamic He retention in near surface [1]

Results from GyM show similar behaviour

Cross machine comparison initiated between GyM, PSI-2 and Magnum-PSI currently underway

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

Summary: Capabilities of LPD’s for W source studies

- Wide variety of conditions achievable with European devices covering expected ITER parameter space for SOL and divertor
- Highly valuable for benchmarking and improvement of codes (e.g. ERO 2.0, SDTRIMSP, MD)
- High quality diagnostics enable studies of important W erosion processes and behaviour in plasma
- Linear plasma devices have been able to elucidate new and important processes relevant for extrapolation of ITER wall performance
- Cross machine studies can offer comparison over wide parameter space
- New machines and upgrades add exciting future possibilities