W fuzz studies in ASDEX Upgrade He plasmas: erosion and formation of W fuzz under L-mode and H-mode conditions

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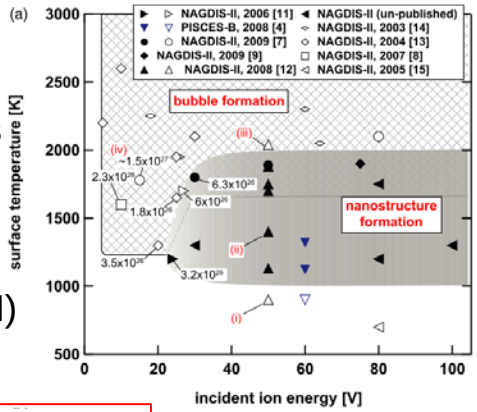
He induced W fuzz formation

Impinging He ions induce coalescence of He in W matrix and formation of He nano-bubbles

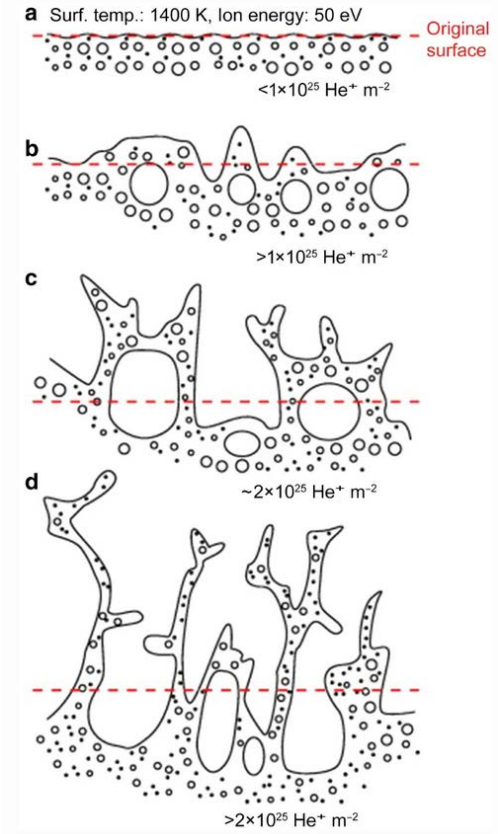
- formation of nanoscale bubbles induces stresses and swelling in W
- stresses relived by cracking and opening of bubbles => forming W nanostructures
- various form of nanostructures: W fuzz, W coral-like structures, W nano-tendrils
- W fuzz influence the erosion and retention properties of W

W fuzz formation requires specific conditions

- W surface temperature T_{surf} > 1000 K, but < 2000 K
- Incident energy of He ion E_{in} > 20 eV
- He ion fluence > 2×10^{24} m^{-2} (also mixed He/H)



S. Kajita, NF (2009)



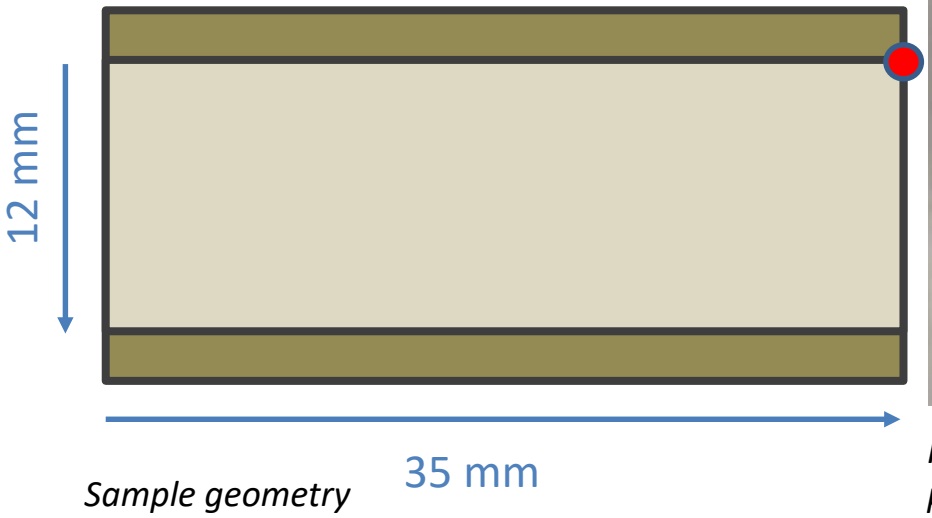
S Kajita, J Nucl Mater. 2011

Mising experiencie from tokamak environment

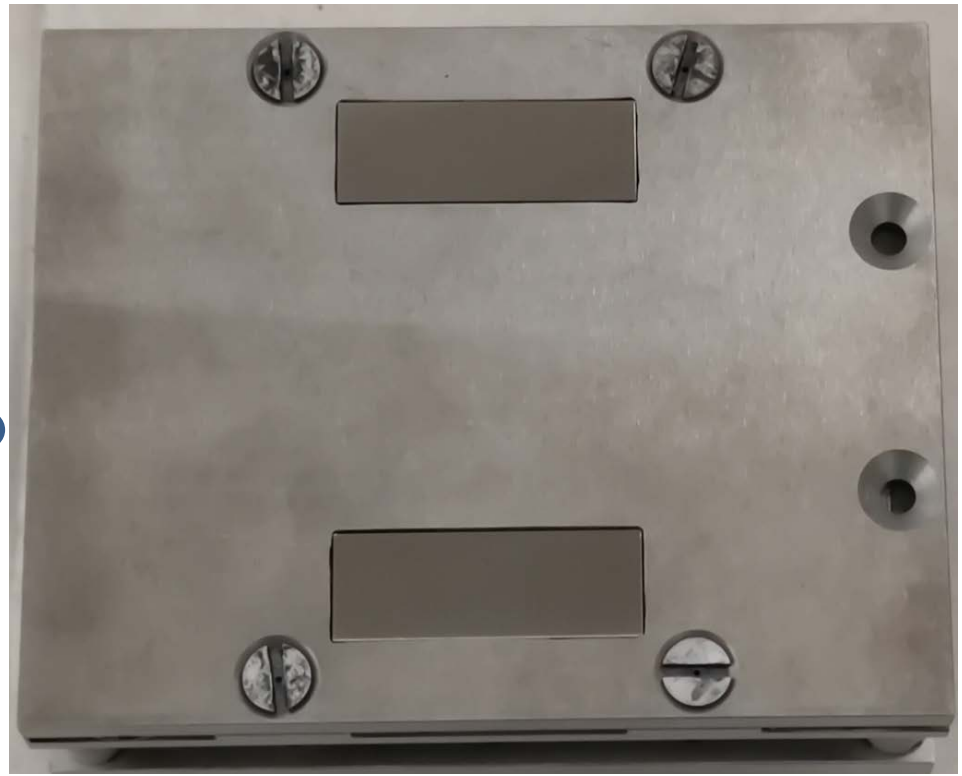
Samples for AUG He exposure

12 samples for AUG He campaign
6 polished + 6 polished and fuzz

PSI-2 exposure - Fuzz formation
Temperature ~ 900 °C
Ion Flux ~ 8.4×10^{21} $m^{-2}s^{-1}$
Fluence ~ 1.5×10^{25} m^{-2}
Energy ~ 80 eV



