EUROfusion

JÜLICH Forschungszentrum

Reporting Meeting PWIE 2024

PWIE SP A: Presentation of 2024 Task Results

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

SPA– 2023 / 2024 - Overview

SP A.1 Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO

SP A.2 High Particle Fluence Exposures of Plasma-Facing Components for ITER

SP A.3 Advanced Materials under thermo-mechanical and plasma loads

SP A.4 High Temperature performance of Armour Materials: Recrystallization and Melting

SP A.5 Compass-U

- Focus on damage evolution of ITER-like MBs (including WEST MBs)
- Recrystallisation evolution in W (incl. modelling)
- Focus on ITER-like MBs testing under multiple seeding, species, ELMs, and He
- Plasma qualification of new materials for DEMO and other toroidal facilities (e.g. W7-X)
- Disruption-like loading for DEMO (incl. OLMAT)
- *Melting of MBs => MEMETO modelling)*
- *KIPT as possible during cicumstances*

Viability of advanced plasma-facing materials for DEMO-assessed including prototype materials such as W VPS on steel (with WPBB). Lifetime assessment linked to WEST, MAGNUM-PSI, GLADIS and JUDITH testing. (DEMO)

Characterisation of exposed WEST W-PFCs regarding recrystallization and damage. Further studies on material recrystallization physics incl. µ-CT studies (ITER).

Exposure of DEMO baseline W mono-blocks (from WPDIV) in MAGNUM-PSI at high plasms fluence and mixed seeding species (DEMO)

Benchmark of MEMOS-U and new MEMENTO code with W melt experiments in ASDEX Upgrade and WEST (with WPTE). (ITER+DEMO)

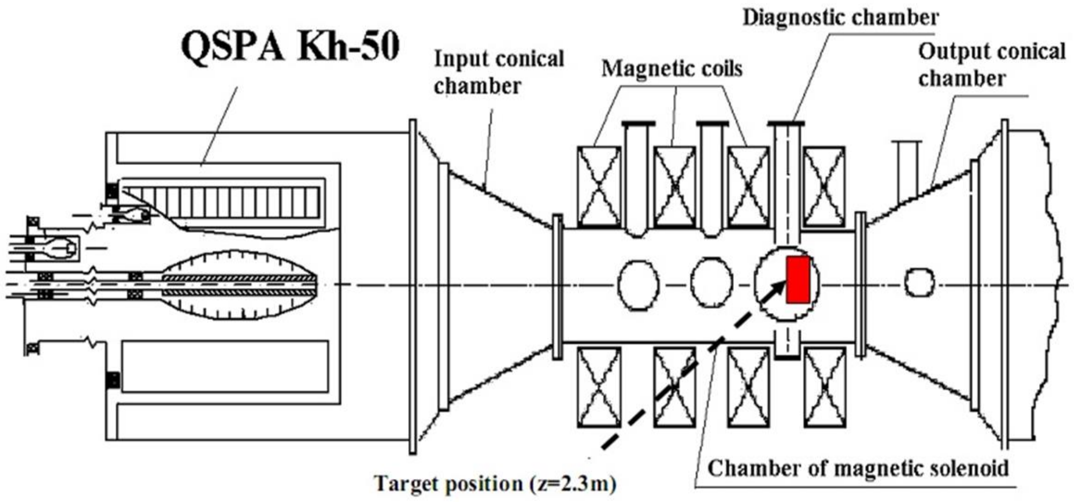
Participants: CEA, CIEMAT, DIFFER, DTU, FZJ, JSI, KIPT, LPP-ERM-KMS, MPG, VR,

Update on KIPT Status

CNN reported that Russia has opened up a new front in its invasion of Ukraine, launching an offensive in the Kharkiv region.

- Unfortunately, a new offensive was launched on May 10, 2024, and is ongoing in the northeastern part of the Kharkiv region.
- Nevertheless, the QSPA Team of technicians and researchers is working onsite to provide technical service for facilities and equipment
- All systems of QSPA Kh-50 were put into operation at the beginning of June 2024
- **After a 2.5 year break, QSPA is producing plasma again**!
- QSPA experiments are currently in progress.

Facility: QSPA Kh-50



Energy density [MJ/m^2]	(0.5-30)
Pulse duration [ms]	0.25
Magnetic field [T]	0.54
Plasma pressure [MPa]	(0.3-1.8)
Particle flux [ions×(m^{-2}s^{-1})]	up to 10^{27}
Diameter of the plasma stream [cm]	18 cm

S.S. Herashchenko et al. 2023 Fus. Eng. & Des. 190 113527

More than one month of successful plasma operation was achieved during the summer 2024

Capable of reproducing both disruptions and ELM loads in terms of energy and particle fluxes!

Milestones 2024

Sequential WP-M ID	Related WBS ID	WP Milestone Title	Due Date [mm/yyyy]
WM82	SP A	Feasibility of advanced plasma-facing materials for DEMO, including prototype materials like W FGMs on steel (with WPBB) assessed. Connecting the assessment of their lifespan to testing conducted in facilities such as WEST, MAGNUM-PSI, GLADIS, and JUDITH. (DEMO)	31.12.2024
WM83	SP A	The damage and evolution of material structure on WEST components, as well as linear facilities, analysed. Further investigations into the physics of material recrystallization, including µ-CT studies. (ITER+DEMO)	31.12.2024
WM84	SP A	High fluence experiments with transients on MAGNUM PSI executed to facilitate lifetime and component evolution for ITER and DEMO. (ITER+DEMO)	31.12.2024
WM85	SP A	Experimental studies on ITER relevant loads such as VDEs, related to new W-Wall PFCs executed and analysed. Accompanying studies utilizing modelling with e.g. Memento. (ITER)	31.12.2024

SP A Tasks 2024

SP A1	SP A2	SP A3	SP A4
Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO	**High Particle Fluence Exposures of Plasma-Facing Components for ITER**	**Advanced Materials under thermo-mechanical and plasma loads**	**High Temperature performance of Armour Materials: Recrystallization and Melting**

SP A1

- **Continuation of activities**
- Include KIT FGMs
- Include Pre-damage of W
- Lifetime assesment

SP A2

- **Continuation of activities**
- Choose new Materials / Mockups
  - *PRD/MAT/DIV*
  - *Slow transients + analysis*

SP A3

- **Continuation of activities**
- New Material Types / Samples
- Synergistic Loads on SMART-W

SP A4

- **Continuation of Activities**
- µm- CT Analyse von Compositen
- Further extension of Recrystallisation activities DTU.CEA.FZJ

Added SPA 5 in 2024 / 2025 related to COMPASS U Materials

Activity Sheets / Topics

- Minor Adaptions for 2024
  - Mostly Continuation of work
  - Added resources in SPA 4 during year
  - Added Resources after Call for Proposals – SPA 5

- All information @
- https://idm.euro-fusion.org/default.aspx?uid=2PBXPU

WP PWIE SPA 1

Results 2024

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Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
M. Wirtz	FZJ	5	D001 (M. Gago, D. Dorow-Gerspach*)
T. Morgan	DIFFER	4	D002, (T. Morgan)
D.Alegra	CIEMAT	6	D003 (D. Alegre)
J.Riesch	MPG	3	D004 (H. Greuner, H. Maier, J.Riesch)
I. Garkusha	KIPT	15	D005 (I. Garkusha)
Total		33	

Device	Beneficiary	Days	Related Deliverable
PSI-2	FZJ	7	D001
JUDITH	FZJ	15	D001
Accelerator	FZJ	3	D001 jointly with SPA 3/SPA 4
GLADIS	MPG	5	D004
MAGNUM-PSI	DIFFER	5	D002
UPP	DIFFER	1	D002
OLMAT	CIEMAT	10	D003

Deliverables:

Deliverable ID	Deliverable Title
D001	Damage threshold for different W materials at varying loading conditions in matrix form / Understanding the damage mechanisms and changes in material properties and changes in the retention behavior (FZJ)
D002	"Evaluation of redeposited tungsten microstructure and evolution under transient loading" (DIFFER)
D003	Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures (CIEMAT)
D004	Qualification of W-Heavy Alloys for use in W7-X in conjunction with test on new tungsten mock-ups (WPMAT) and PFUs for WEST (WPTE) (MPG)
D005	Analysis of material properties after sequential HHF transient and steady-state plasma loading (KIPT).

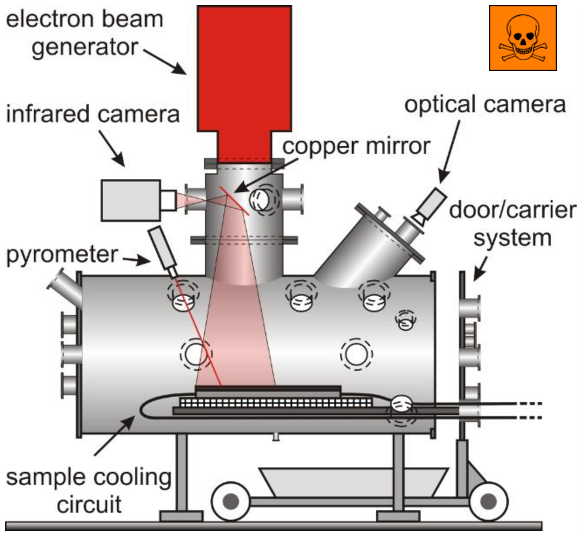
FZJ – Wirtz et al

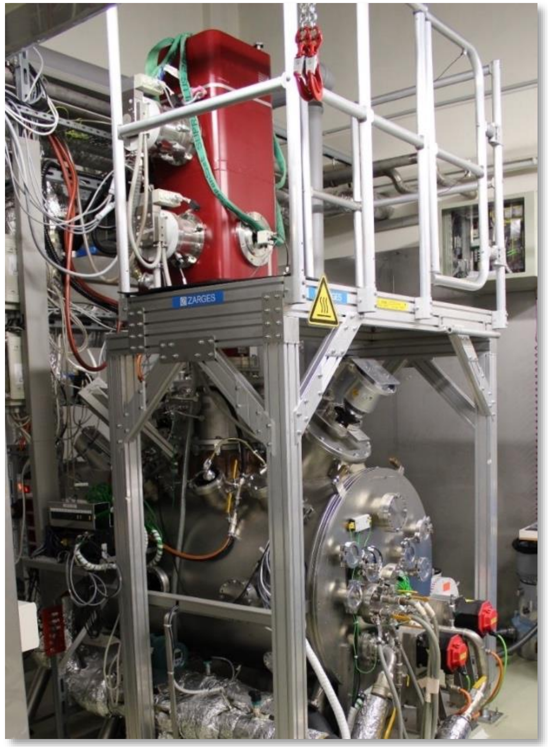
Retention experiments before and after thermal shock exposure haven been performed; post mortem analysis and interpretation of the data is ongoing

First experiments regarding Off normal events haven be performed in PSI-2; post mortem analysis is ongoing

Experimental devices

JUDITH 2





Machine parameters

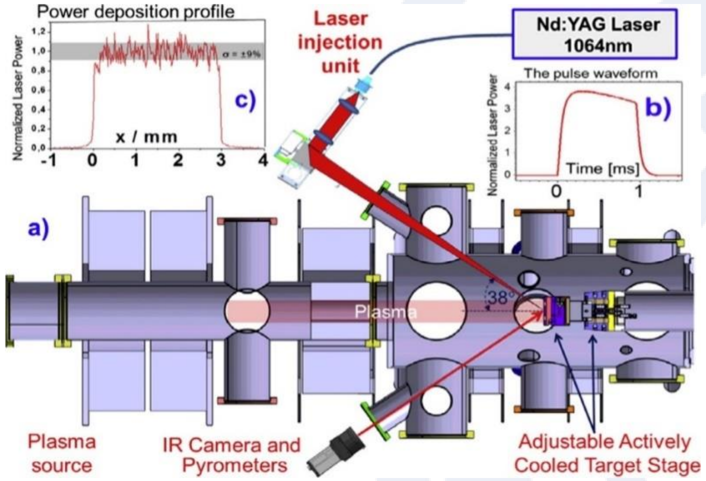
total power:	200 kW
acc. voltage:	40 – 60 kV
irrad. area:	40 × 40 cm^2
power density:	≤ 2 GWm^{-2}
pulse length:	5 µs – cont.
beam FWHM:	3 – 12 mm (typ. 8 – 10 mm)

Cooling circuit

temperature:	20 – 120 °C
max. pressure:	4 MPa
max. flow:	200 l/min
cooling power:	≤ 150 kW

monitoring of water quality

PSI-2

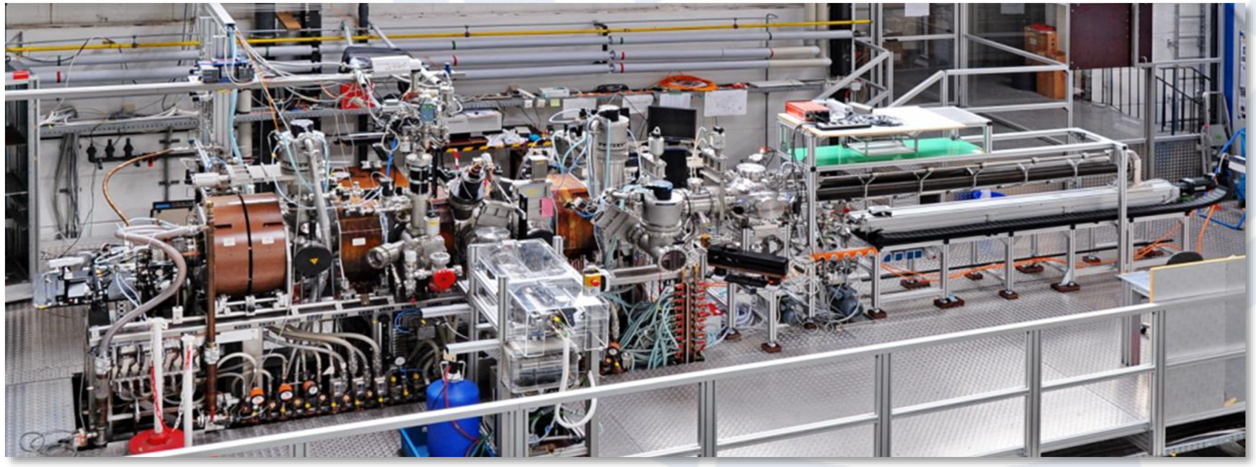


Stationary loads

D, He, Ar plasma
plasma column Ø 60 mm
ion flux ≤ 10^{23} $m^{-2}s^{-1}$
incident E_i (bias) 10 – 300 eV

ELM-like heat pulse

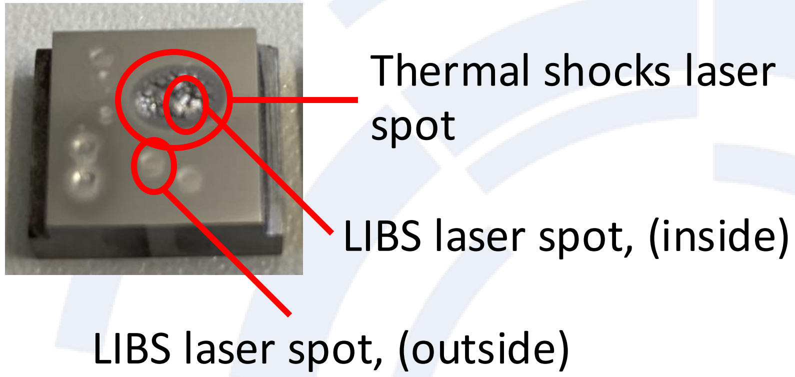
Nd:YAG laser λ 1064 nm
laser energy 32 J

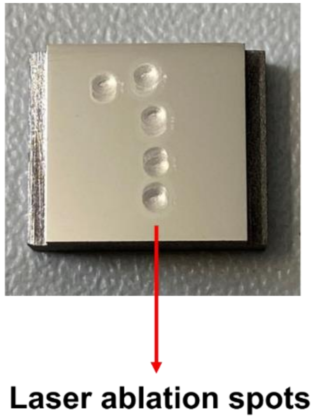


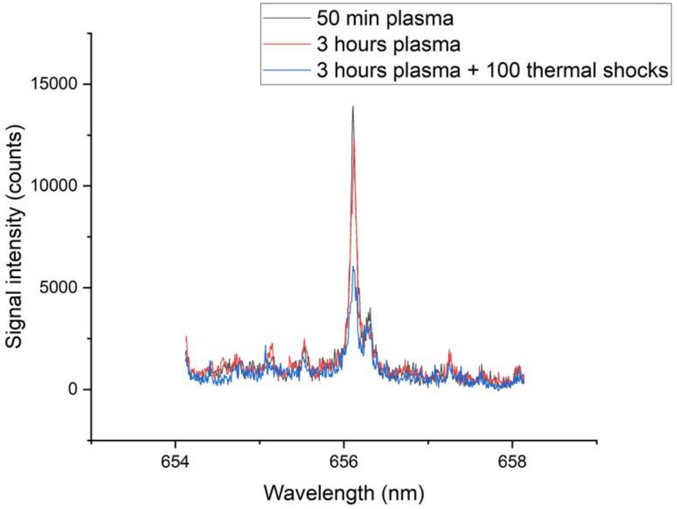
Deuterium retention (LIBS)