Sample geometry



PSI-2 sample holder with 2 samples mounted before He plasma exposure

PSI-2 preparation

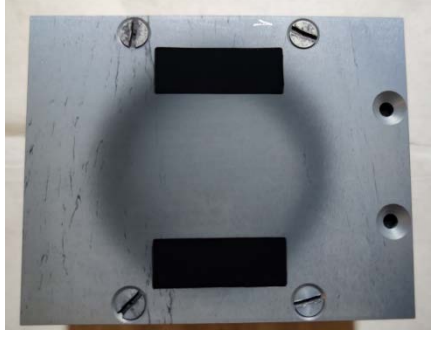
PSI-2 He exposure - Fuzz formation

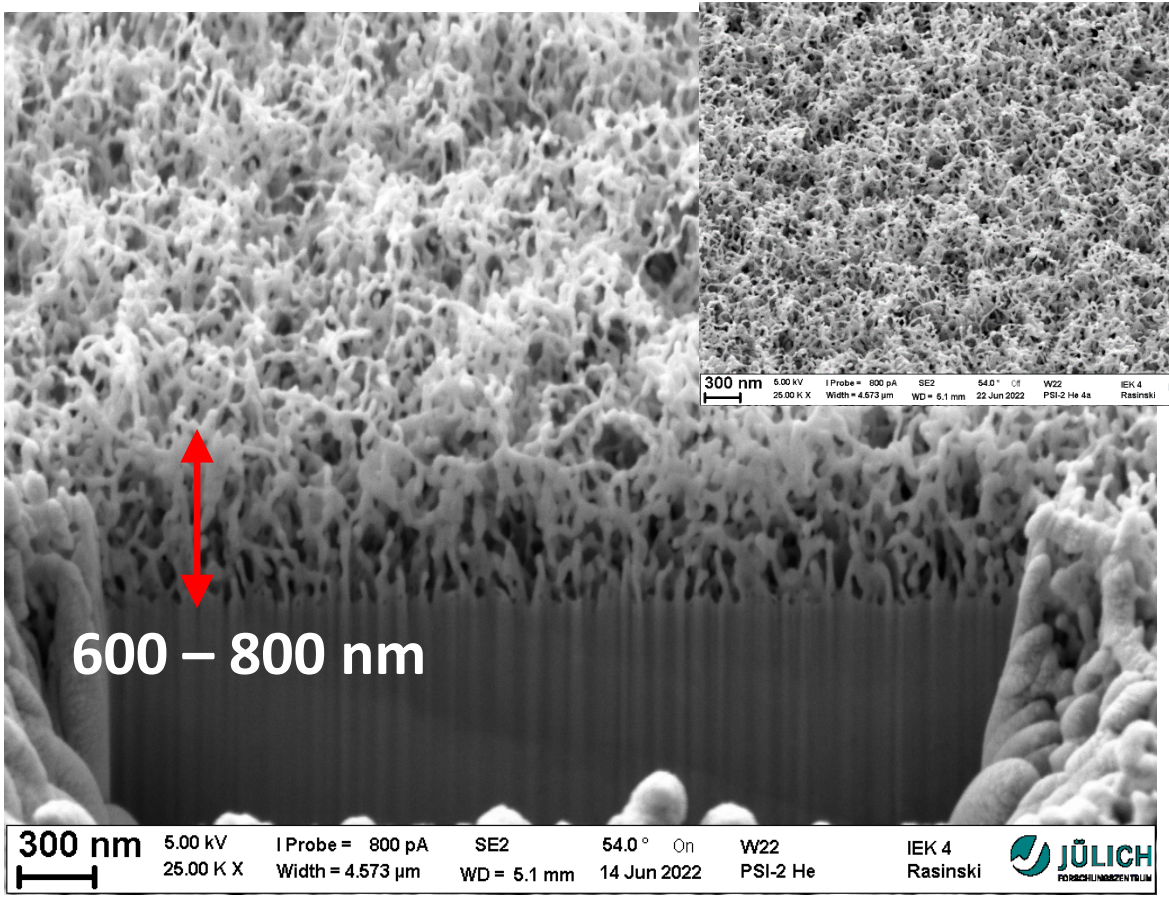
Temperature ~ 900 °C

Ion Flux ~ 8.4×10^{21} $m^{-2}s^{-1}$

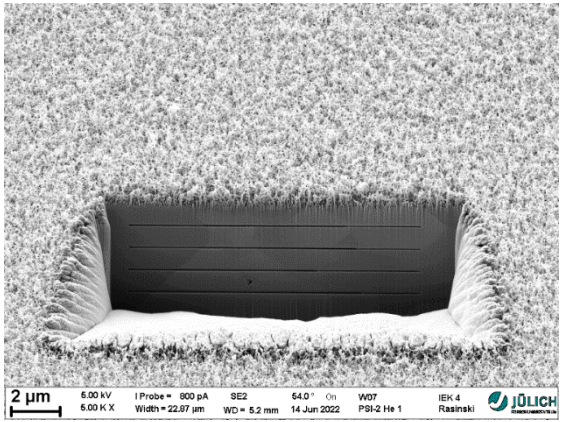
Fluence ~ 1.5×10^{25} m^{-2}

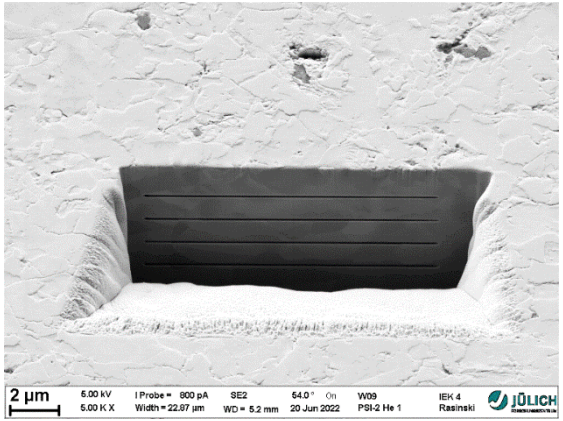
Energy ~ 80 eV

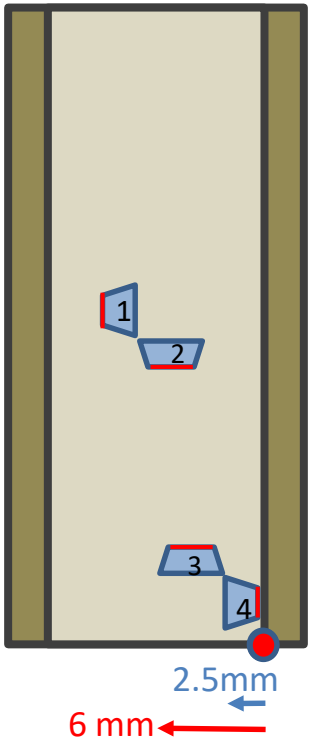




FIB cross-section preparation



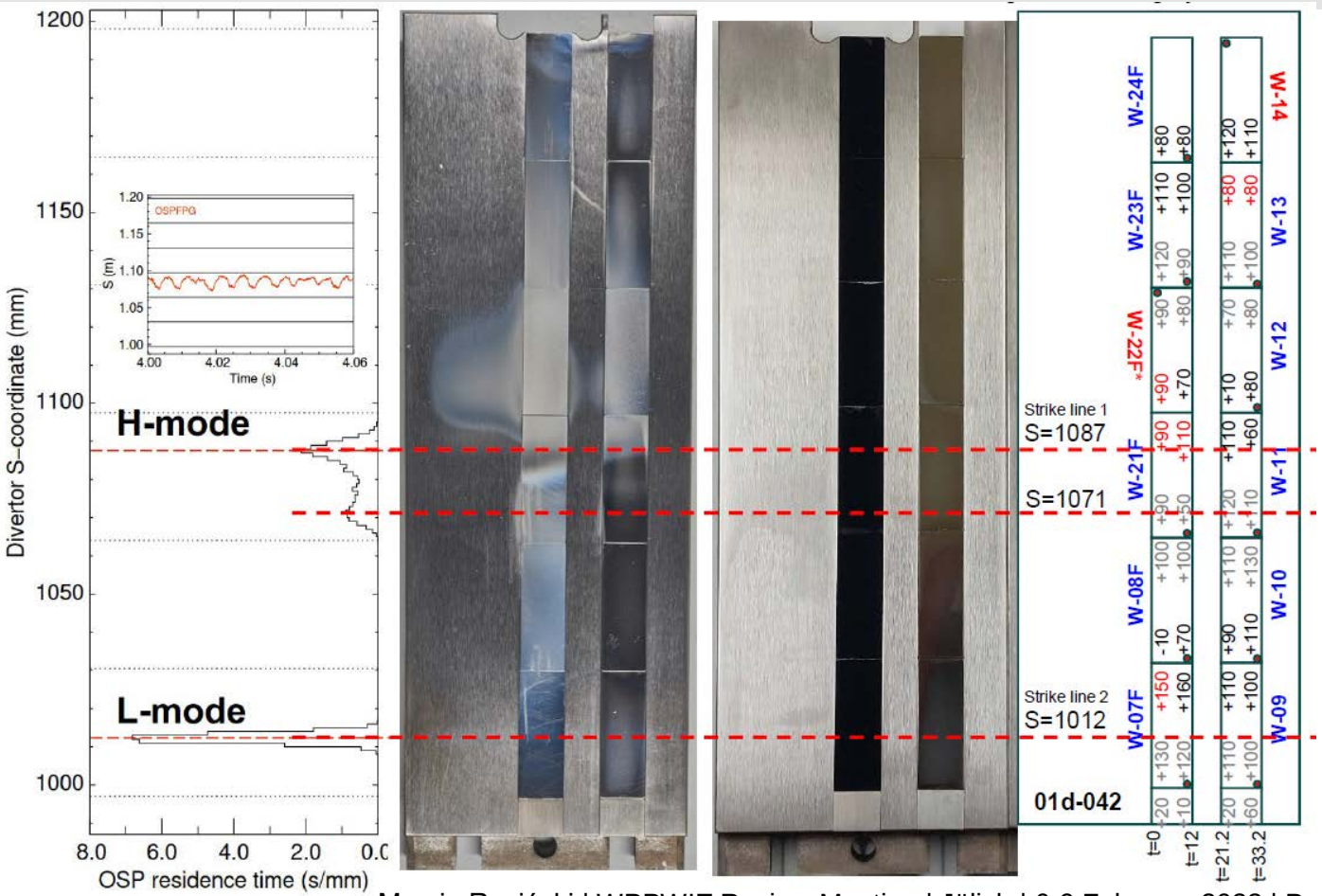




- On each sample **4 FIB cross-sections** with line marking were prepared
- **Different position and orientation** of each cross-section for better understanding the influence of plasma direction
- Cross-section examined **after AUG He** campaign to determine the erosion/deposition and fuzz formation

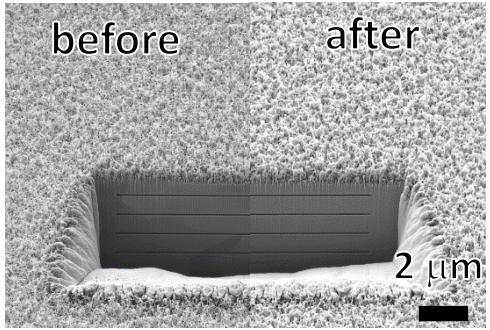
AUG He exposure

- 8 ok H-mode
- 6 ok L-mode



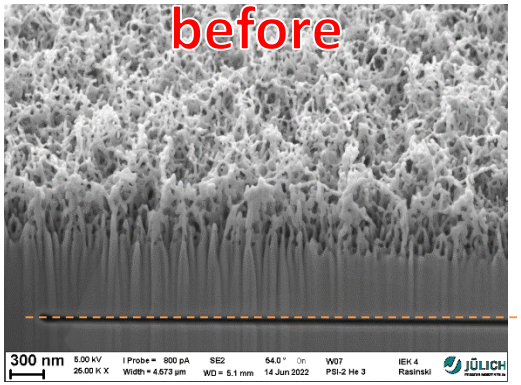
Below L-mode outer strike line position

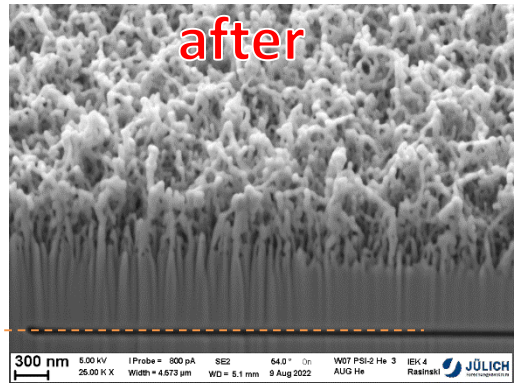
Sample W07 **fuzz** cross-section 3

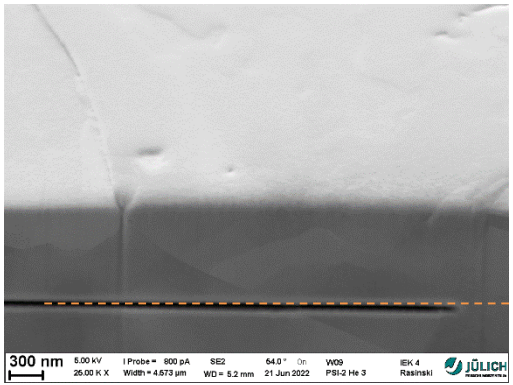


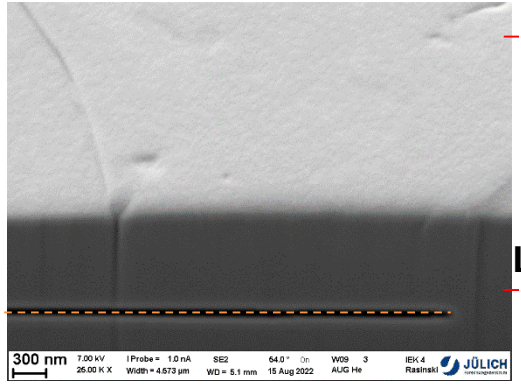
Fuzz from PSI-2
- no visible surface modifications
- PSI-2 fuzz preseved

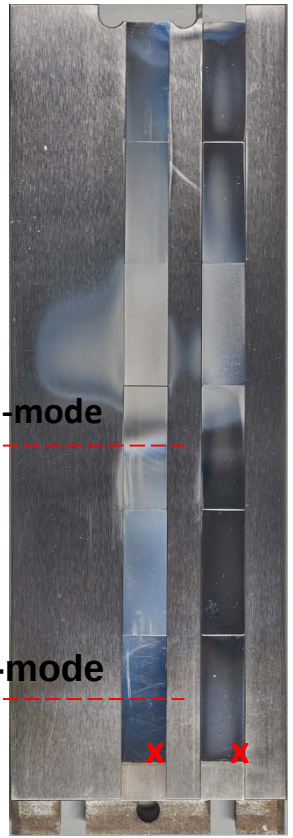
Polished
- no visible surface modifications





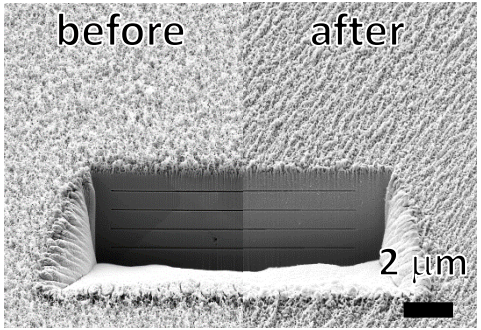






Near L-mode outer strike line position

Sample W7 **fuzz** cross-section 1

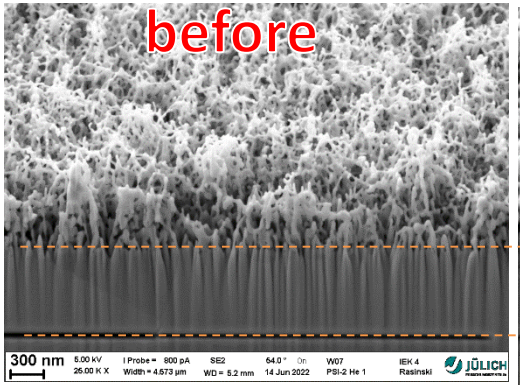


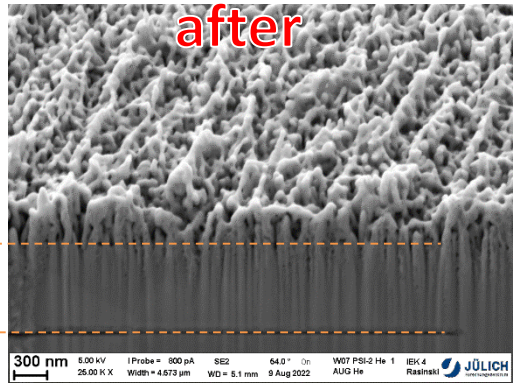
Fuzz from PSI-2

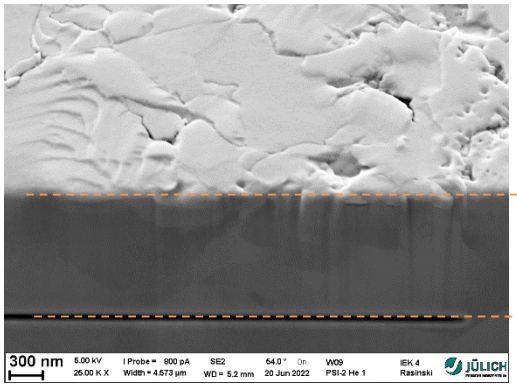
- top part of the fuzz eroded/modified.
- underlying fuzz not modified

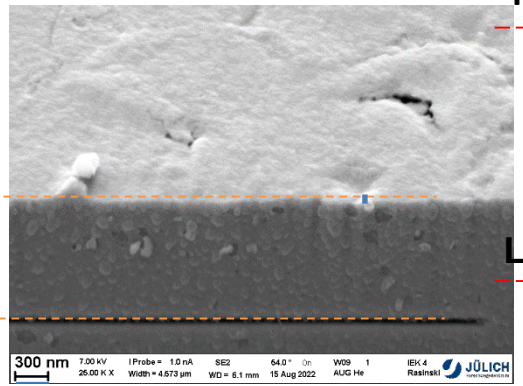
Polished

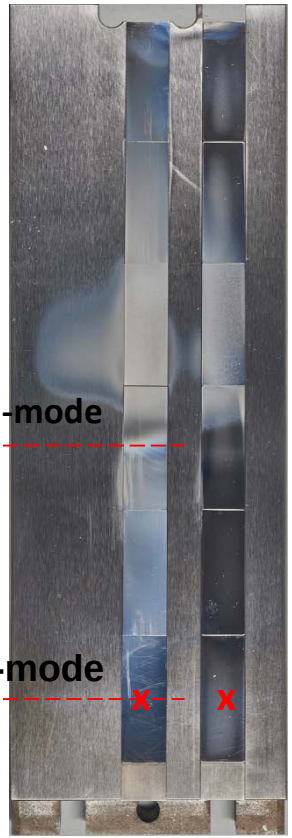
- erosion of ~ 50 nm





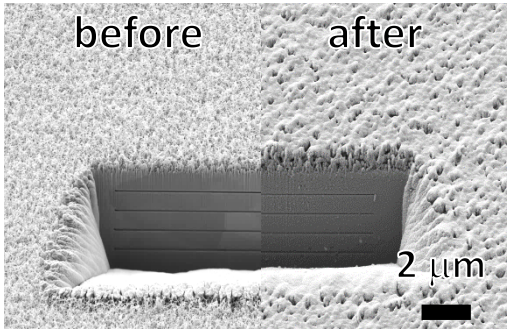






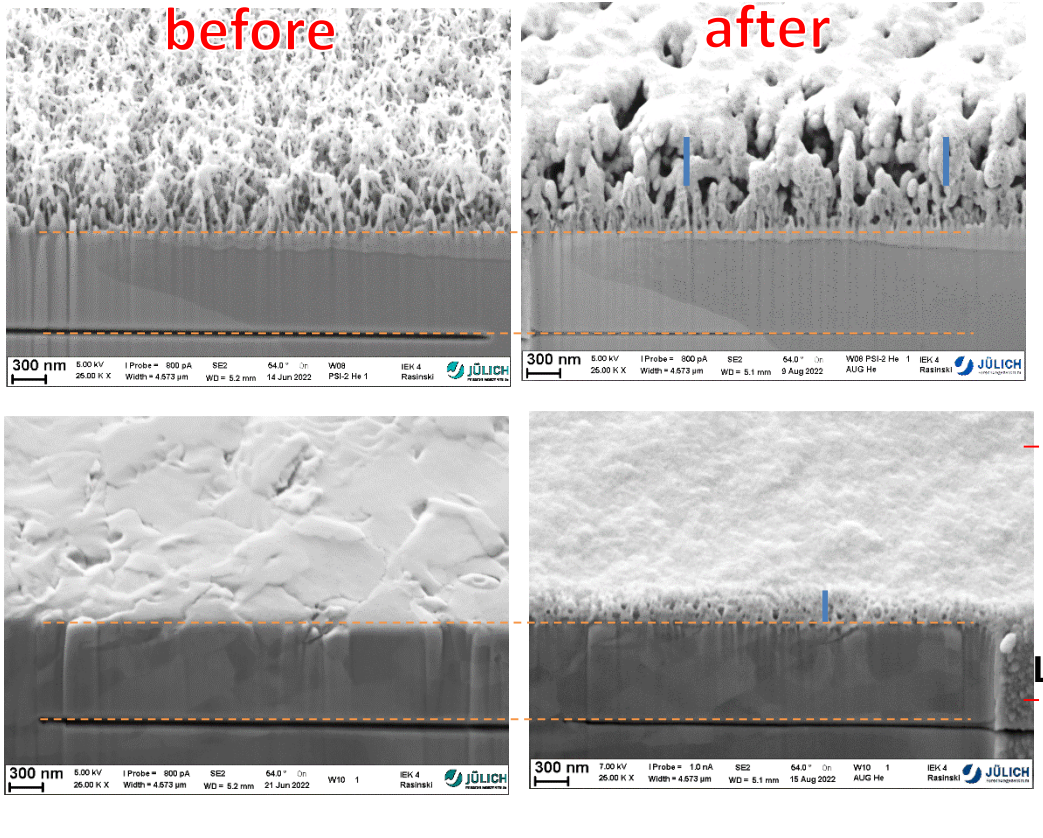
Above L-mode outer strike line position

Sample W08 **fuzz** cross-section 1



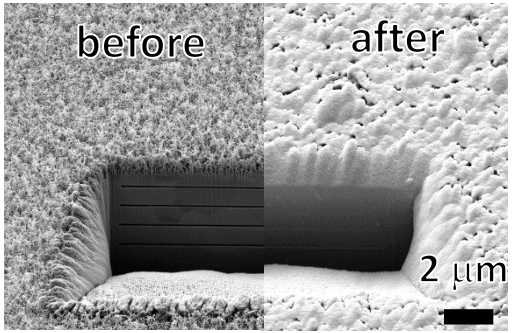
Fuzz from PSI-2
- deposition ~ 400 nm covering the initial fuzz
- underlying fuzz not modified