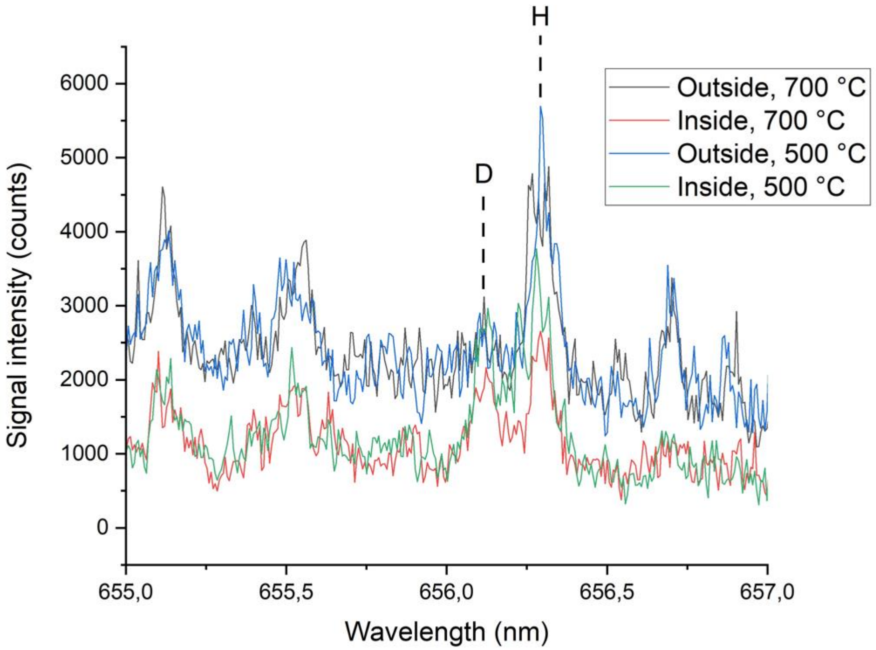
- Measurement of deuterium retention *in-situ* via laser-induced breakdown spectroscopy (LIBS)

- Enables measurement of dynamic deuterium retention at different times, also after thermal shock tests



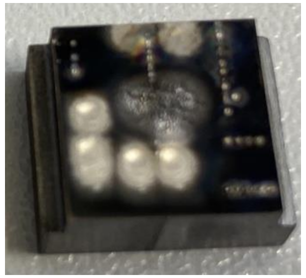




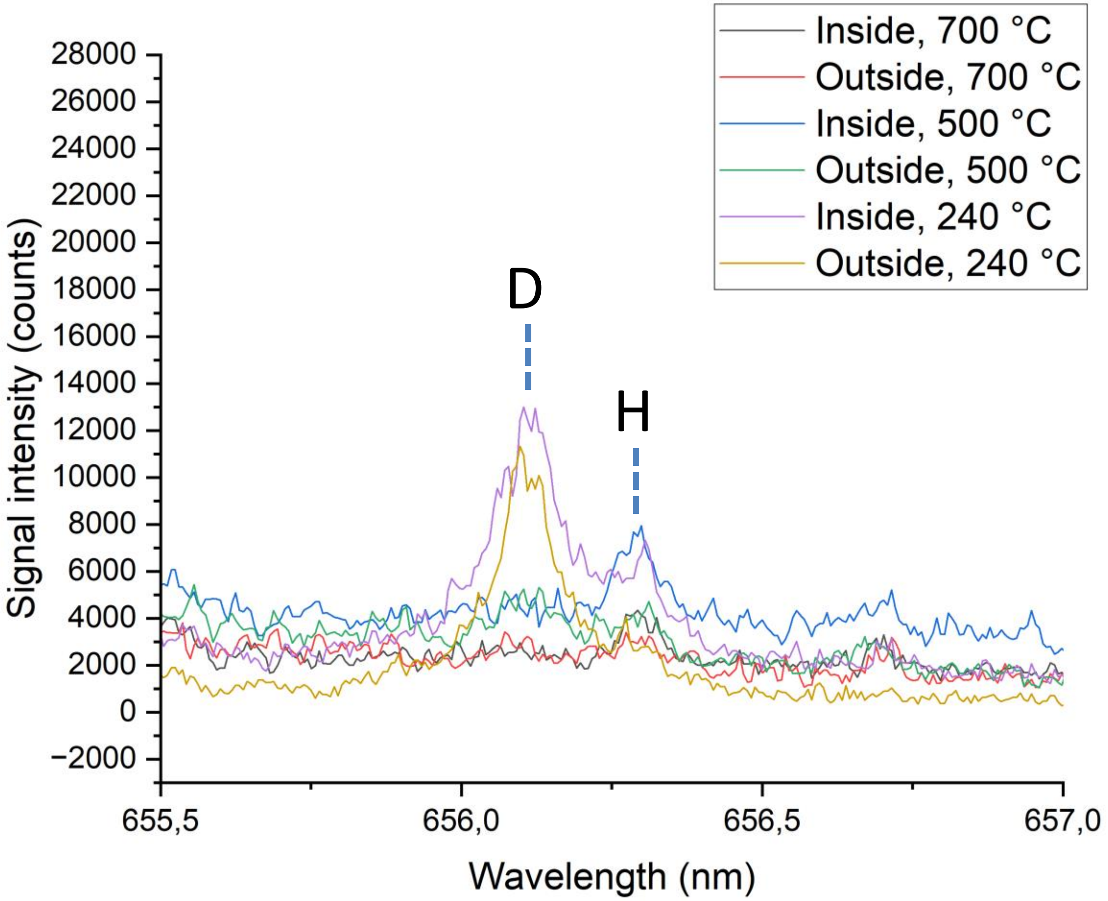


Deuterium retention after thermal shocks

- At 700 °C, deuterium retention remains low



- At 240 °C the D signal is similar as in the sample without ELMs and D only plasma
- No observed difference in dynamic deuterium retention during plasma exposure outside or inside the affected area, matrix effects difficult to determine
- Deuterium retention in „fuzzy“ areas seems to decrease significantly if a LIBS shot has been performed nearby, making determination of deuterium retention more difficult



Deuterium retention in PIM-W alloys

- 6 different PIM-W alloys have been exposed to D plasma, as well as ITER-grade W (Plansee)
  - W-1TiC
  - W-2Y_2O_3
  - W-3Re-1TiC
  - W-3Re-2Y_2O_3
  - W-1HfC
  - W-1La_2O_3-1TiC

- LIBS performed, results being analyzed
- NRA analysis and TDS to be performed

Off-Normal Loads for ITER

Full W fist wall for ITER - Qualification of W first wall components under VDE-like loads

planned range of loading conditions in JUDITH 2:

200 MW/m^2 up to 300 MW/m^2 for 200 ms up to 500 ms, number of pulses to be decided, on passively cooled small pure tungsten samples

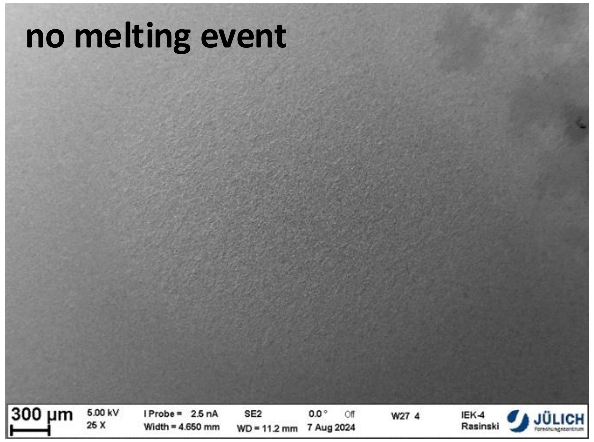
Resources: JUDITH 2 and PSI-2 operation

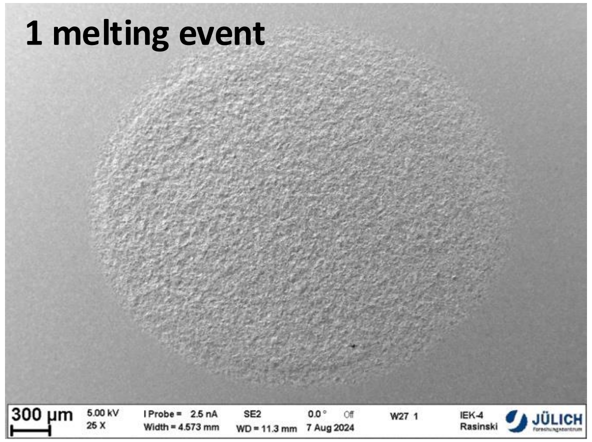
Optional: W first wall component provided by ITER/F4E?

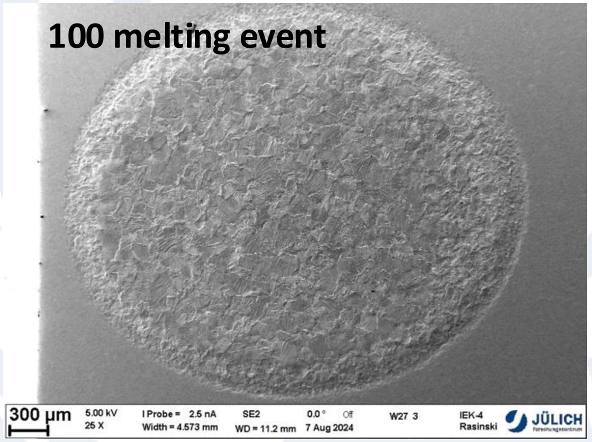
Off-Normal Loads for ITER

First experiments have been performed in PSI-2

- IGP WT reference material
- Base temperature 1000 °C
- Melting event 1.6 GW/m² for 2 ms and pulse number of 1, 10, 100
- ELM-like event 0.38 GW/m² for 1 ms and pulse number of 1000, repetition 0.5 Hz







Post mortem analysis is ongoing

DIFFER L.J.Bouwmeester, T.W. Morgan

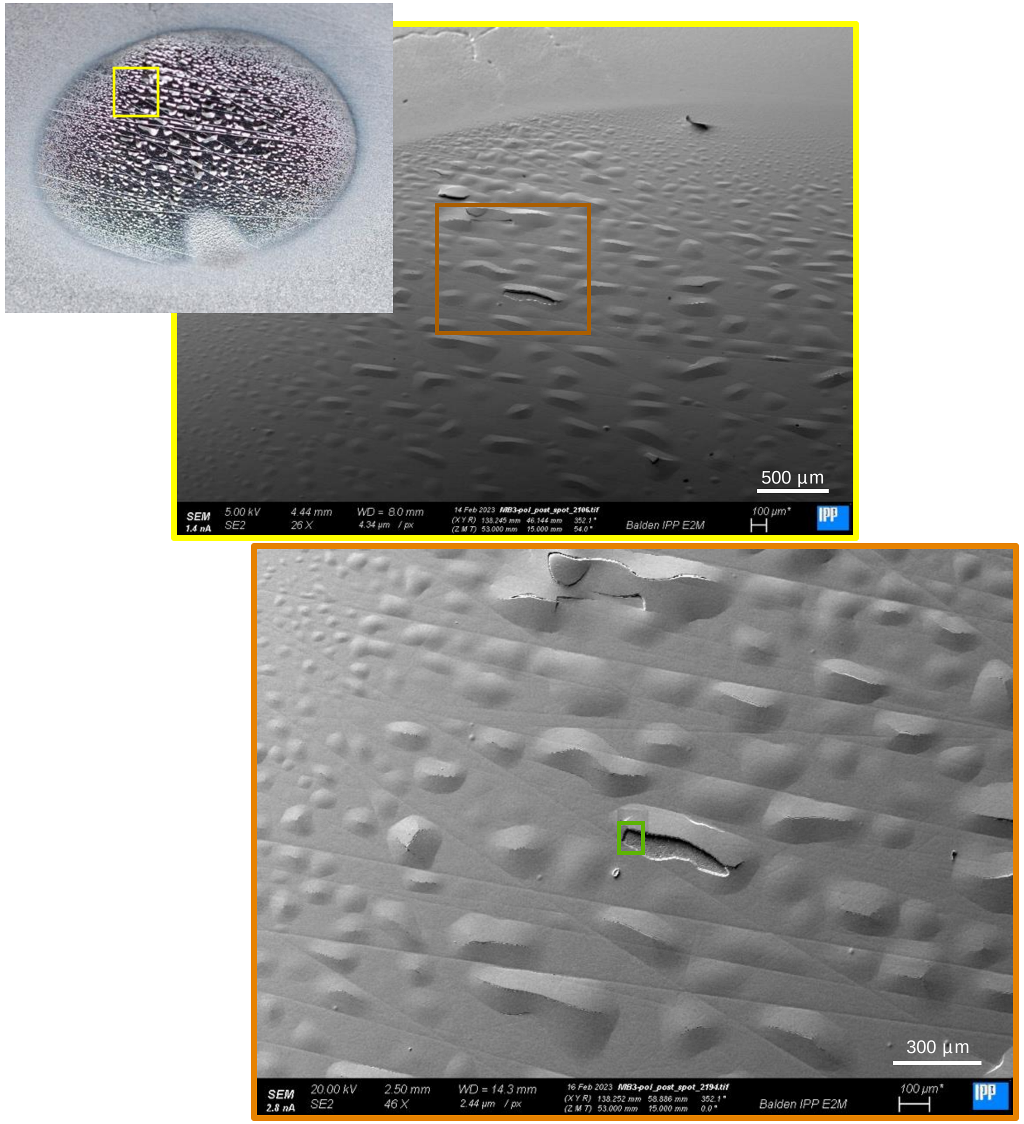
- Structure of redeposited W layers
- Investigation on the structure, and D-retention in W redeposits created by sputtering at various growth rates.

Summary

- Technique of upstream sputtering and downstream deposition effective
- Pure W layers created at various thicknesses within one exposure. (Similar structures to Magnetron sputtering) ~1-10um thick
- Main observation- at higher layer thicknesses: delamination and peeling. Change in substrate shows better adhesion/less flaking. Small flakes higher growth rate?

Background and motivation

- Switch of ITER wall from Be to W gives additional W source which may lead to thick deposition layers
- Thick W layers observed in WEST with ‘UFO’ flaking events
- Previous Magnum-PSI results show strong re-deposition of sputtered W leading to thick partially de-laminated layer
- Motivation to investigate this further in a controlled manner



Goal

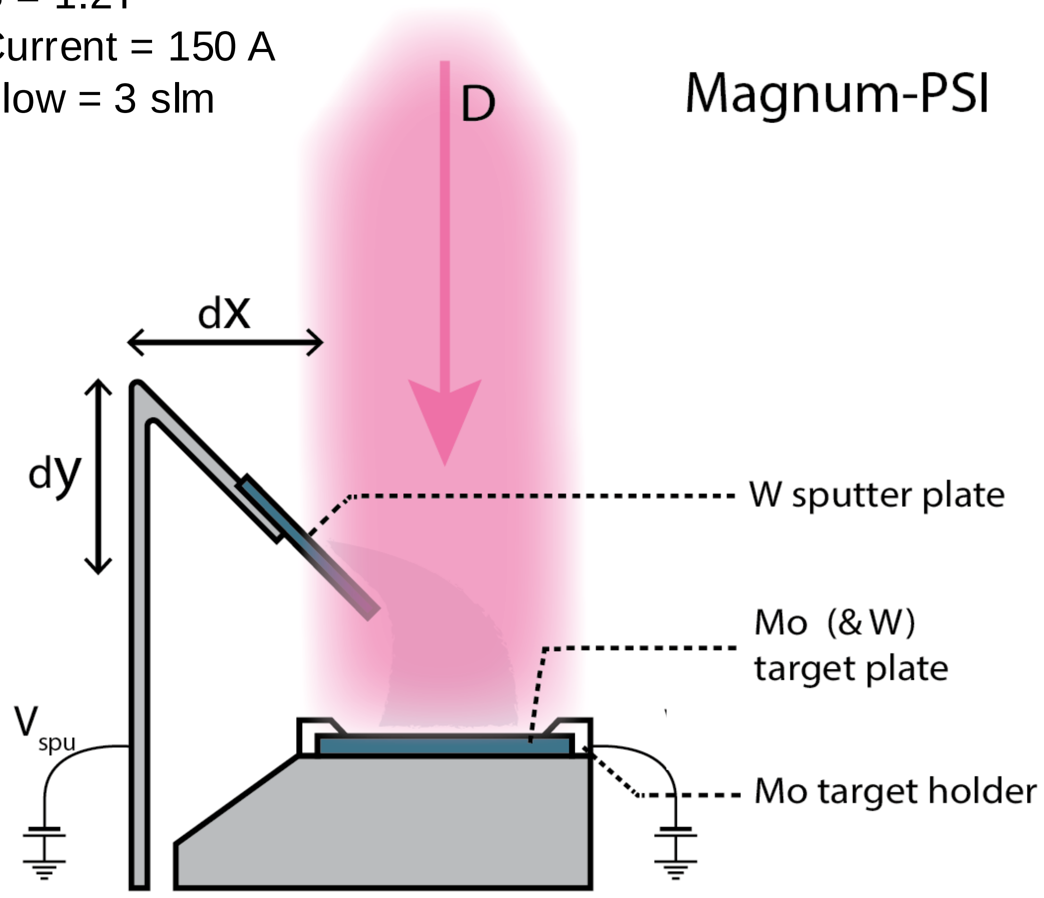
- Create “realistic” W redeposits with a sputtering & redeposition setup in Magnum-PSI;
  - Compare redeposited W to redeposited-like W layers from other research
  - Determine how redeposition rate influences formed structure
- Determine how W redeposited layers impact the divertor
  - Tungsten in plasma is detrimental for fusion. Increased sputtering, Flaking etc.
- Main Goal: Get more information about structure and impact of (thin) W layers formed by redeposition on divertor ITER.
  - Comparison with layers created by other methods
  - Finally: Assess the risks/performance of redeposits under ELM like loading.