Polished
- homogeneous deposition ~ 250 nm



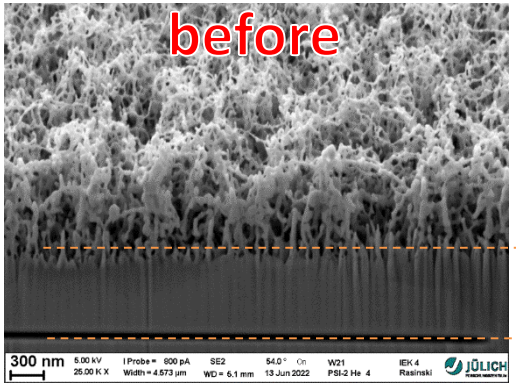
Below H-mode outer strike line position

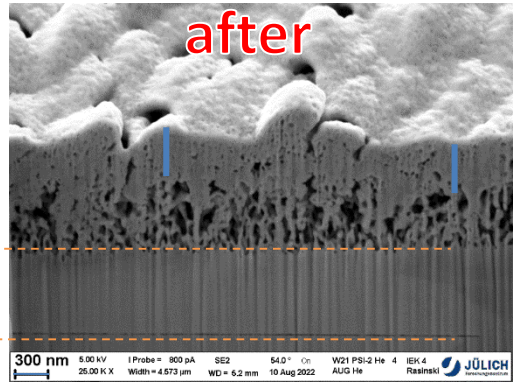
Sample W21 **fuzz** cross-section 4

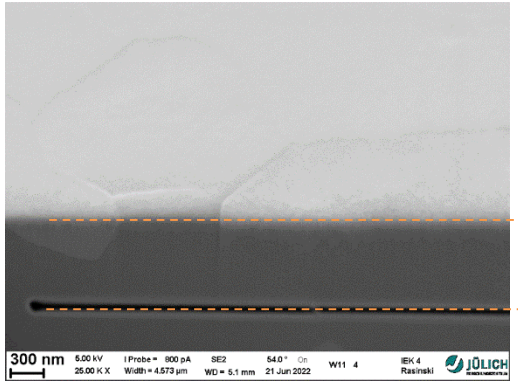


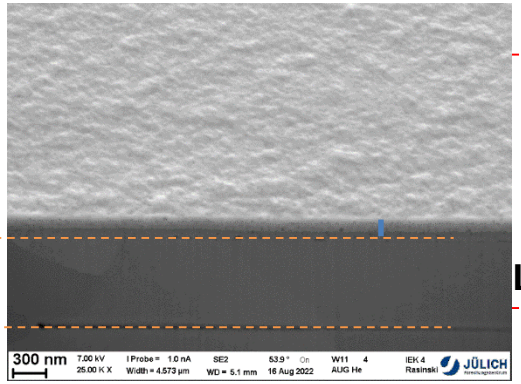
Fuzz from PSI-2
- deposition ~ 400 nm covering the initial fuzz
- underlying fuzz not modified

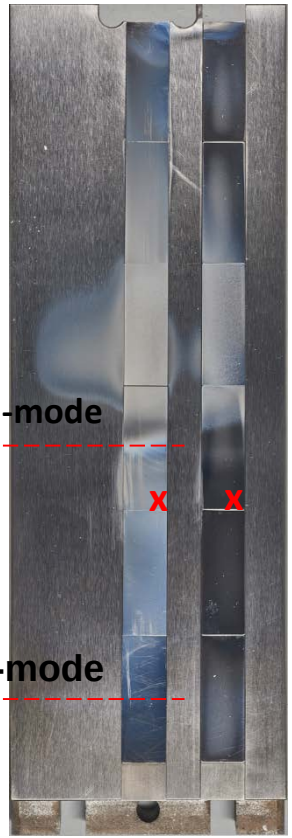
Polished
- homogeneous deposition ~ 200 nm





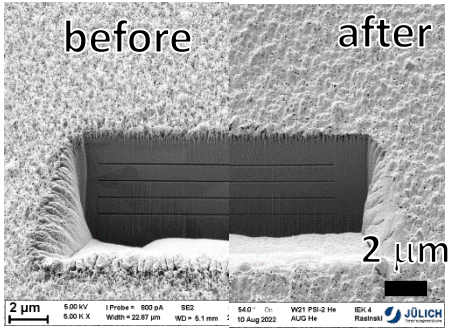






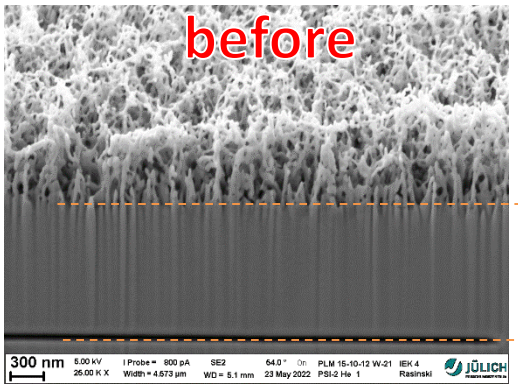
Near H-mode outer strike line position

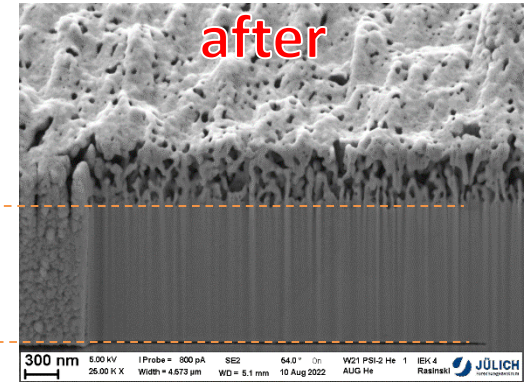
Sample W21 **fuzz** cross-section 4

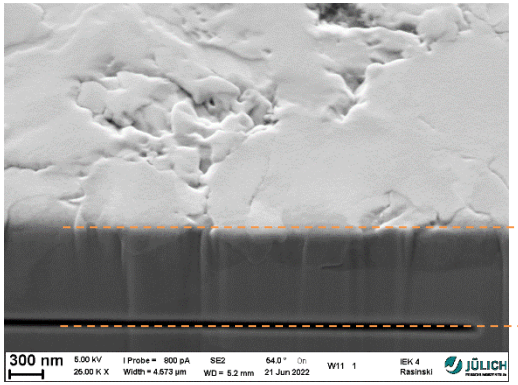


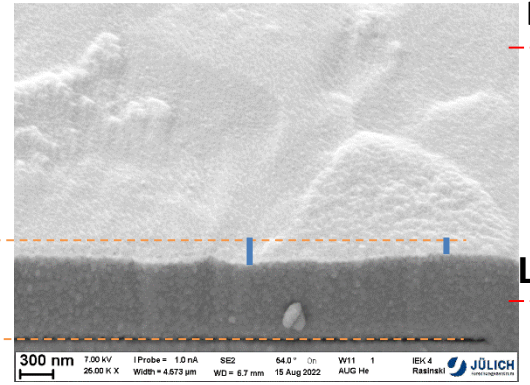
Fuzz from PSI-2
- partial fuzz erosion
- below the erosion fuzz unmodified

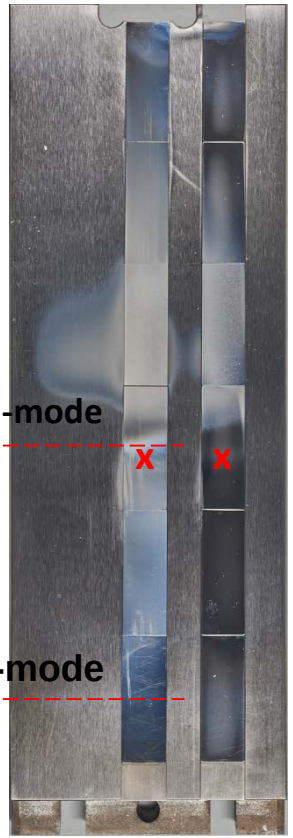
Polished
- erosion 100 – 250 nm



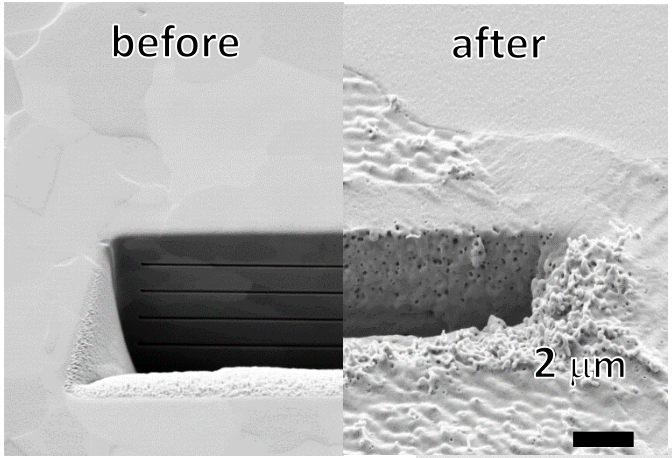


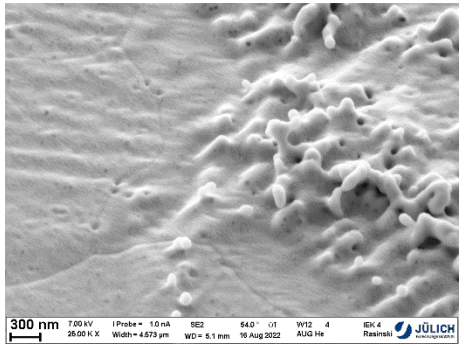




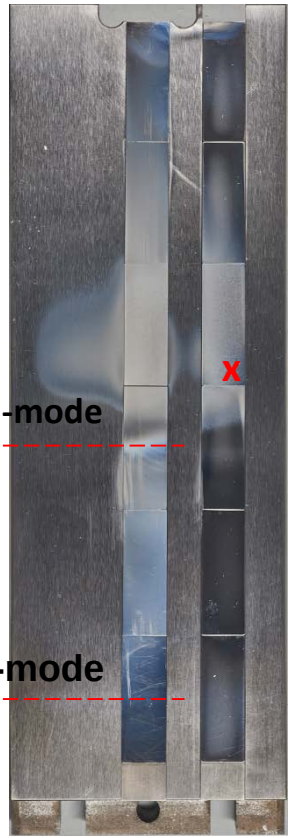


Above H-mode outer strike line position



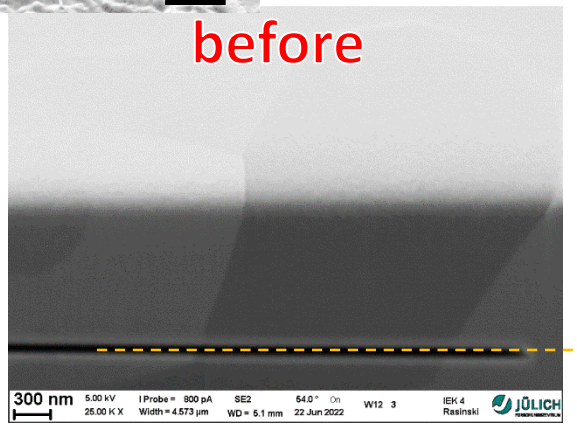


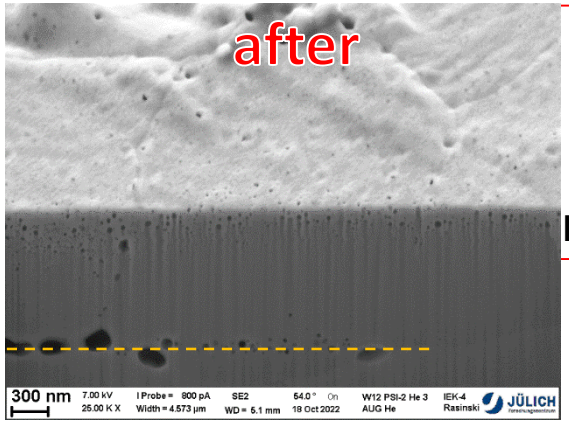
Sample W12 polished cross-section 3



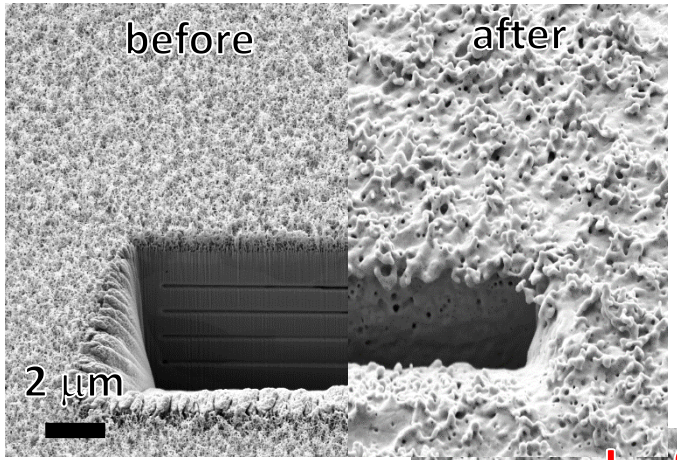
Polished

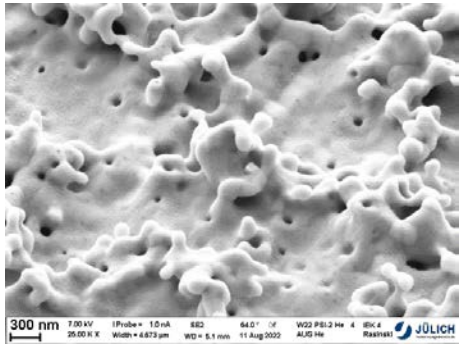
- new fuzz localy present
- formation of the fuzz strongly dependant on grain orientation
- nano-bubble formation



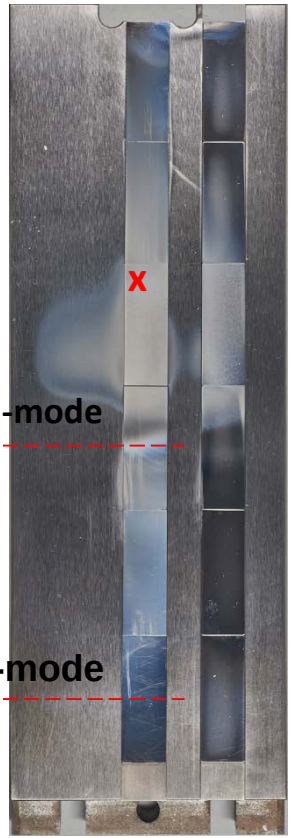


Above H-mode outer strike line position



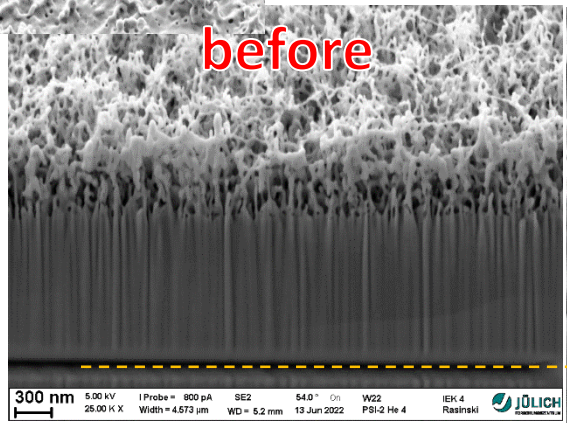


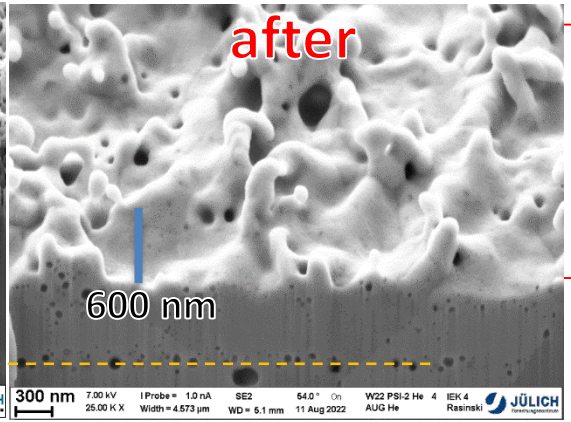
Sample W22 **fuzz** cross-section 4



Fuzz from PSI-2

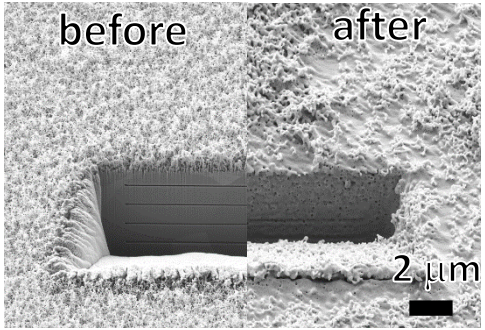
- Fuzz from PSI-2 removed/modified
- new fuzz with thickens below 1 µm was formed
- formation of nano-bubbles below the surface





Above H-mode outer strike line position

Sample W23 **fuzz** cross-section 2

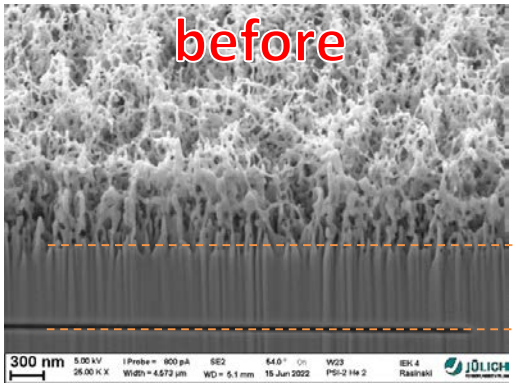


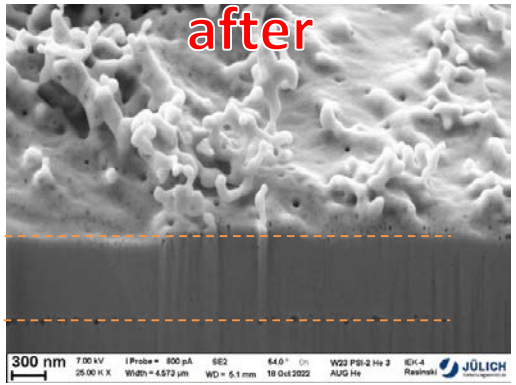
Fuzz from PSI-2

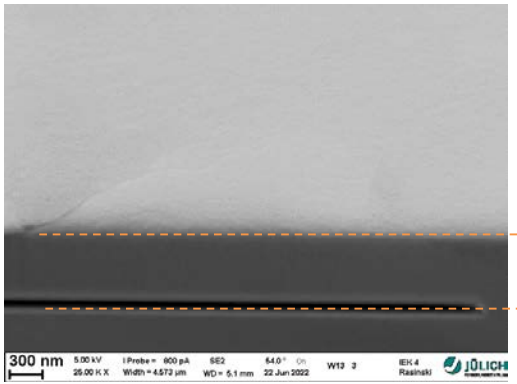
- fuzz from PSI-2 removed/modified
- new fuzz formed

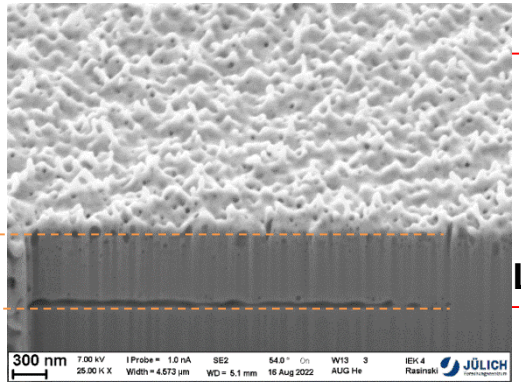
Polished

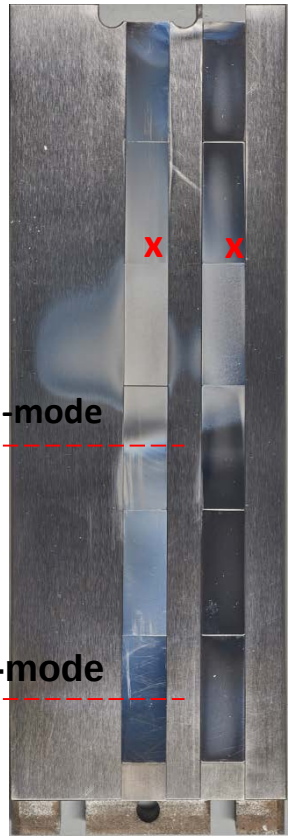
- surface modified with visible roughening and bubble formation