Method

- Biased W sputtering target mounted above sample
  - (~20mm wrt center of plasma)
- Ar plasma sputters W, this is entrained and deposited on Mo or W sample.
- Change V_{spu} to impact sputter yield & deposition rate

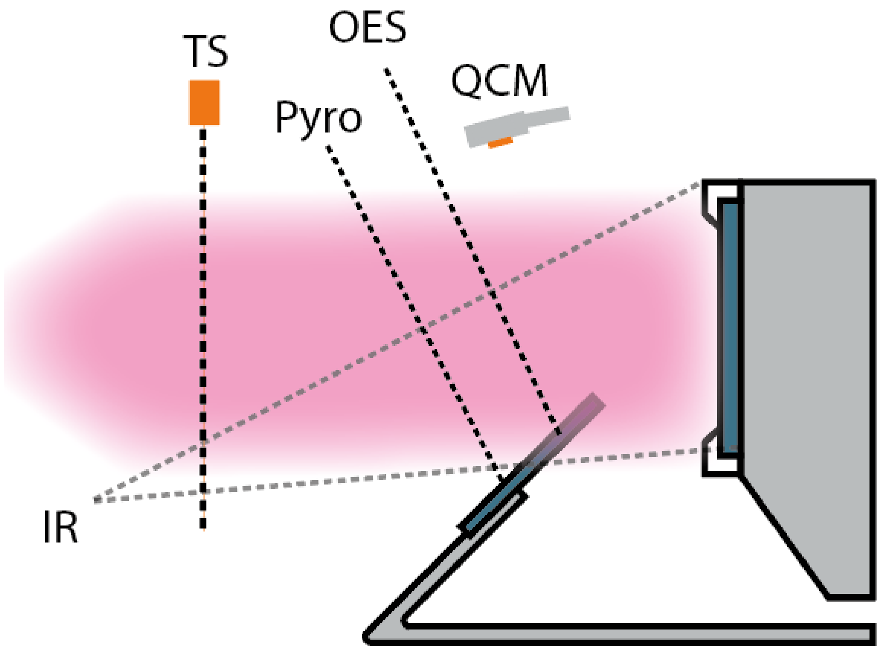
- Post mortem analysis: D retention, grain structure etc.
  - (SEM, RBS NRA, others)

Ar plasma
B = 1.2T
Current = 150 A
Flow = 3 slm



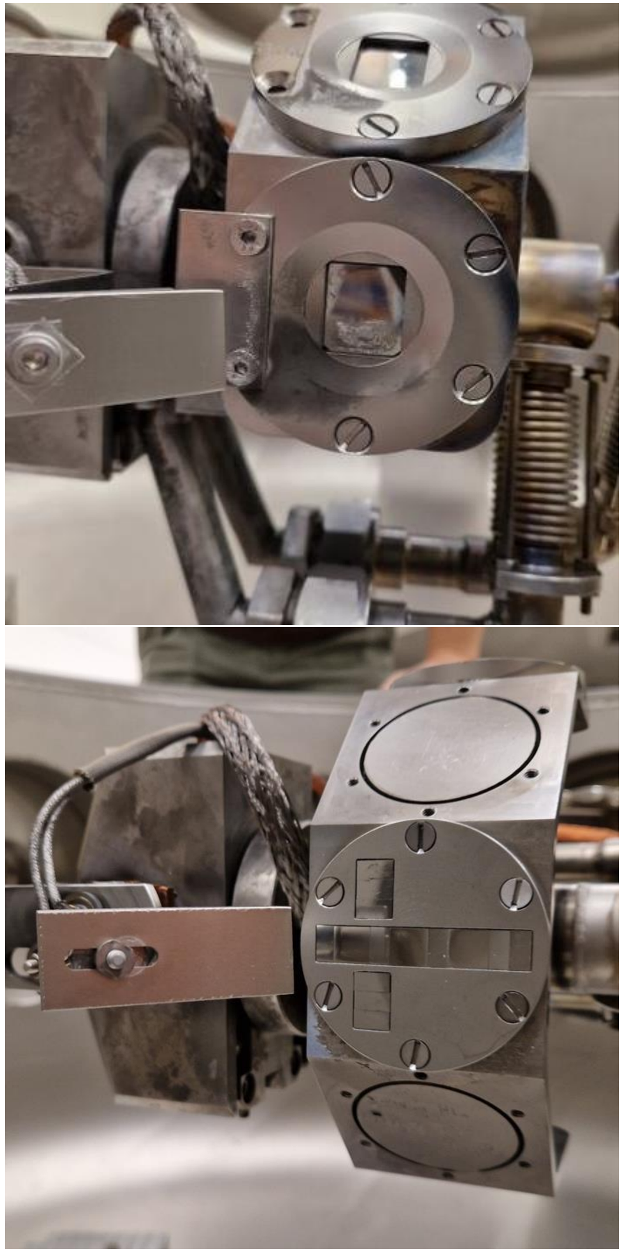
Diagnostic plan

- Weigh sputter plate + samples & clamping ring before & after exposure
- TS: Electron density and temperature in plasma above Target/sample
- OES: Avantes 2-channel: Erosion rate tungsten of sputter target
- FLIR fast IR: Monitor temperature Mo sample
- FAR Pyrometer: Monitor temperature W sputter target in real time (and as calibration for IR)
- FAST camera with W filter: monitor W emission.



Progression of experiment

- Initial experiment:
  - Started with D plasma ->Sputtering plate rapidly heats >2000 °C (expected) -> Switch to Ar to ensure sufficient deposition (higher density, higher sputtering yield)
  - Identified that W sputtering is made from Mo (Mo lines, Measured density, EDX of flake)
  - Mo thickness not identifiable by RBS on a Mo substrate! -> Add steel witness plates to collect Mo in different thicknesses (reported midterm meeting)
- Second experiment [new]:
  - Similar setup; Ar plasma, W sputtering plate (better cooled), more target samples to collect W on Mo & W substrate
  - Sputtering at different rates -> impacts growth rate.
  - Sputtering on different substrates: Polished, Sandblasted, Native oxide layer removed (by biassing substrate prior to sputtering W)
  - Wide range of thickness' formed. different flakes observed, deposition patterns differ.

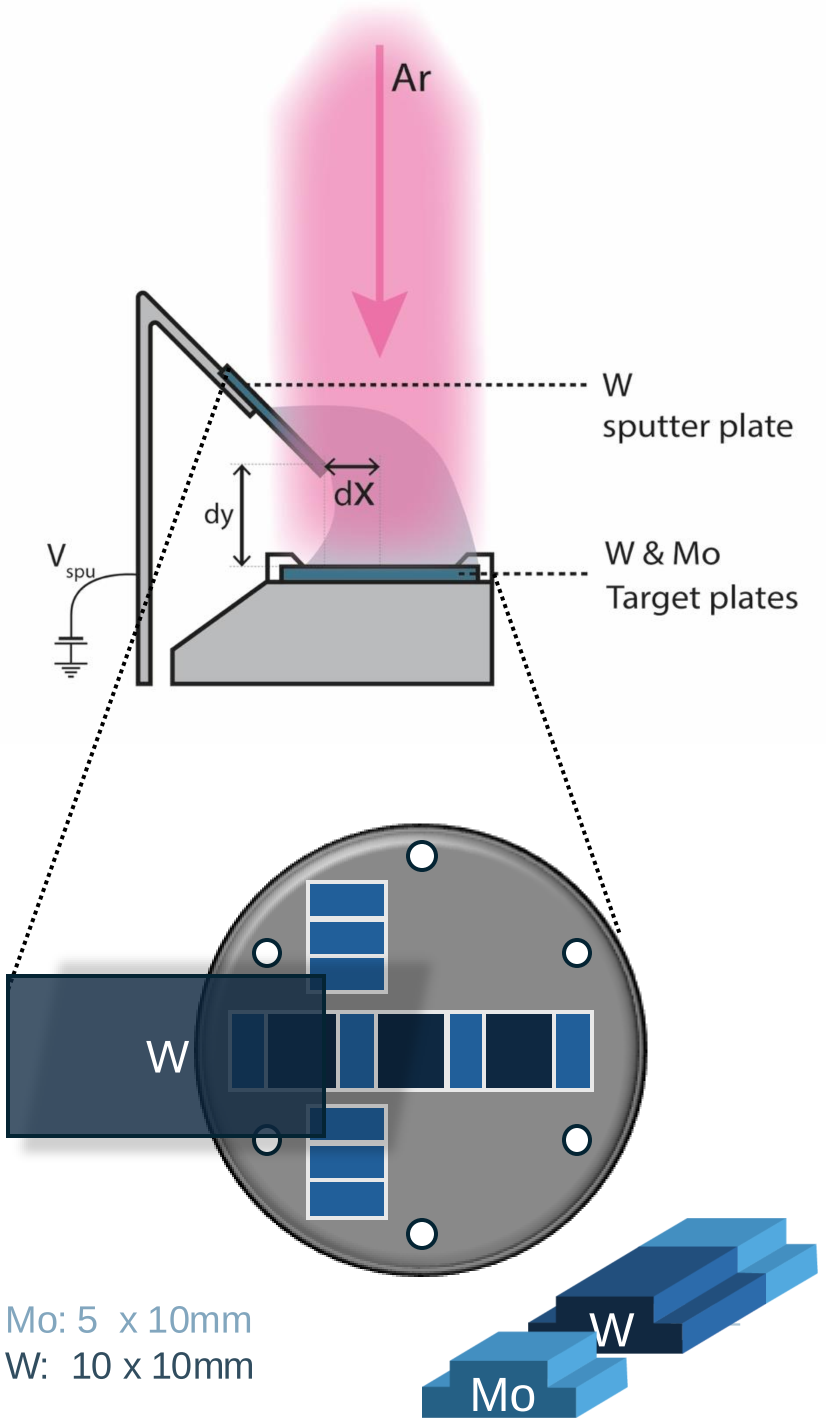


Summary of 2nd experiment

Exposure & Name	V_{spu} (V)	Location sputter plate (dy)	Duration (s)	Est. thickness (from weight) (nm)	observations
#1: short	-100	20mm	170	90-1200	Too thin layers, not spread out
#2: medium bias	-100	20mm	1000	700-7500	Thick layers, clear spread
#3: low density	-100	20mm	1000	2700-52000	Very thick, big flakes, more sputtered W
#4: 40mm	-100	40mm	1000	400-6200	Many small flakes, deposition spread out more
#5: rough	-100	20mm	1000	860-8600	No flakes, good adhesion
#6: high bias	-250	20mm	167	330-3700	Many flakes, blisters(?), thin layers? (contaminants?)
#7: low bias	-60	20mm	5600	430-10000	Only microscopic flakes
#8: bias substrate	-100	20mm	1000	600-6600	No clear flakes, good adhesion

Ar (0.8T, 4.4slm, 110A) : T~1.2 eV, n_e~1.1E21, FWHM ~30mm

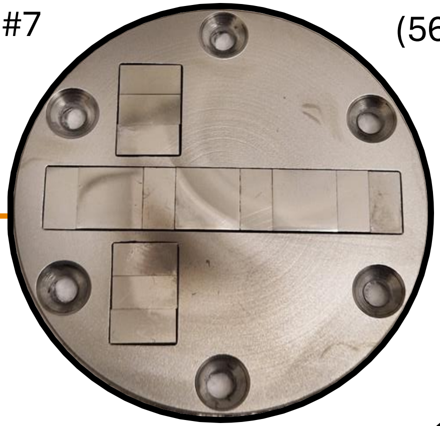
Ar (0.3T, 3slm, 110A) : T~1.2 eV, n_e~1 – 4E20, FWHM ~45mm



Mo: 5 x 10mm
W: 10 x 10mm

Overview of results

#7

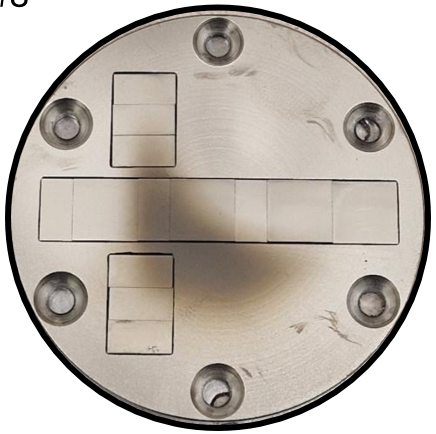


low bias
(5600s@ -60V)

medium bias

(1000s@ -100V)

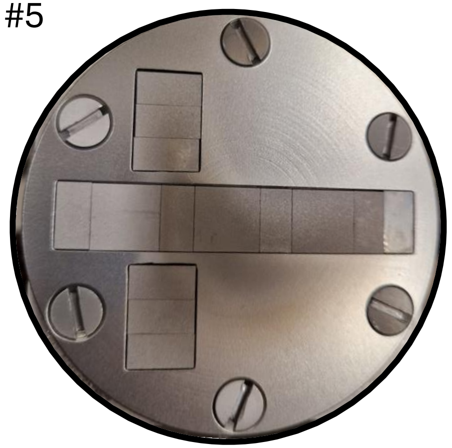
#8



bias substrate

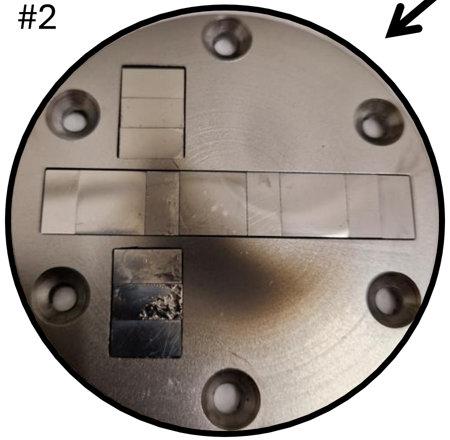
(1000s@ -100V)

#5



rough
(1000s@ -100V)

#2



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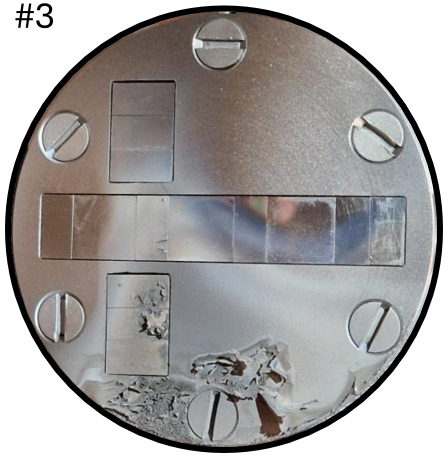
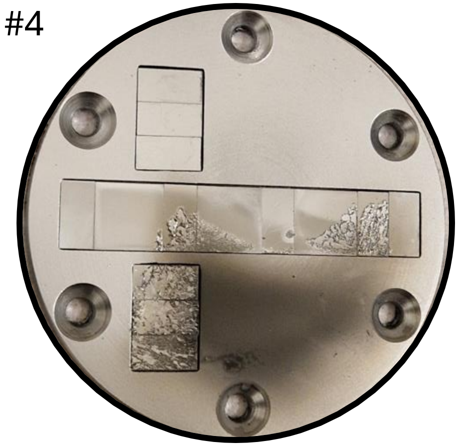


low density

(1000s@ -100V)