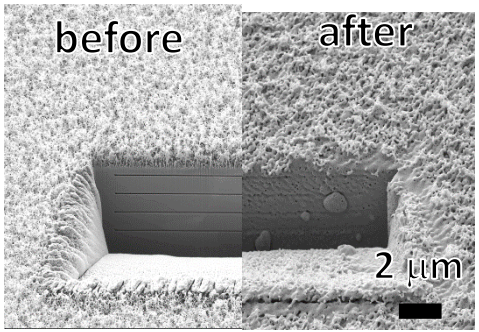






Above H-mode outer strike line position

Sample W22 **fuzz** cross-section 3

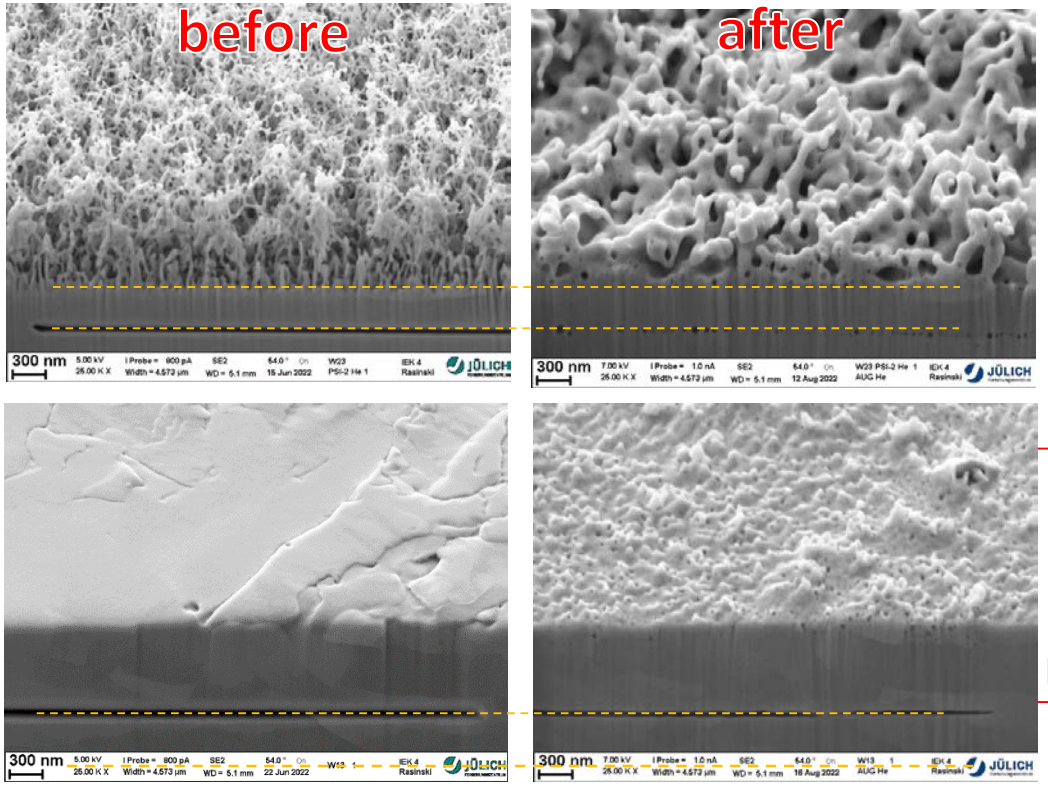


Fuzz from PSI-2

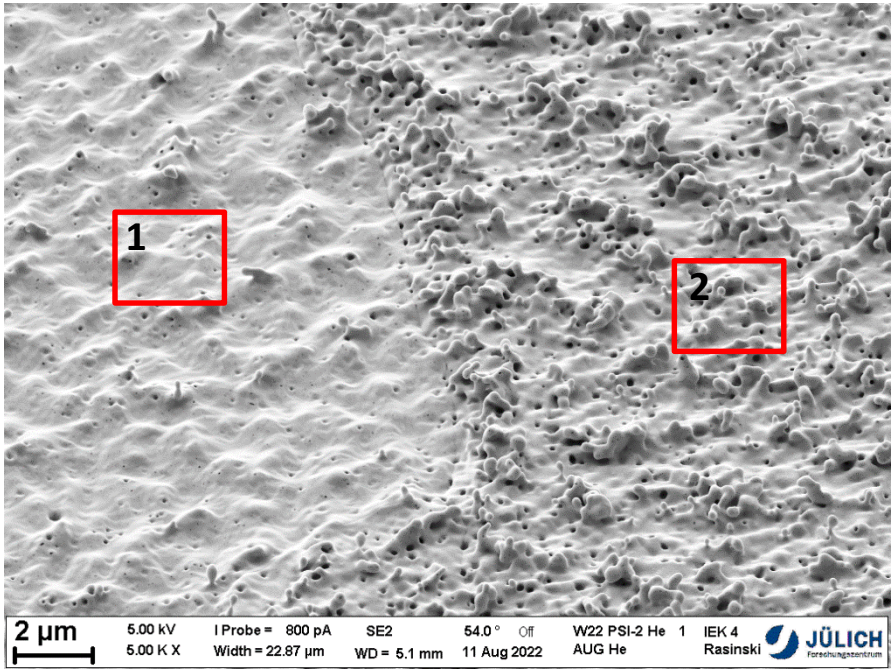
- fuzz from PSI-2 removed/modified
- new fuzz formed

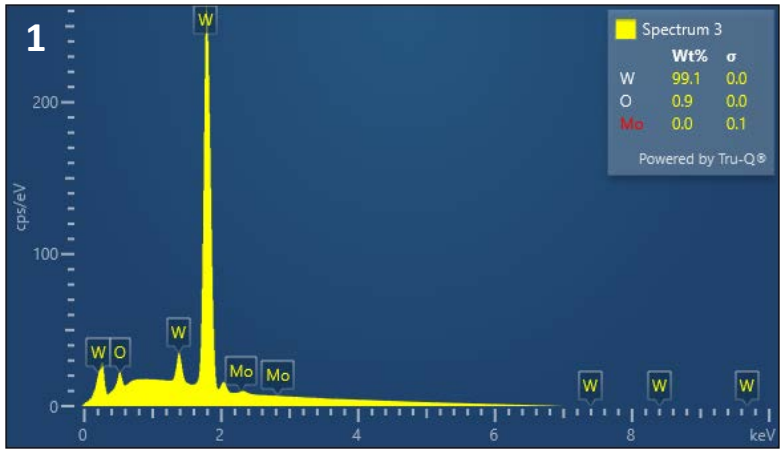
Polished

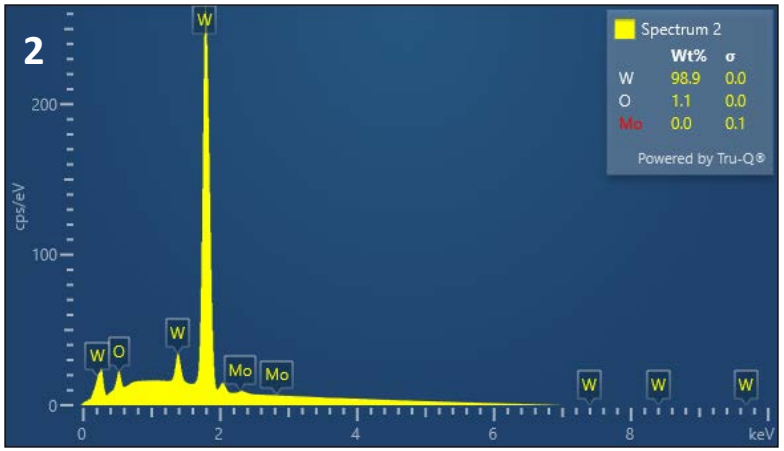
- surface modified with visible roughening and bubble formation



Fuzz formation - EDX



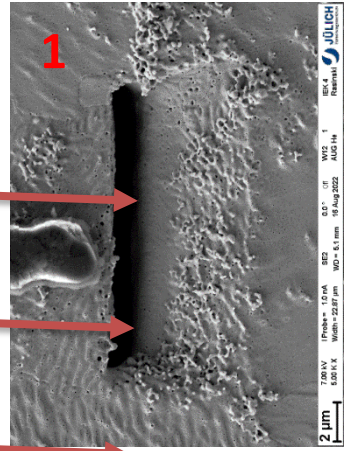


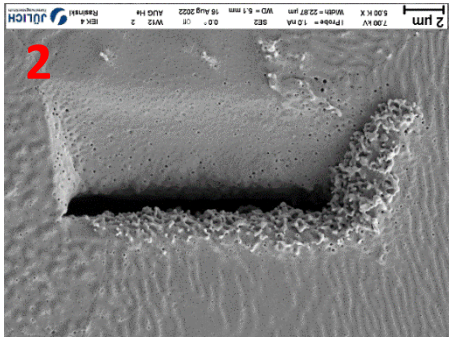


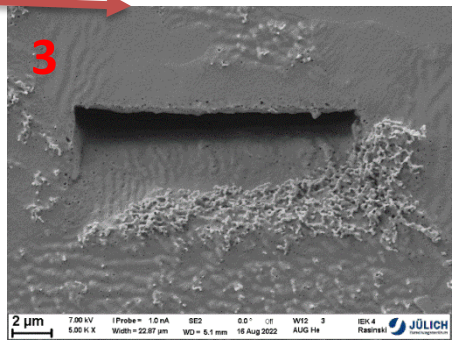
No trace of Mo found on a surface with new fuzz formed under AUG He discharges.

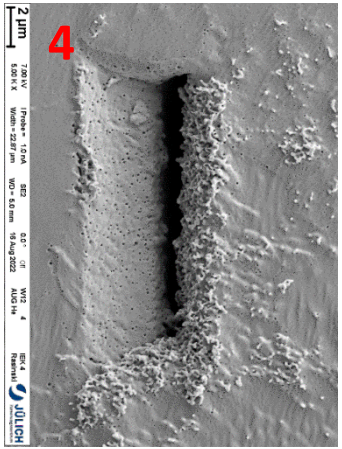
Fuzz formation

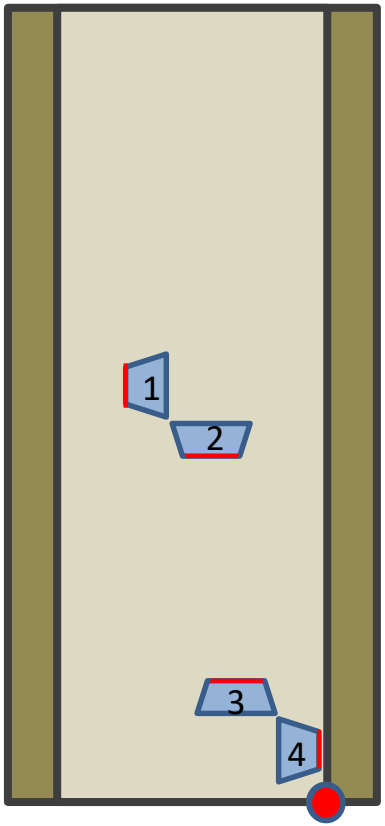
α = -2º, θ = -1.0º



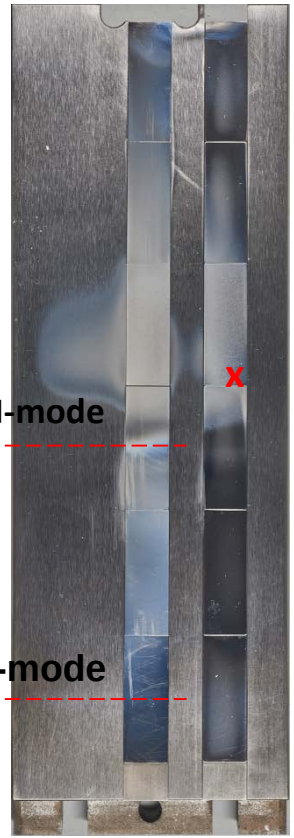








Sample W12 polished



AUG He fuzz analysis

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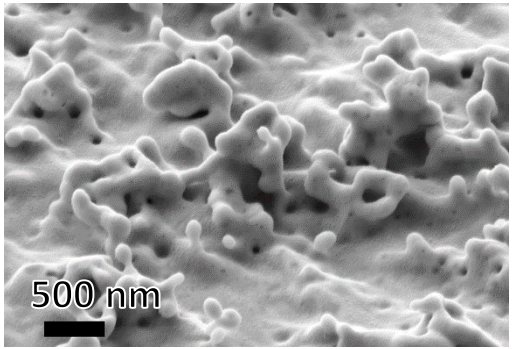
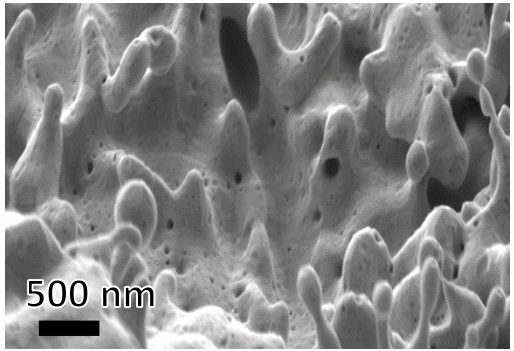
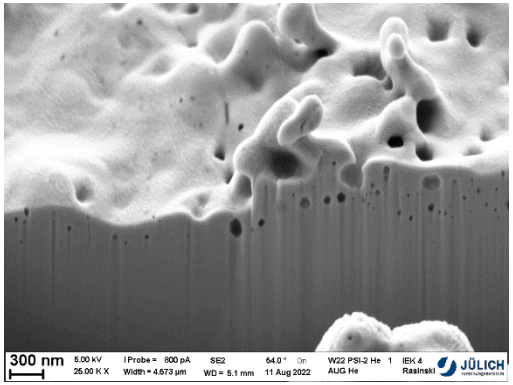
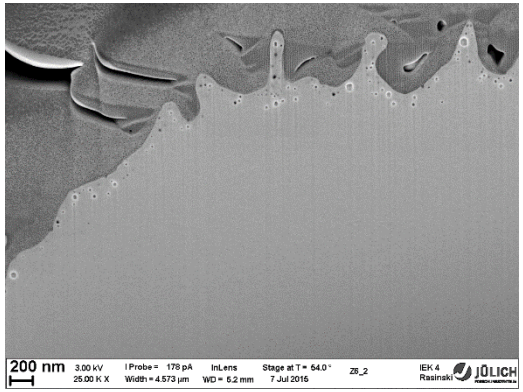






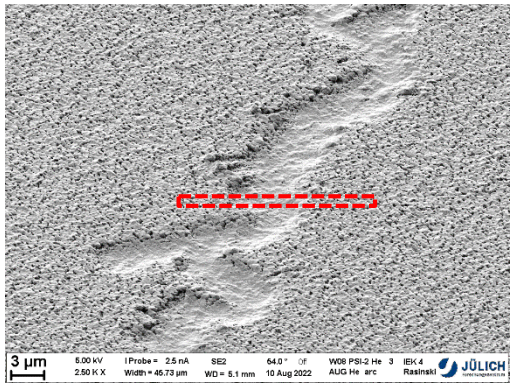


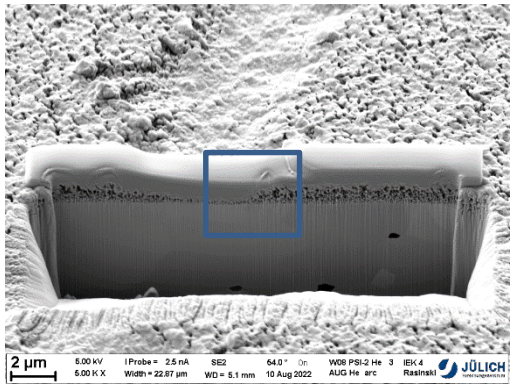
- Similarities between fuzz formed during AUG He and simultaneous PSI-2 He plasma and laser.
- Fuzz structures and bubble formation present after AUG He might be reproducible by simultaneouss laser and plasma loading

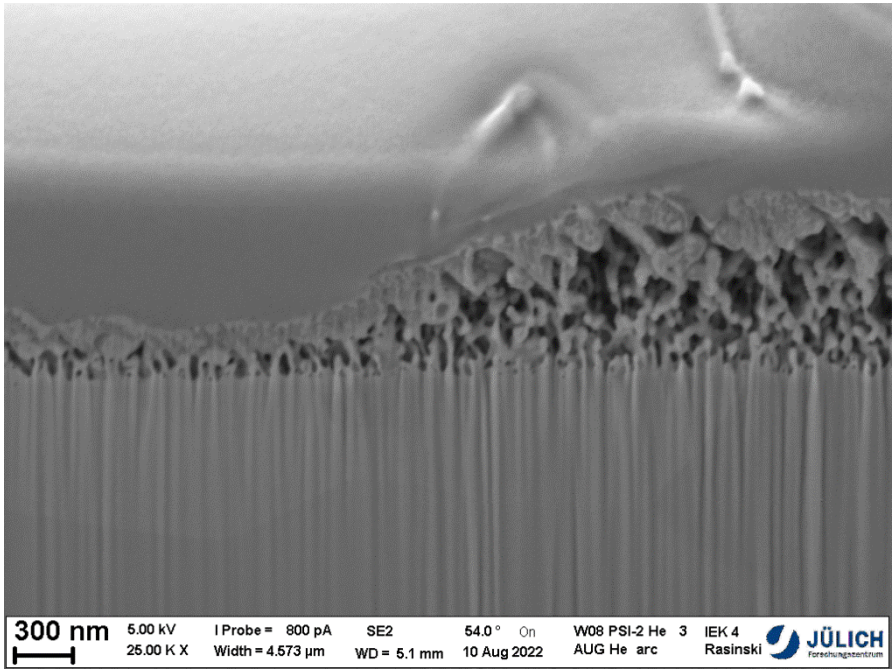
SEM image of a surface and FIB-cross section of the He and laser exposed sample (absorbed power density 0.76 GW/m², 1000 pulses): simultaneous laser and He-plasma exposure at 850 °C;

Arcing

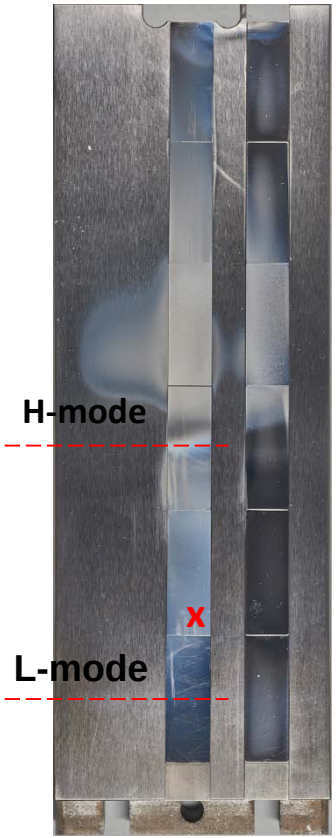
Sample W08 **fuzz**





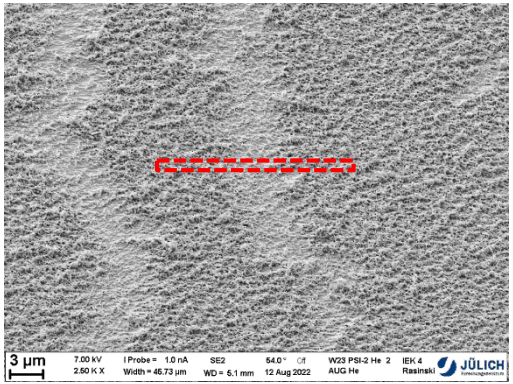


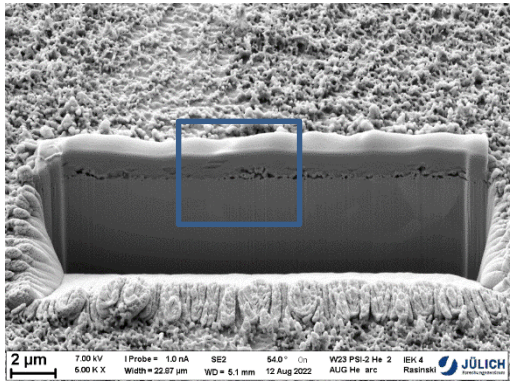
Arc removing the fuzz
No damage to underlying regions in the bulk

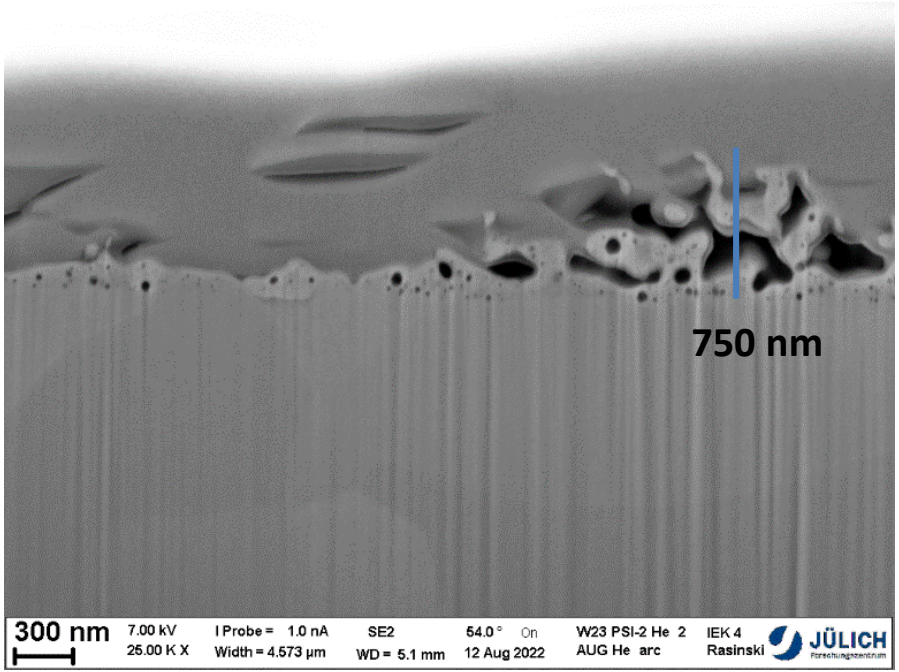


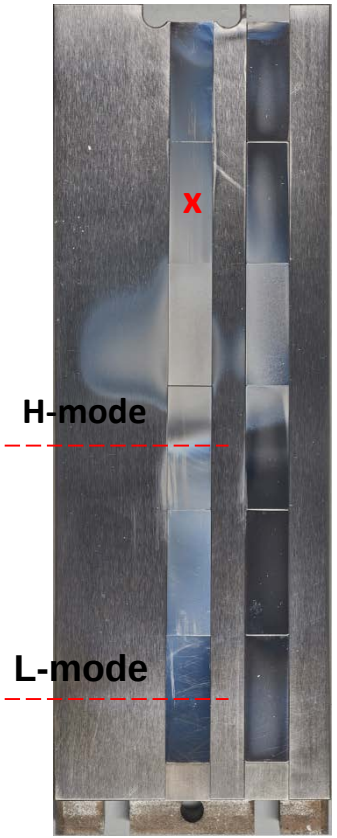
Arcing

Sample W22 **fuzz**









Arc removing the fuzz
No damage to underlying regions in the bulk

Summary

- During **PSI-2 He** plasma exposure **fuzz** with thickness of **600 – 800 nm** was produced
- 48 **FIB cross-section** with line marking was prepared on 6 polished and 6 samples with PSI-2 fuzz
- Prepared samples exposed to 8 H-mode and 6 L-mode **AUG He** discharges