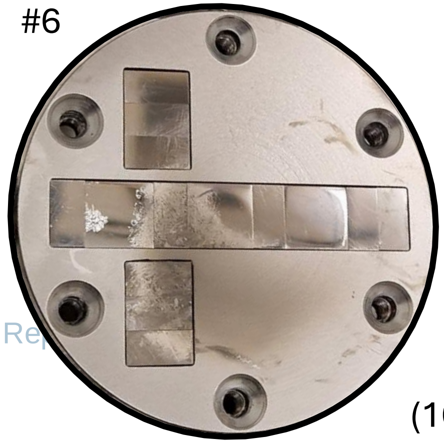
#4



5 dy=40mm

(1000s@ -100V)

#6



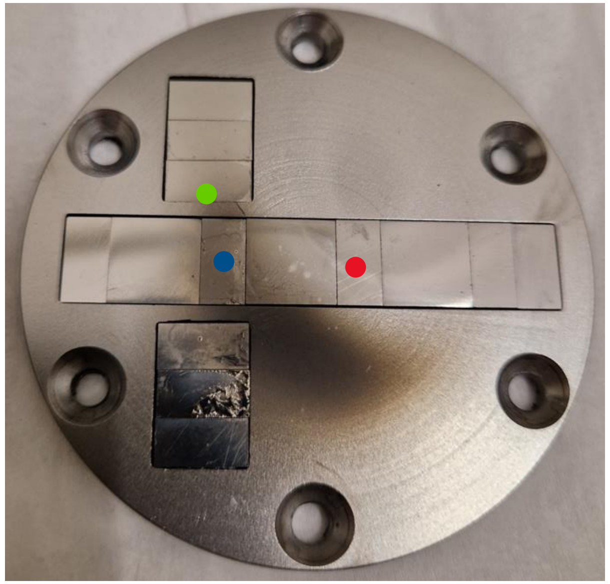
high bias

(167s@ -250V)

Overview of results: SEM/EDX & FIB cuts

- Clear high density thick and thin layers created
- Columnar grain structure (similar to e.g. magnetron sputtering)
- Large-scale de-lamination (peeling/flaking) observed once thickness reached a certain level
- Better adhesion for rough & pre-biassed substrate
- EDX: mainly W with small Mo background (from substrate or plasma?)
- Low flux expt shows extremely thick layers because plasma was much wider and thus much higher level of sputtering

#2 set 7 (1000s@ -100V)



variable		Sample	Thickness
thickness	thin	#2 7h3	~470
	medium	#2 7v3	~4000
	thick	#2 7h2	~8500
substrate	sandblasted	#5 8v3	~4200-6200
	Bias substrate	#8 2v3	~4200
growth rate	low	#7 4v3	~4000
	high	#6 6v3	~1300

CIEMAT D.Alegre

- Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures
- OLMAT BEAM: fatigue studies in large holder

SP A.1 Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO: CIEMAT

- **D003: Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures**

OLMAT BEAM: fatigue studies in large holder

- **Installation finished:** we had issues in June with the sample holder:
  - *Bad thermal contact*: around 500 ºC at the center and 200 ºC at borders. Now always < 200 ºC.
  - New design to protect copper beam dump.
- **Experiments ongoing this week (5 days):** ~3000 Pulses at a 1-15 MW/m^2 power distribution.

75 samples:
- 10 PM-WfW (Jülich)
- 11 ITER-like W (Jülich-PLANSEE)
- 7 WCrYZr self-passivating alloy (CEIT)
- 2 porous W by additive manufacturing for CPS (liquid metals)
- 45 stainless steel dummies. (Not enough samples)

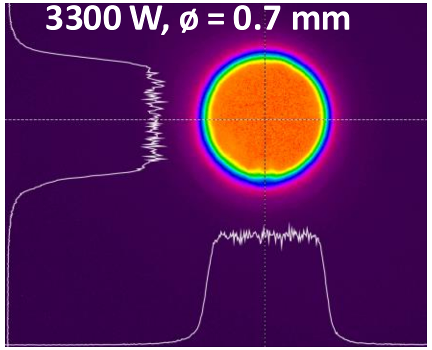
Deliverable: PWIE-SP A.1.T-T003-D003
Status: *ongoing*
Facilities: *OLMAT 5 days*
Linked WP or TSVV: *none*

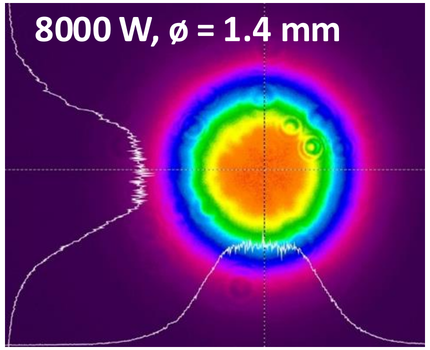
Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO

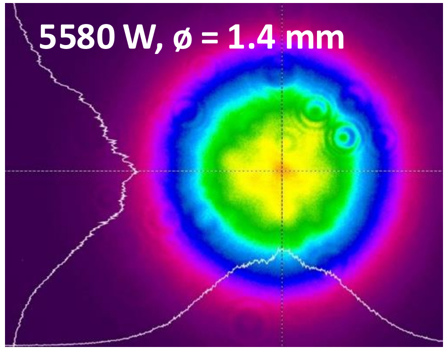
- **D003: Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures**

Laser: beam characterization top hat profile

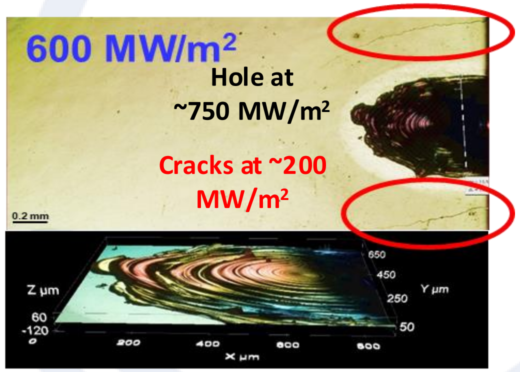
- **Characterization finished:** we had issues in 2023 for disruption simulation experiments
  Beam profilometer: complex for so a powerful laser (10^{-4} attenuation and 90 J energy!)
  - *Flat profile close to focal point*:
  - *Gaussian profile when decreasing power density*: defocusing (spot size) and lower powers.







5580 W
Gaussian beam



- **Use larger optical fiber:** to increase spot size and to be at focal point. (Thanks to M. Zlobinsky!).
- **Perform disruption-like experiments at COMPASS-U samples** (new 2024-5 task)

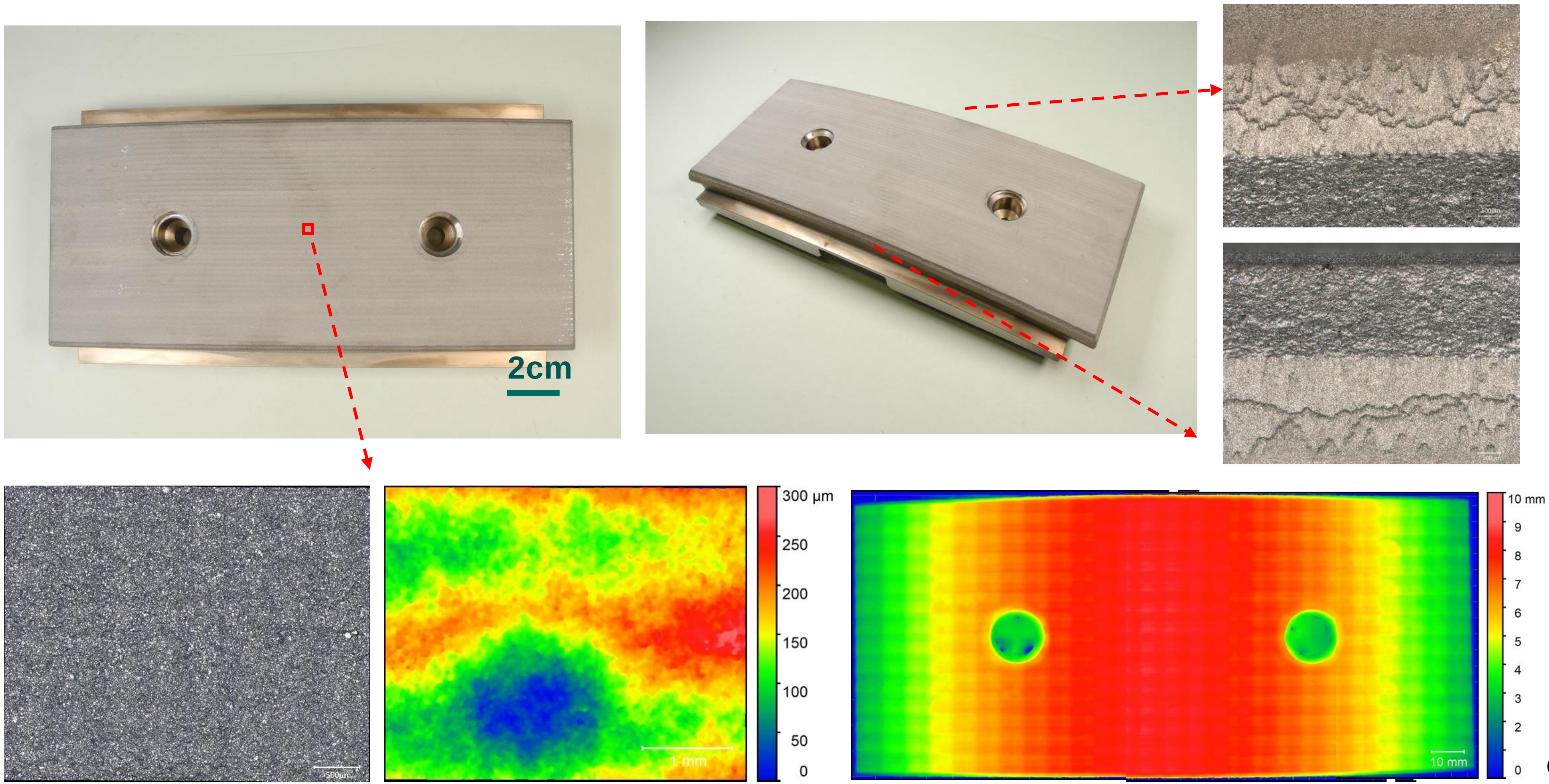
Deliverable: PWIE-SP A.1.T-T003-D003
Status: *ongoing*
Facilities: *OLMAT 5 days*
Linked WP or TSVV: *none*

IPP -J. Riesch, B. Böswirth, H. Greuner, K. Hunger, H. Maier, R. Neu

- GLADIS HHF loading of Cold Spray W/Ta coated Asdex Upgrade heat shield tile

- **The Cold Spray W/Ta coating showed good performance during HHF tests, no indication of delamination visible.**

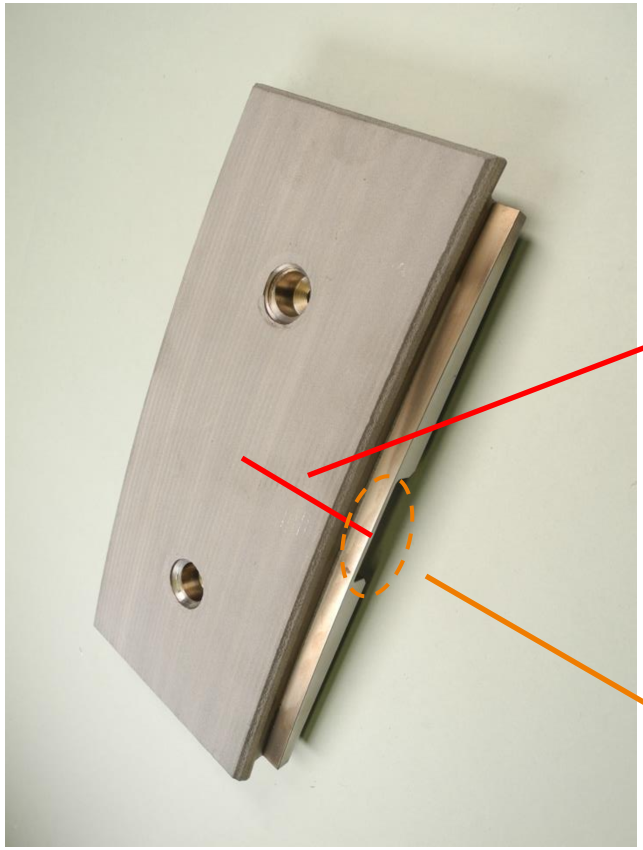
Pre-characterisation

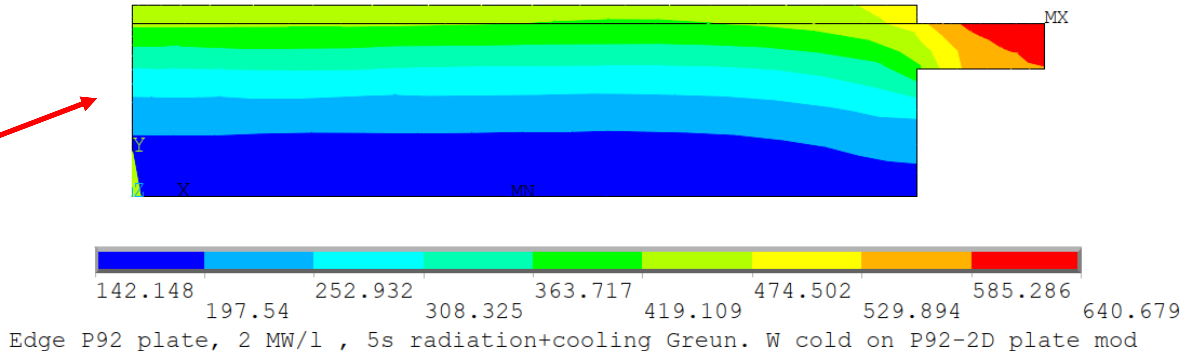


(castellation in picture is an artefact)

Microscopical examination of the coating in the beam center and the central edge areas, including height profile measurements (performed by K. Hunger).

FEM calculation



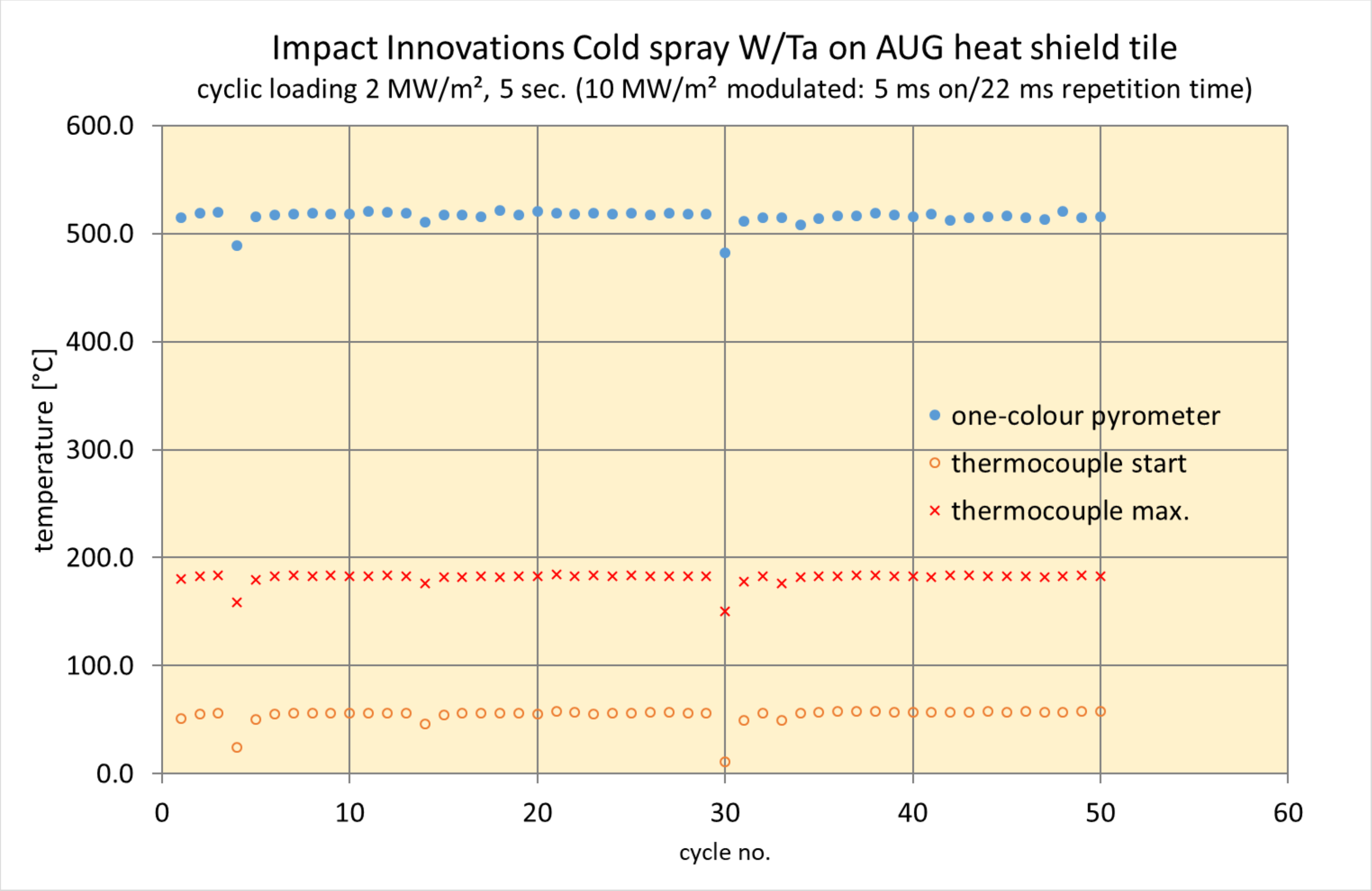


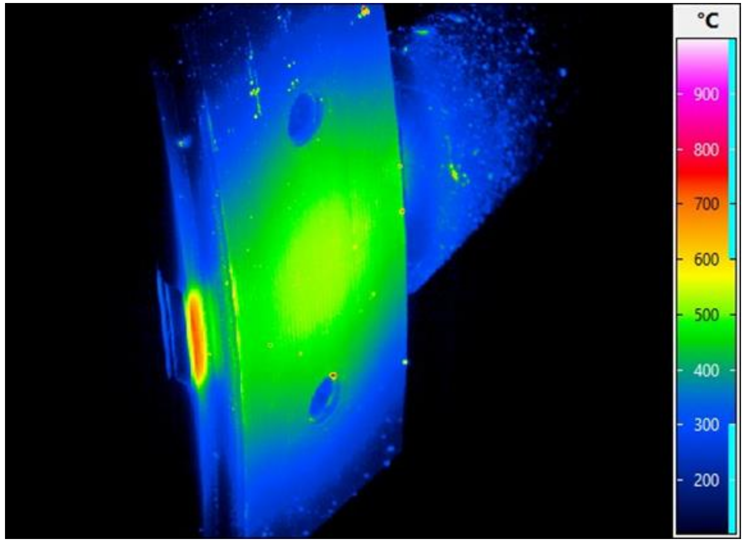
The FEM calculation (performed by H. Greuner) shows the resulting temperature profile at the pulse end of a 2 MW/m², 5 sec. loading in the marked area.

The thin wing of the tile shows the highest temperature (640 °C).

To avoid overloading and damaging the tile, the cyclic loading should be in the range of 2 MW/m², 5 sec. (see calculation)

Cyclic loading, 2 MW/m², 5 sec.





IR image of 50th pulse 2 MW/m², 5 sec. at pulse end (emissivity corrected according pyrometer measurement)

The surface temperature of the tile center is stable during the cyclic loading. The visible hot spots were existing already from the first pulse.

PWIE-SP A.A1.T-T004-D005

Analysis of material properties after sequential HHF transient and steady-state plasma loading (KIPT)

Conditions of sequential loads

- Samples
  We received 12 conventional tungsten samples from DIFFER. 12x12 mm square samples with a thickness of 2 mm were cut from ITER-grade tungsten produced by PLANSEE.

- Pre-loading
  Samples were exposed in Upgraded Pilot-PSI (UPP) and Magnum-PSI (Magnum) at DIFFER. In UPP, a fluence and temperature scan was performed, exposing samples to 400-500-600-700 K and a fluence of $10^{25} - 10^{26} - 10^{27}$ m^{-2} in successively D - H -D plasma exposures. In Magnum the same temperature scan was performed, at a fluence of 10^{27} m^{-2}.

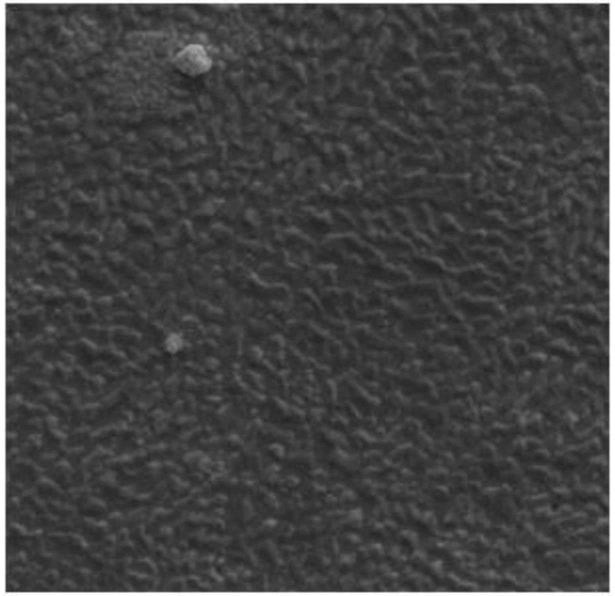
- Post-mortem and in-situ ion beam analyses were performed between plasma exposures to analyze the retention in these samples.

- **QSPA load**
  Samples W3, W4, W13, W14, W1, W2, W6, W7
  were irradiated with 10 QSPA plasma pulses of 0.9 MJ/m²

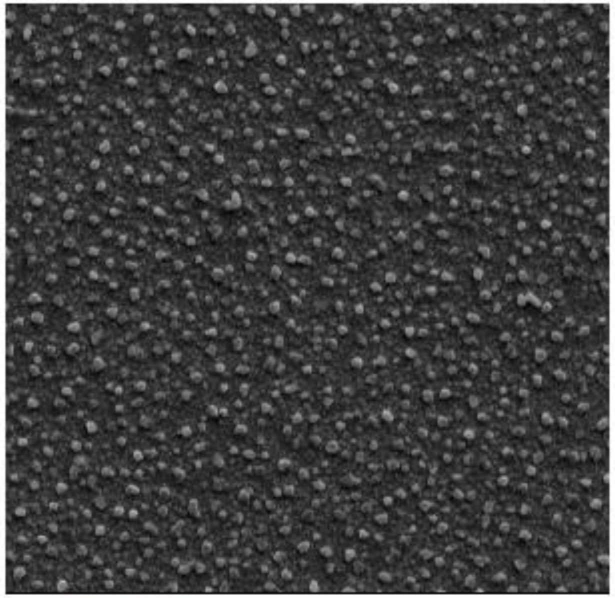
https://pure.tue.nl/ws/portalfiles/portal/319778422/0952393_-_Elenbaas_J.K._-_MSc_thesis_Thesis_-_NF.pdf

Magnum + QSPA

Magnum

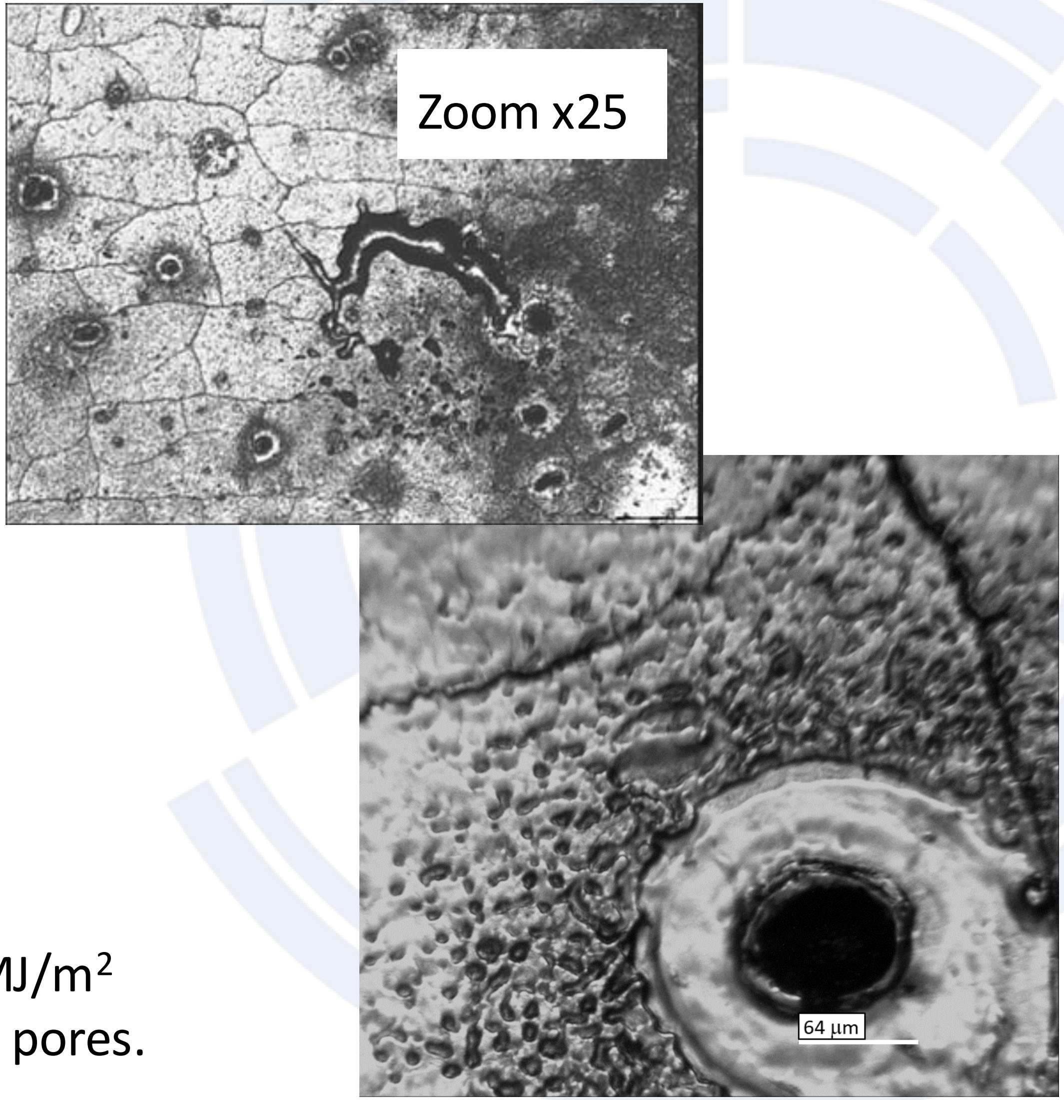


(a) W14 on the edge of the beam spot. 10 kV with zoom 25.000x



(b) W14 in the center of the beam spot. 15 kV with zoom 10.000x

QSPA



- After Magnum exposure: T =700 C, 10^{27} m^{-2}

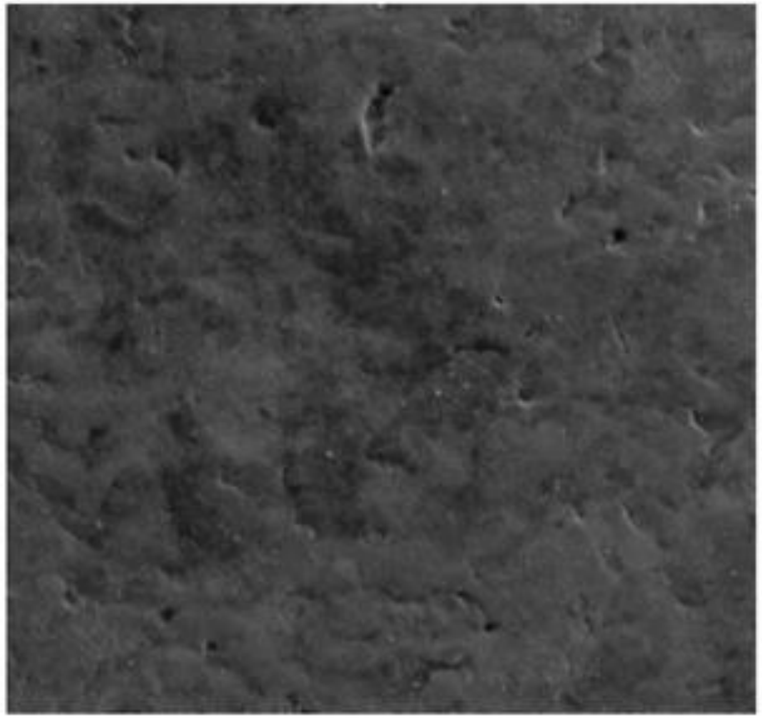
Blisters, surface relief typical for physical sputtering

- After additional QSPA exposure: T=RT, 10 pulses, 0.9 MJ/m^2

Surface melting, cracking (large and intergranular cracks), pores.

UPP + QSPA

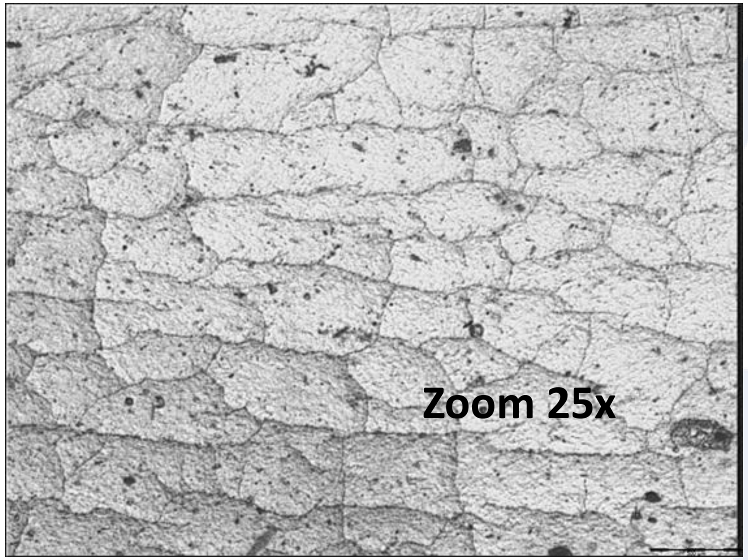
Upgraded Pilot-PSI

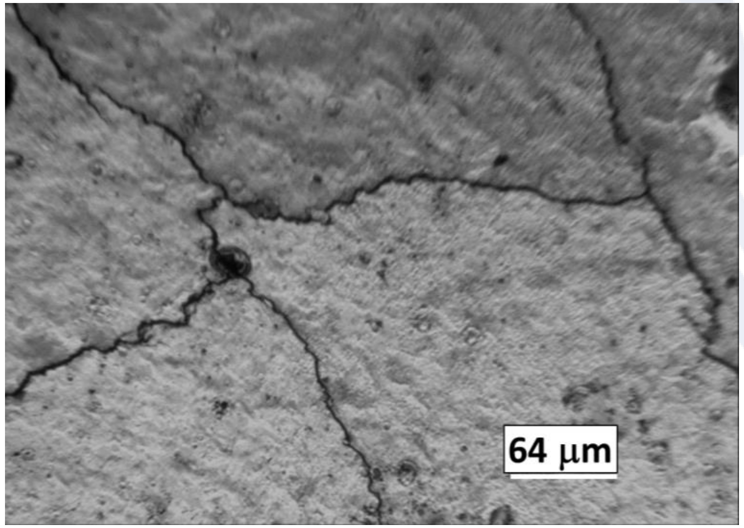


(c) W3, 20.000x at 15kV

- After UPP exposure: T =500 C, 10^{27} m^{-2}
- Surface relief typical for physical sputtering

QSPA





- After additional QSPA exposure: T=RT, 10 pulses, 0.9 MJ/m^2
- Surface melting, cracking (large and intergranular cracks), pores.

SUMMARY: Samples initially exposed within Upgraded Pilot-PSI (UPP) and Magnum-PSI were irradiated within QSPA Kh-50 at a target heat load of 0,9 MJ/m^2 and duration of 0,25 ms.

Post-mortem analyses of the exposed samples are in progress.