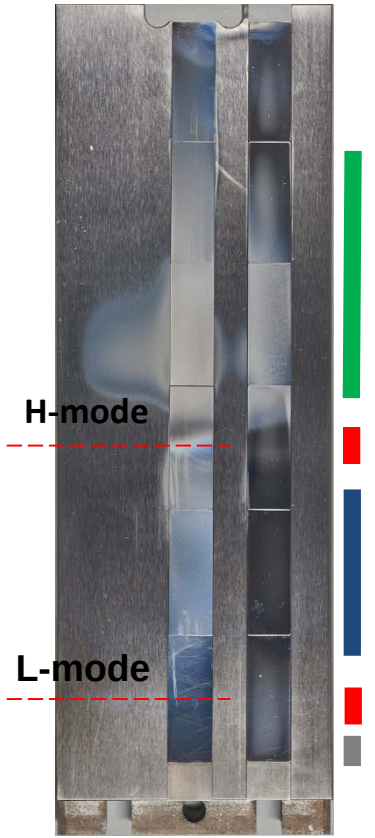
L-mode

- **Below L-mode** OSP **no visible** surface modification
- **Near the L-mode** OSP **erosion** of PSI-2 fuzz as well polished surface was observed
- **Above L-mode** OSP **deposition** of W was found.

H-mode

- **Below H-mode** OSP **deposition** of W was found
- **Near the H-mode** OSP **erosion** of PSI-2 fuzz as well polished surface was observed
- **Above H-mode** OSP **new fuzz** was formed. Fuzz from PSI-2 removed/modified.

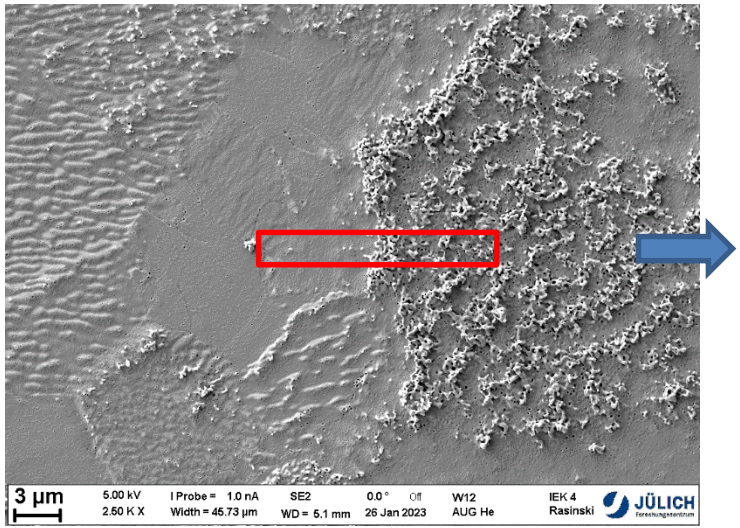
- No traces of Mo was found
- Visible traces of **arcing**, mostly at fuzzy surfaces. Arcs removed the fuzz but did not damage underlying material.



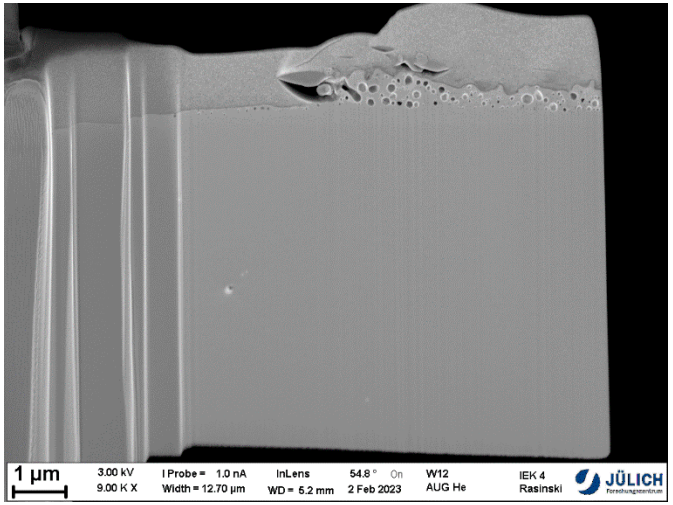
Outlook for 2023

- Correlation between exposure conditions (surface temperature, ion flux, etc.) and fuzz formation.
- Comparison between linear devices and tokamak environment fuzz formation.

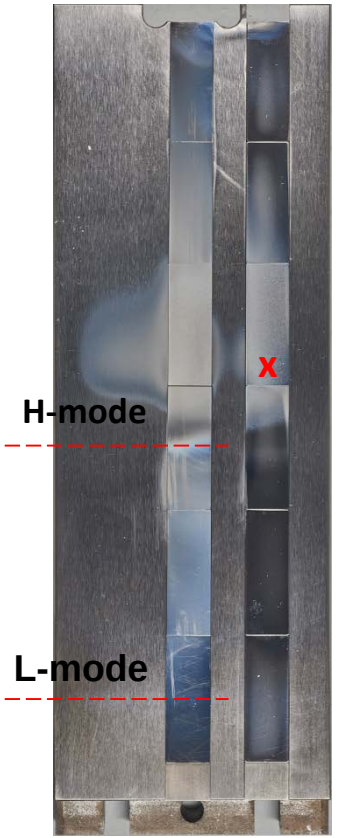
- Investigation on the W grain orientation and fuzz formation by means of TEM/EBSD



SEM image of a AUG He exposed surface. Visible localized fuzz formation

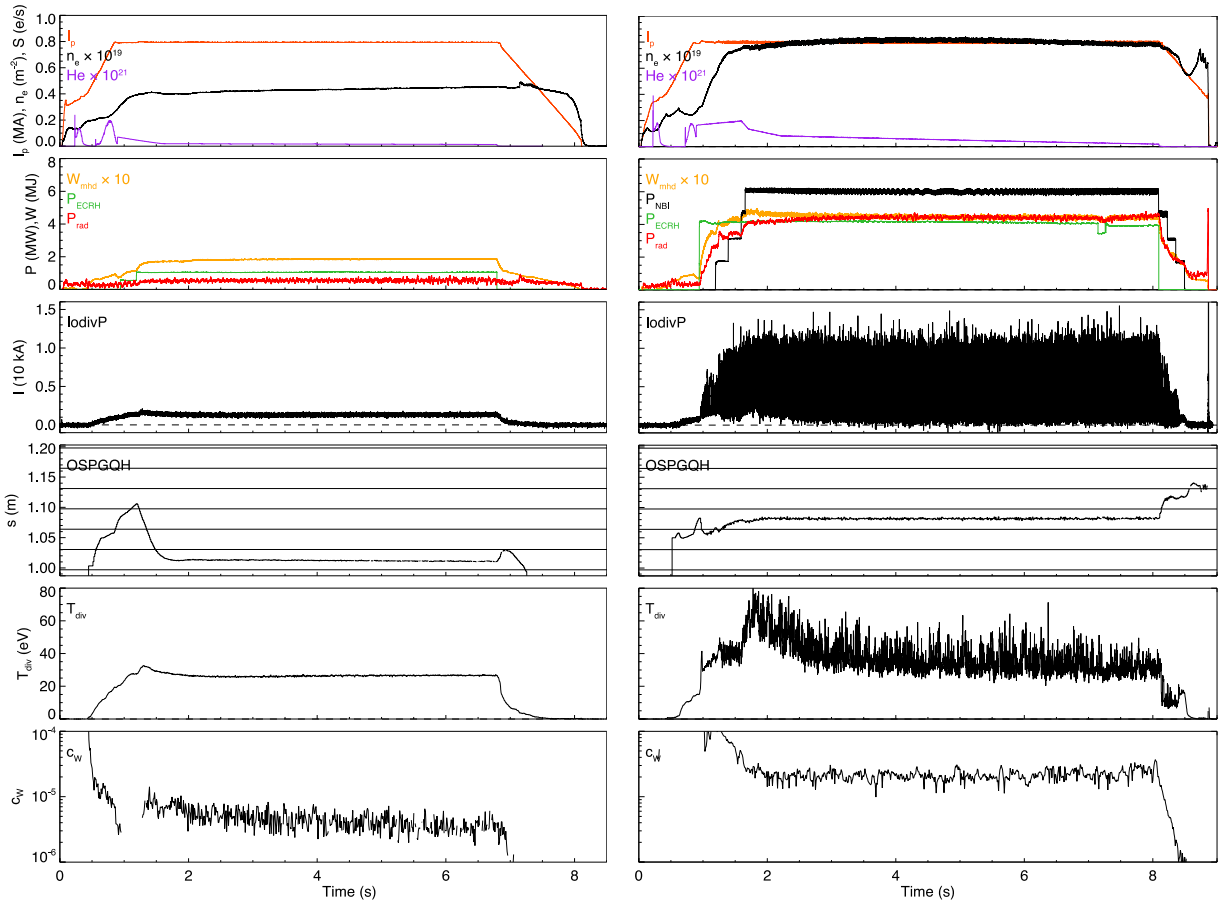


SEM image of a preared TEM lamella.



Scenario – long flat-top 0.8 MA, -2.5 T

L-mode #41480



H-mode #41471