WP PWIE SPA 2

Results 2024

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

High Particle Fluence Exposures of Plasma-Facing Components for ITER

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
T. Morgan	DIFFER	5	D001 (T. Morgan)
M. Balden	MPG	2	D002 (S. Elgeti)
Total		7	

Device	Beneficiary	Days	Related Deliverable
MAGNUM-PSI	DIFFER	8	D001
UPP	DIFFER	1	D001

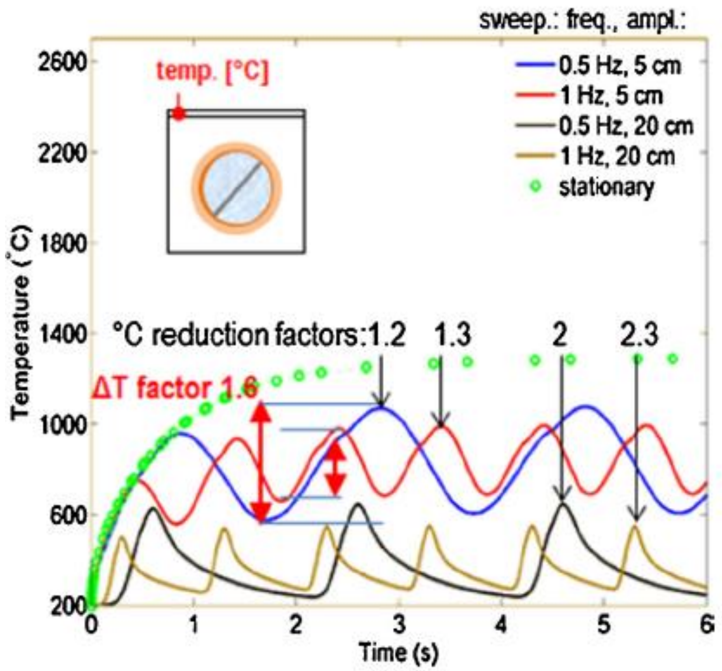
Deliverable ID	Deliverable Title
D001	Fatigue cracking and creep evolution of W samples and W-monoblocks exposed to strike point sweeping (DIFFER)
D002	Pre- and post-characterization of samples (MPG)

DIFFER - J Hargreaves & T. W. Morgan

- The low cycle fatigue cracking of W due to reattachment events

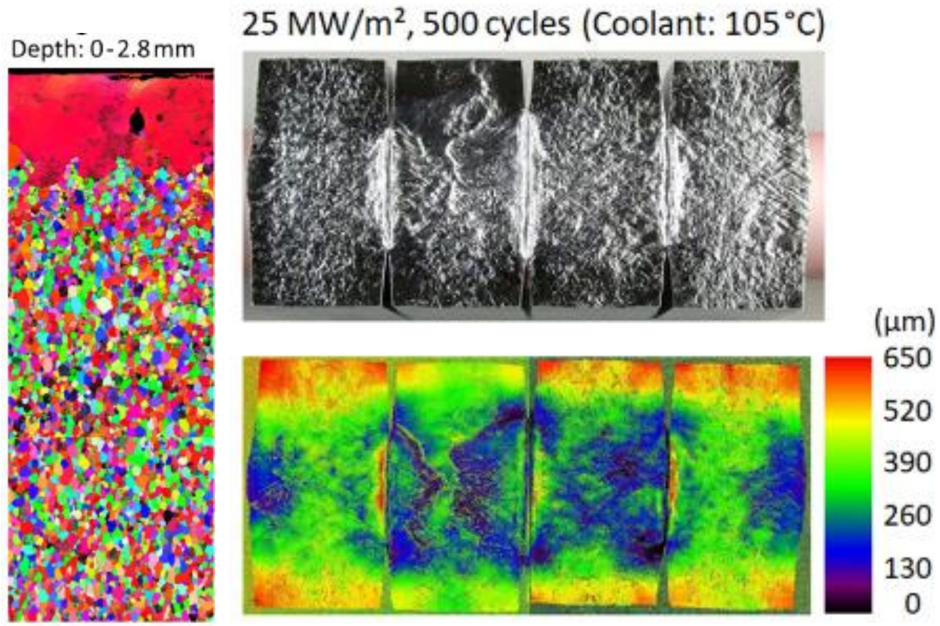
Motivation: Divertor Reattachment Events in ITER & DEMO

Divertor re-attachment events (slow transients) will impose **cyclic thermal loads** on the divertors of ITER & DEMO, giving rise to **thermal fatigue**.

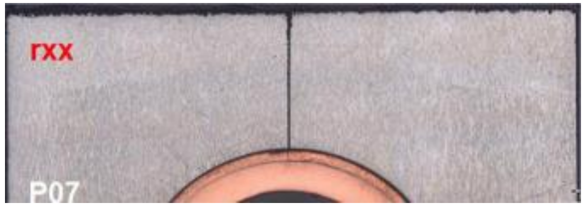


predicted monoblock temperature reduction achieved by strikepoint sweeping in DEMO (F. Maviglia et. al. 2021)

Recrystalisation and surface roughening of ITER-like W monoblocks under ITER reattachment loading (J.H. You et. al. 2022)



Deep cracking of a W monoblock after 300 cycles of 20 MW m^{-2} (M. Li et. al, 2015)

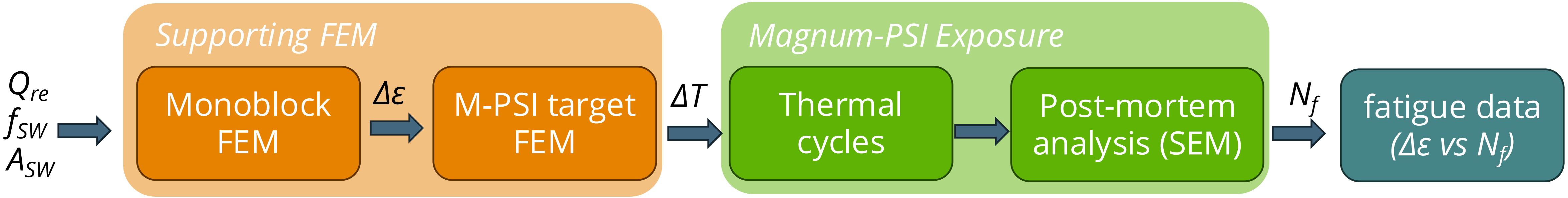


Using Magnum-PSI to explore PMI effects on W fatigue life

1. Use FEA to scale the thermomechanical response of a DEMO monoblock during strikepoint sweeping to a Magnum-PSI W target, and determine target temperature range (*ΔT*)

2. Use Magnum-PSI to impose *DEMO-representative* thermal cycling on ITER-grade tungsten targets, while simultaneously imposing plasma-material interaction effects.

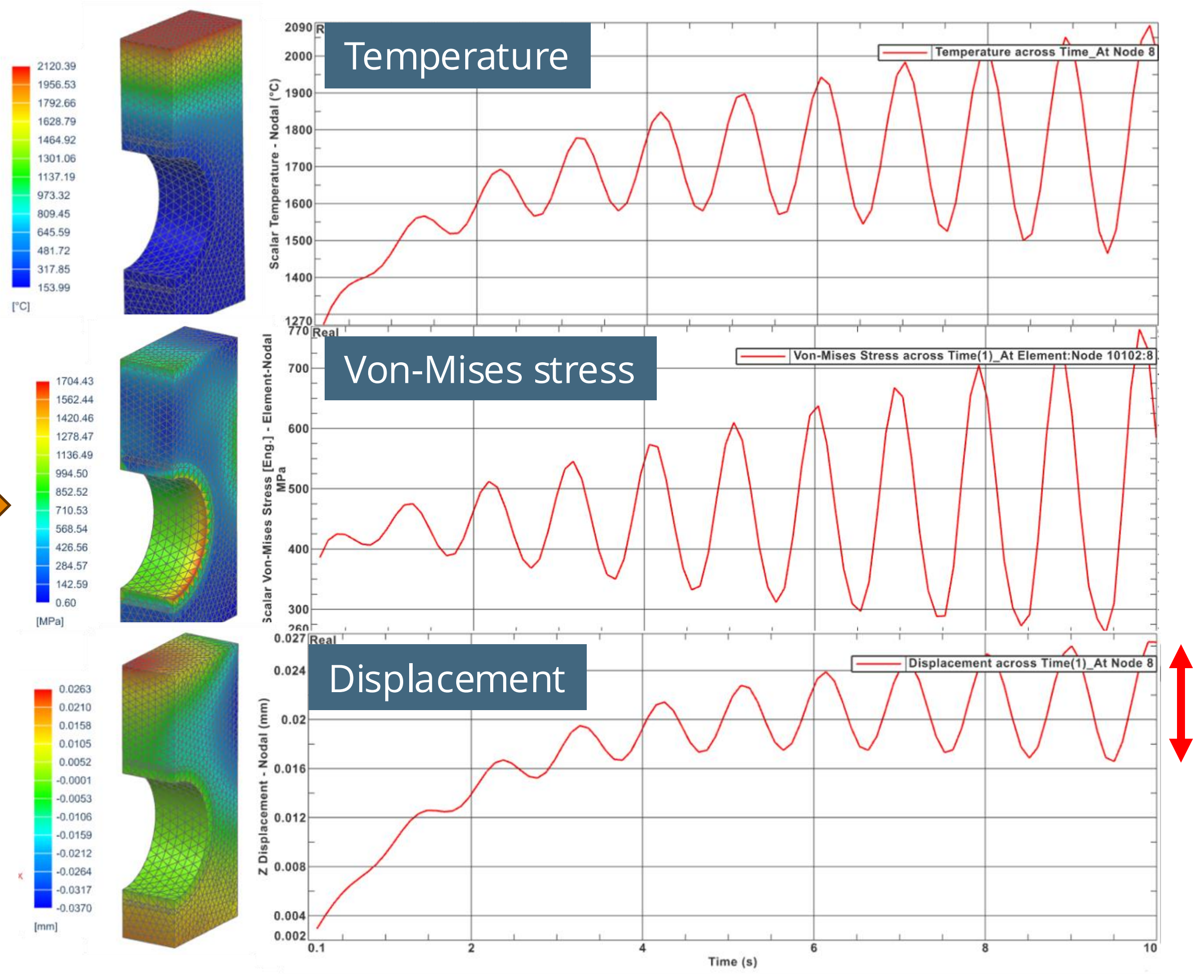
3. Check targets for cracking via SEM to determine N_f, cycles until failure, for a given Δε.



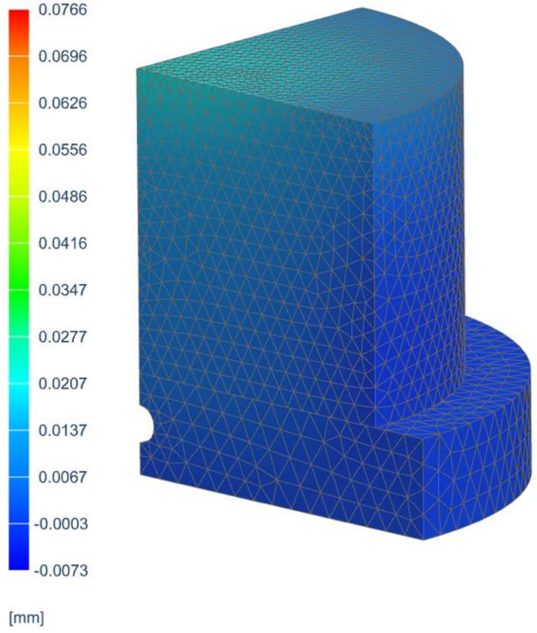
Supporting FEM simulations

Scaling a DEMO divertor monoblock's thermomechanical response to a Magnum-PSI target

Q_{re}
f_{SW}
A_{SW}



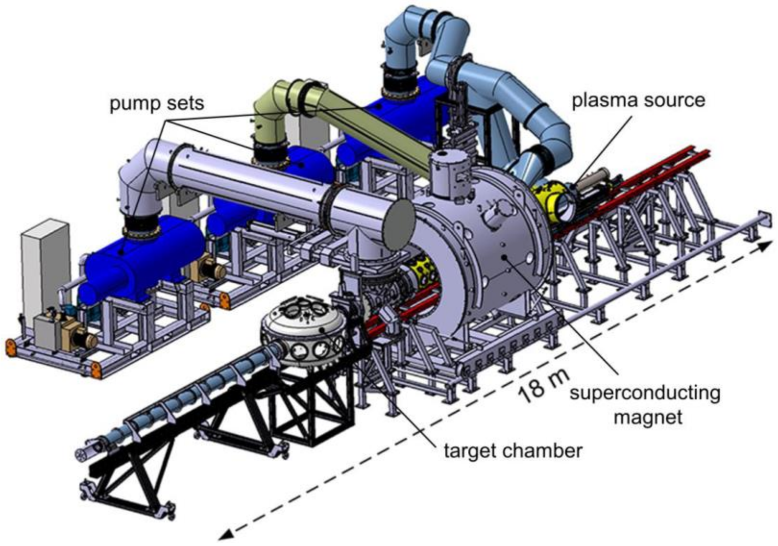
$\Delta\varepsilon_{mb}$

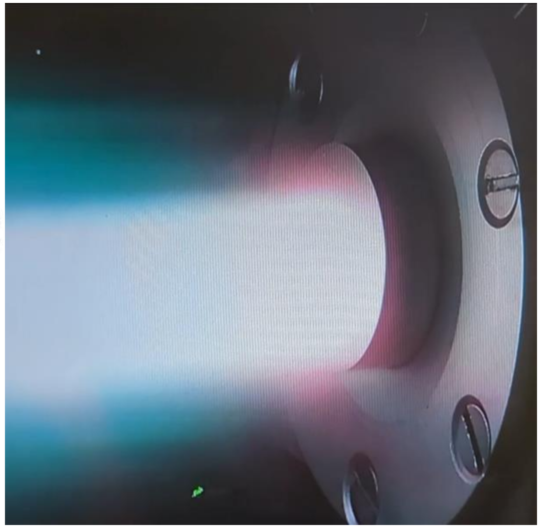


ΔT_{tgt}

Emulating stikepoint sweeping using Magnum-PSI

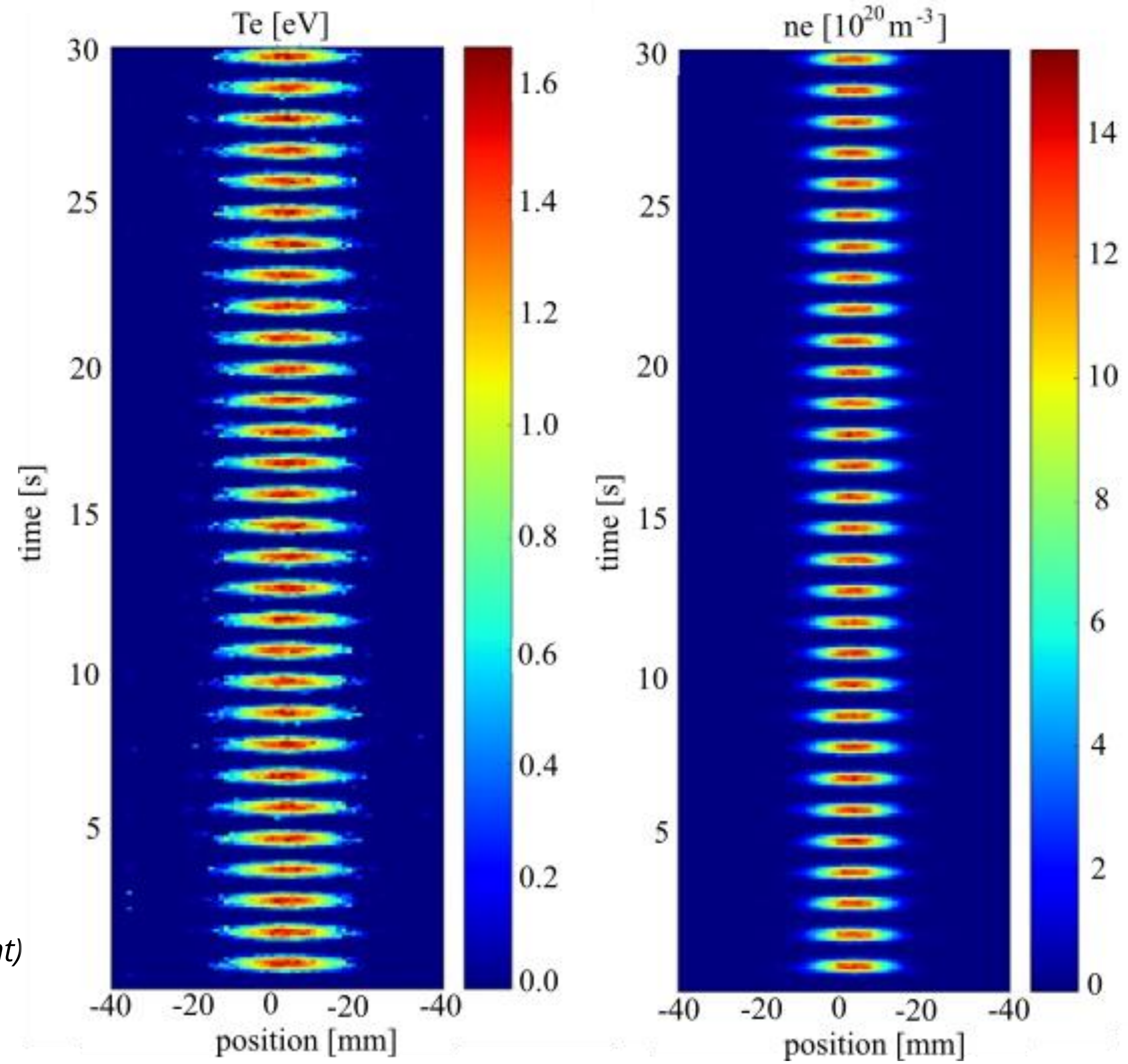
Testing shows that current modulation is capable of replicating the range of strikepoint sweeping frequencies under consideration for DEMO (*0.5 – 5Hz*).





General arrangement of Magnum-PSI (left) and video of plasma during plasma pulsing (right)

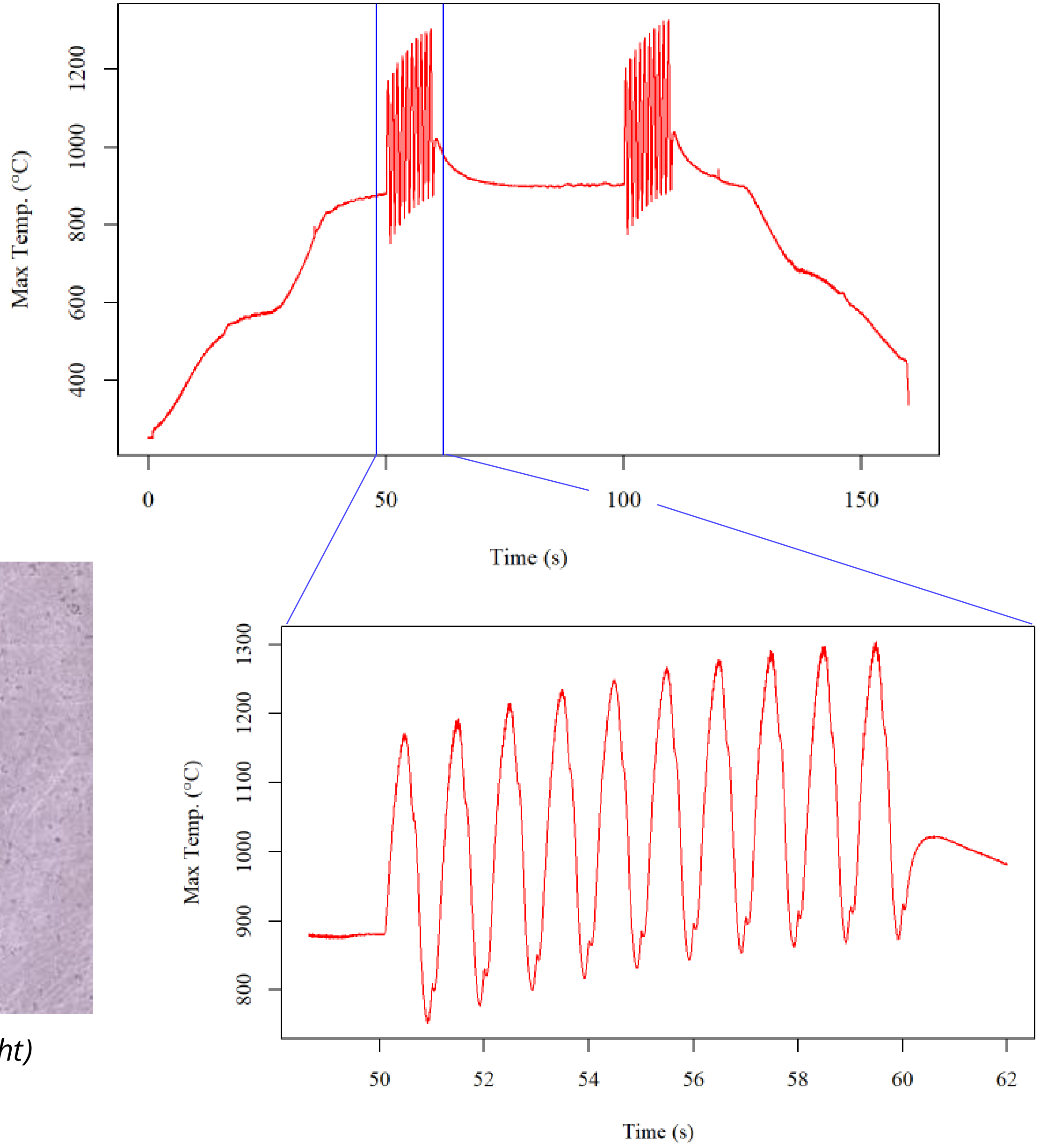
Synchronous TS measurements of T_e (left) and n_e (right) during H plasma pulsing, Est. peak thermal flux = 40 MW m^{-2}

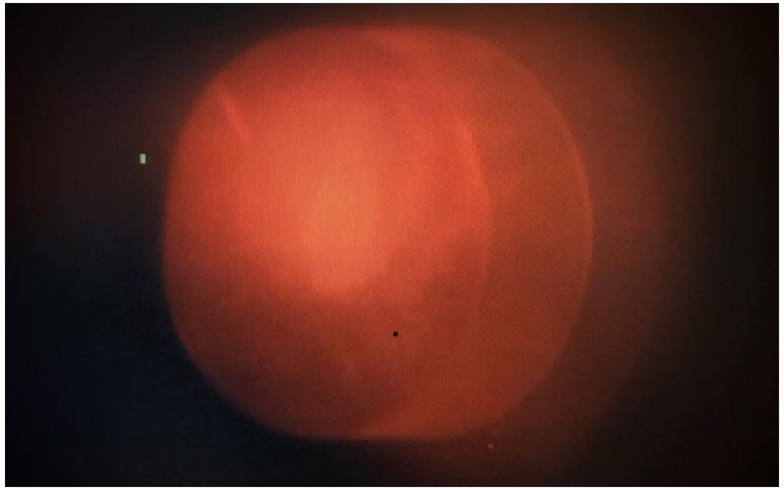


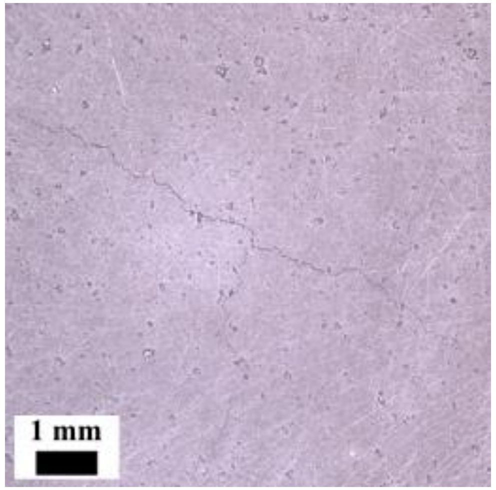
Emulating stikepoint sweeping using Magnum-PSI

- Target temp. monitoring via fast IR camera (380 Hz)
- Tested up to $N = 2000$, $\Delta T_{max} = 500°C$
- Slow current ramp up/ramp down to prevent thermal shock cracking

Target temperature (max) showing 2 sets of 10 cycles at 1.0 Hz



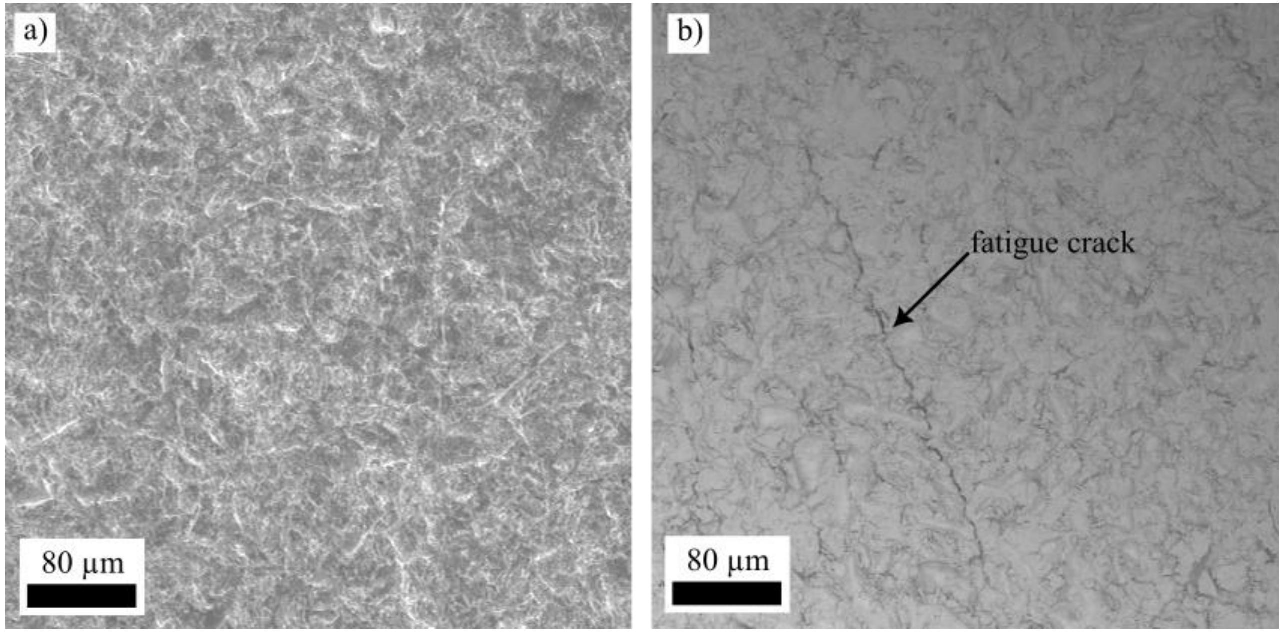




Fast IR capture of W target during exposure (left), post-exposure LOM micrograph (right)

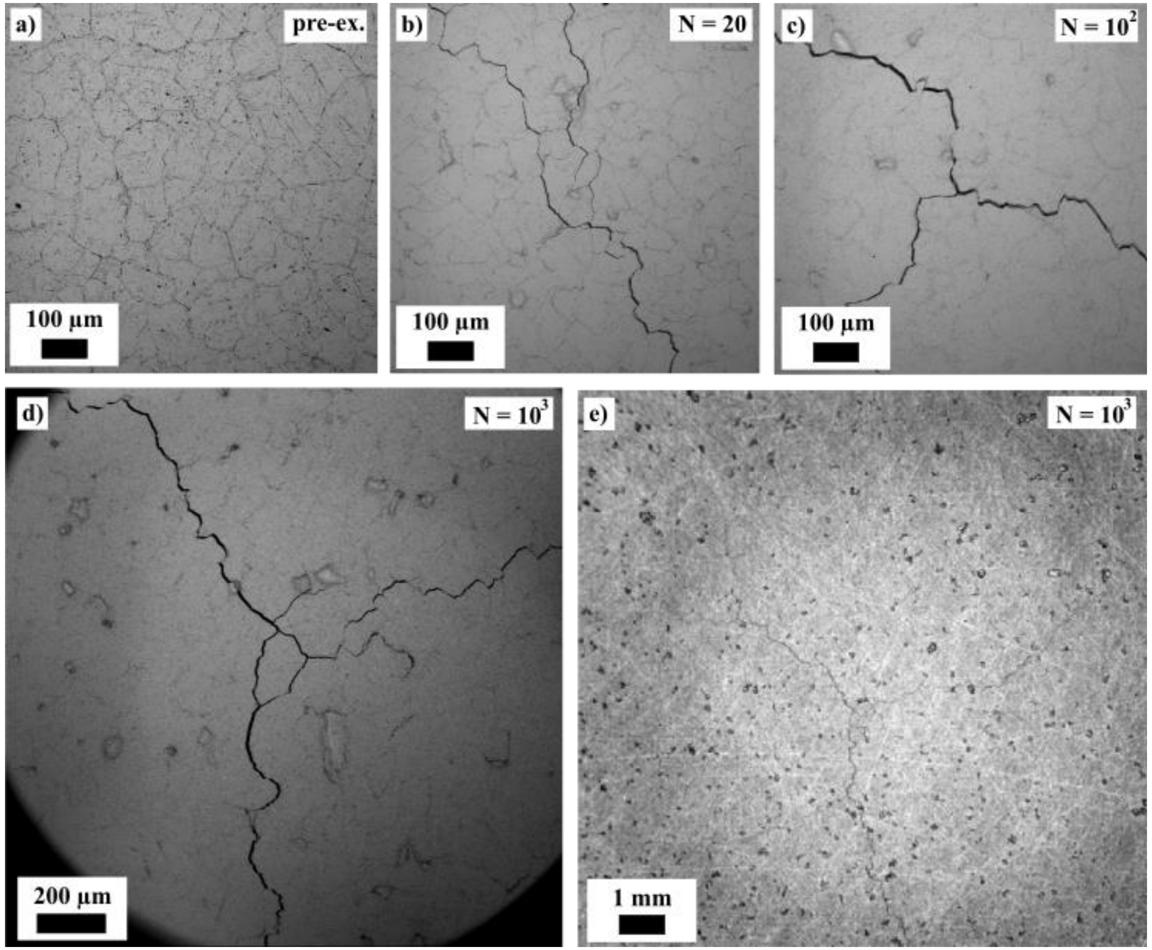
Fatigue cracking of ITER-grade W by pulsed H plasma

- ITER-grade W targets exposed at 1 Hz to 20, 50, 100, 250, 500, 1000 cycles of 1250 – 1750 °C
- After 1000 cycles many transverse fatigue cracks (*L = 280 ± 40 μm)* were observed.
- However, cracking behavior in other targets was very inconsistent. Cracks appear up to 3.8 mm away from the centre, with unpredictable lengths.
- Some targets did not crack.
- No clear relationship between number of cycles *N*, and crack length



a) Surface prior to exposure (sandblasted), b) fatigue crack after 1000 cycles of 1250 – 1750 °C

Fatigue cracking of ELM/Pre-cracked W by pulsed H plasma



W pre-exposure (a) and after 20 (b), 100 (c), and 1000 cycles (d, e)

- W targets (non-ITER grade) with pre-existing microcrack network *(L = 130±30 μm)* approximating ELM cracking were exposed to 20, 50, 100, 500 and 1000 cycles of H+ plasma.

  - $\Delta T_e = 0 – 1.6$ eV
  - $\Delta n_e = 0 – 1.4\times10^{21}$ m^{-3}
  - $\Delta T_{target} = 850 – 1250$ °C
  - $f_{SW, DEMO} = 1.0$ Hz
  - $A_{SW, DEMO} = 50$ mm
  - $Q_{SW, DEMO} = 20$ MW m^{-2}

- Large mm-scale cracks observed extending radially out from target centre of all targets. Even after only 20 cycles (20 reattachment events for ITER)

Takeaways

- A novel method using Magnum-PSI to investigate the surface fatigue cracking of W under plasma loading is under development.
- Further method development required, in particular guiding cracks with a stress concentration notch, and *in-situ* crack characterization, to enable study of PMI effects on fatigue behavior.
- Initial results indicate that strikepoint sweeping a 20 MW m^{-2} reattached load at 1Hz, 50 mm, will propagate ELM-induced micro-cracks to the mm-scale after **just *20* cycles.** This suggests that sweeping the strikepoint over ELM-cracked monoblocks may be problematic.
- Future work aims to generate ε-N curves for H-loaded W, fuzz-affected W, and include high temperature effects (inc. recrystalisation). Fatigue cracking of redeposited W may also be explored.

MPG M.Balden

- High Particle Fluence Exposures of Plasma-Facing Components for ITER
- Pre- and post-analysis of material and components D002: Pre- and post-characterisation of samples

- Task finished with Midterm Meeting

WPPWIE SP A.2: High Particle Fluence Exposures of Plasma-Facing Components for ITER

Mid-Term-Meeting

Pre- and post-analysis of material and components

D002: Pre- and post-characterisation of samples

Motivation:
What is the effect of slow transients?

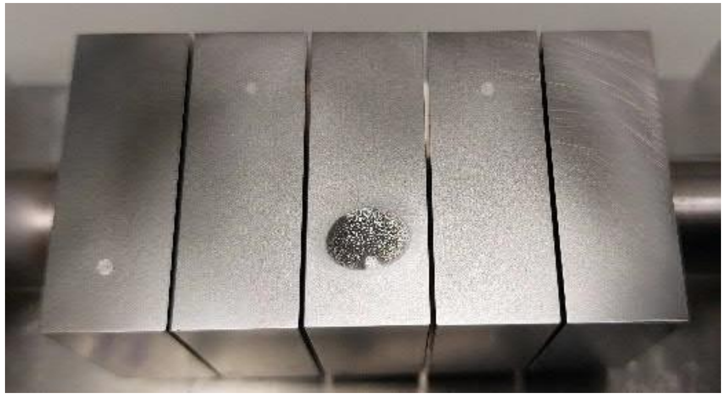
See T. Morgan, Invited talk, 26th PSI in Marseille (2024)

What happens during slow transients?

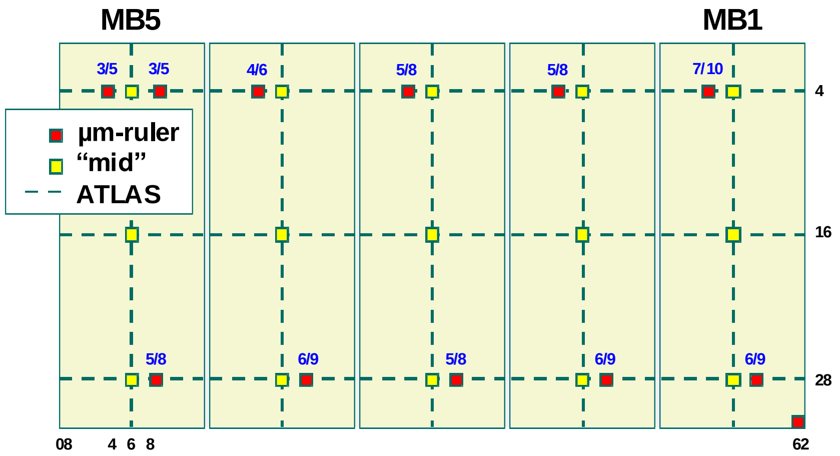
- heat flux increase at divertor (10-20 MW m^{-2}) due to loss of detachment
- T_{surf} > 2000 °C ➔ depth of recrystallisation: 2 mm deep in 21 hour, loss of yield strength, (macro)cracking(?)
- T_e increase, sputtering due to entrained impurities

➔ Magnum-PSI exposure of pre-characterized W-monoblock mock-up

DIFFER

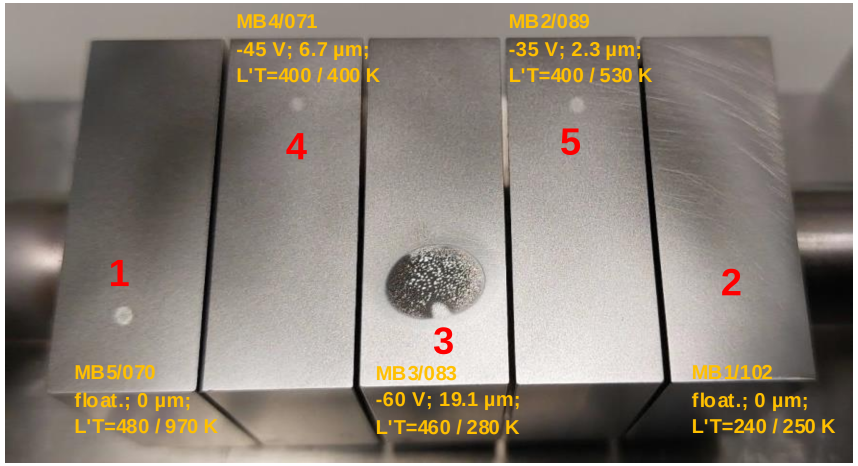


Magnum exposure Feb 2023 ("Magnum19"-chain)



Exposure conditions:

- fix: 1e27 Ar/m²; T_{surf}=550 °C; 1e4 laser pulses
- variation: L'T=250…970 K; float. … 60V; expected sputter depth: 0…19 µm



- Post-characterisation at
  - 12 FIB-prepared µm-ruler with SEM & CLSM ➔ mixture of erosion & deposition ✓
  - SEM & CLSM of centre of laser spots ➔ roughening ✓
  - CLSM of complete area of chain (x5) ✓
  - Cross-sections of shiny spot on MB3 ➔ deposition ✓
  - Cross-sections of filled crack in laser spots ➔ deposition ✓

} Reported 2023

➔ 1st round of evaluation done

➔ 2nd round of evaluation done: FIB cross sectioning perpendicular to µm-ruler plane — Work in 2024

WP PWIE SPA 3

Results 2024

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Advanced Materials under thermo-mechanical and plasma loads

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
J.W. Coenen	FZJ	10	D001 (M. Wirtz, J.W. Coenen, A. Litnovsky)
T. Morgan	DIFFER	3	D005
I. Garkusha	KIPT	15	D004
D. Terentyev	LPP-ERM/KMS	4	D003
J. Riesch	MPG	2	D002, D006 (J.Riesch, S. Elgeti)
D. Terentyev	LPP-ERM/KMS	1.91	D007
Total		29.91	

Device	Beneficiary	Days	Related Deliverable
PSI-2	FZJ	6	D001
JUDITH	FZJ	10	D001
GLADIS	MPG	5	D002, D003, D006
Accelerator	MPG	10	D002, D003, D006
QSPA	KIPT	10	D004
MAGNUM-PSI	DIFFER	4	D005
UPP	DIFFER	1	D005

Deliverables:

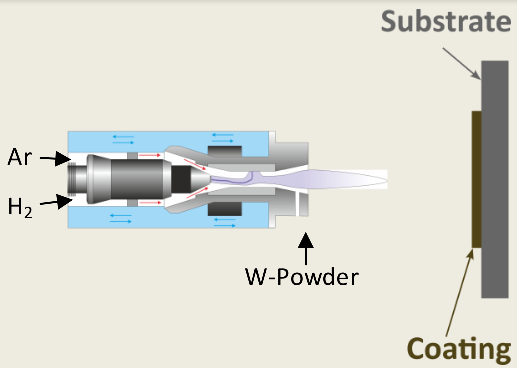
Deliverable ID	Deliverable Title
D001	Analysis of Material behavior under Plasma and heat loading regarding mechanical properties e.g. cracking, embrittlement, and microstructure. Link to SP A4 (FZJ)
D002	Performance of advanced materials under high heat loads and their microstructural characterization (MPG)
D003	Results from tests of small-scale samples of W and other advanced materials and components (LPP-ERM/KMS)
D004	Investigation of advanced materials and coatings under ELM-like/disruption transient loading and subsequent analysis.(KIPT)
D005	"Effect of ELM loading on microstructure evolution of W coated RAFM steels" (DIFFER)
D006	Effect of energetic ion irradiation on the strength of W wire (MPG)
D007	Results from tests of small-scale samples of W and other advanced materials and components (LPP-ERM/KMS) (2023 Transfer)

FZJ J.W.Coenen, Y.Mao A.Litnovsky G.Schmidtmann

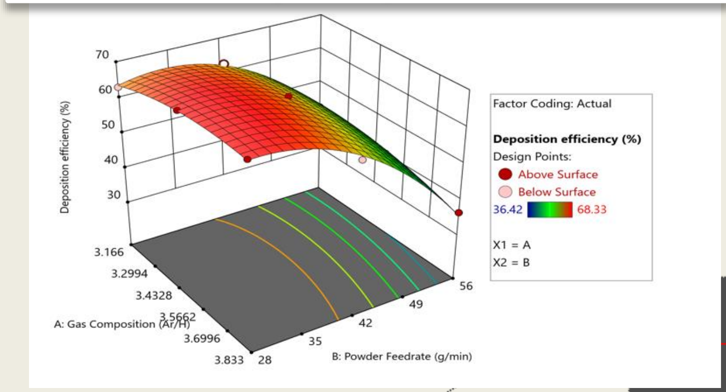
- Plasma Sprayed Materials for W7-X
- Tungsten Composites

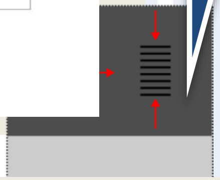
Low Pressure Plasma Spraying (LPPS) of tungsten (W) on different substrates

Variation of process parameter

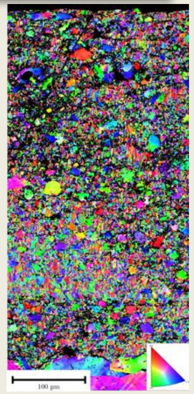


Evaluation of quality parameters
→ two optimized parameter sets

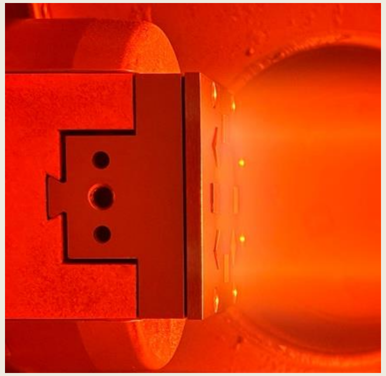




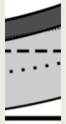
Scaling-up coating thickness, residual stress measurements (XRD), and grain structure



Plasma exposure experiments in PSI-2

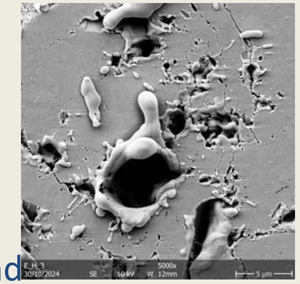


One parameter set was exposed:
- Ne- Plasma
- D- Plasma



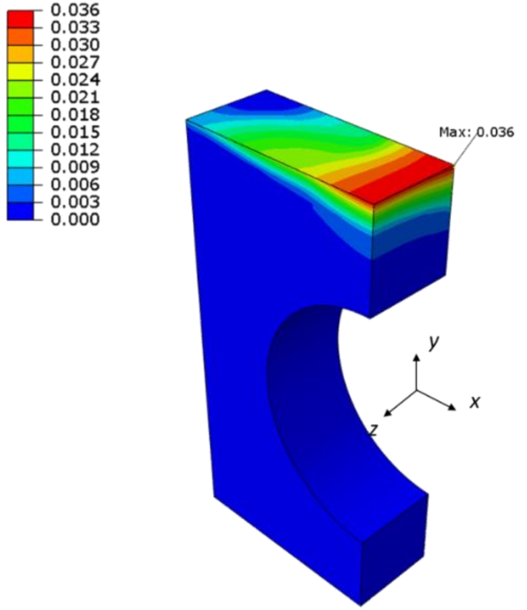
Current status

Evaluation of:
- Hydrogen retention
  - NRA
  - TDS
- Sputter yield
  - Weight loss
  - FIB-marker
- Surface roughening and modifications



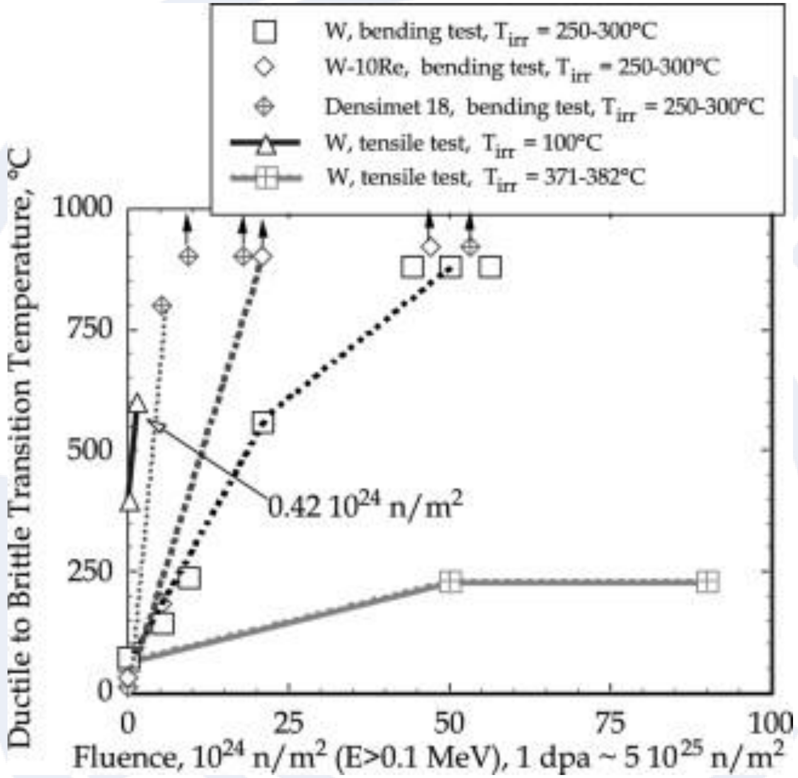
Crack formation for tungsten armor

- Intrinsic brittleness of tungsten material
- Thermal heat load at the divertor: thermal stress and thermal fatigue



Accumulated equivalent plastic strain field in the tungsten armor block after the 5th HHF load cycle at 20 MW/m^2.
-M.Li 2015.

G. Pintsuk et al. / Fusion Engineering and Design 88 (2013) 1858– 1861 1861



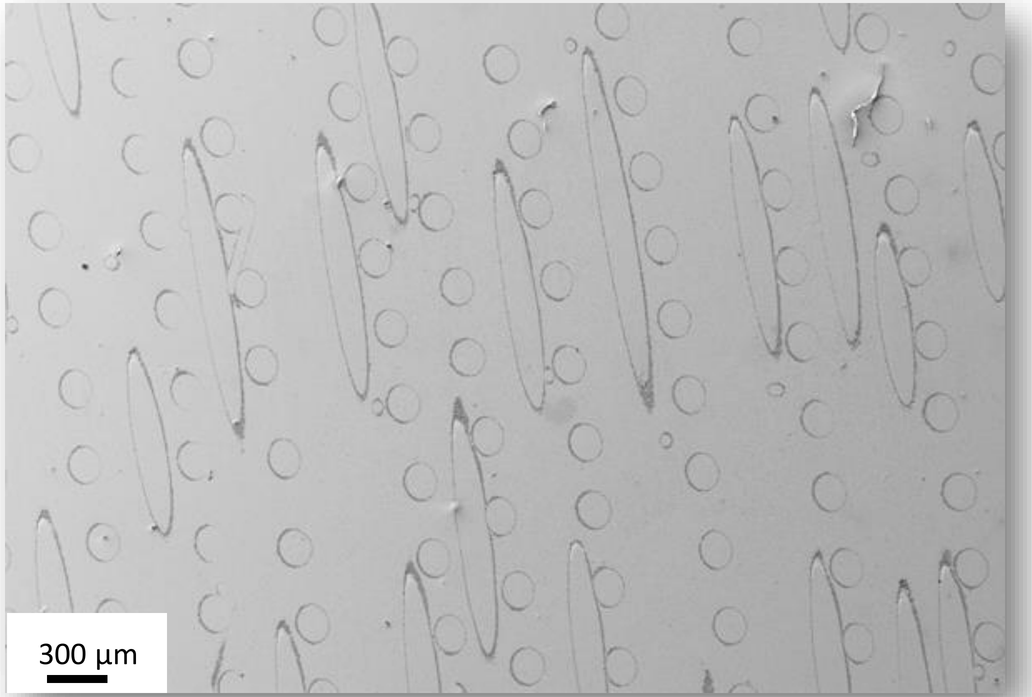
H Bolt, et al; Journal of Nuclear Materials, Volumes 307–311, Part 1, 2002, Pages 43-52

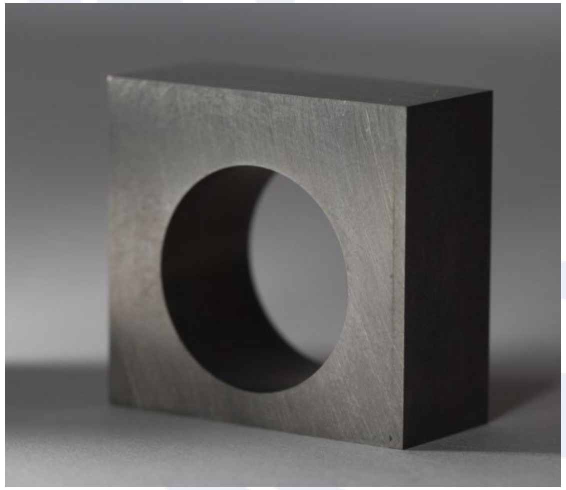
Neutron embrittlement

A damage resilient material is required

Products and microstructure

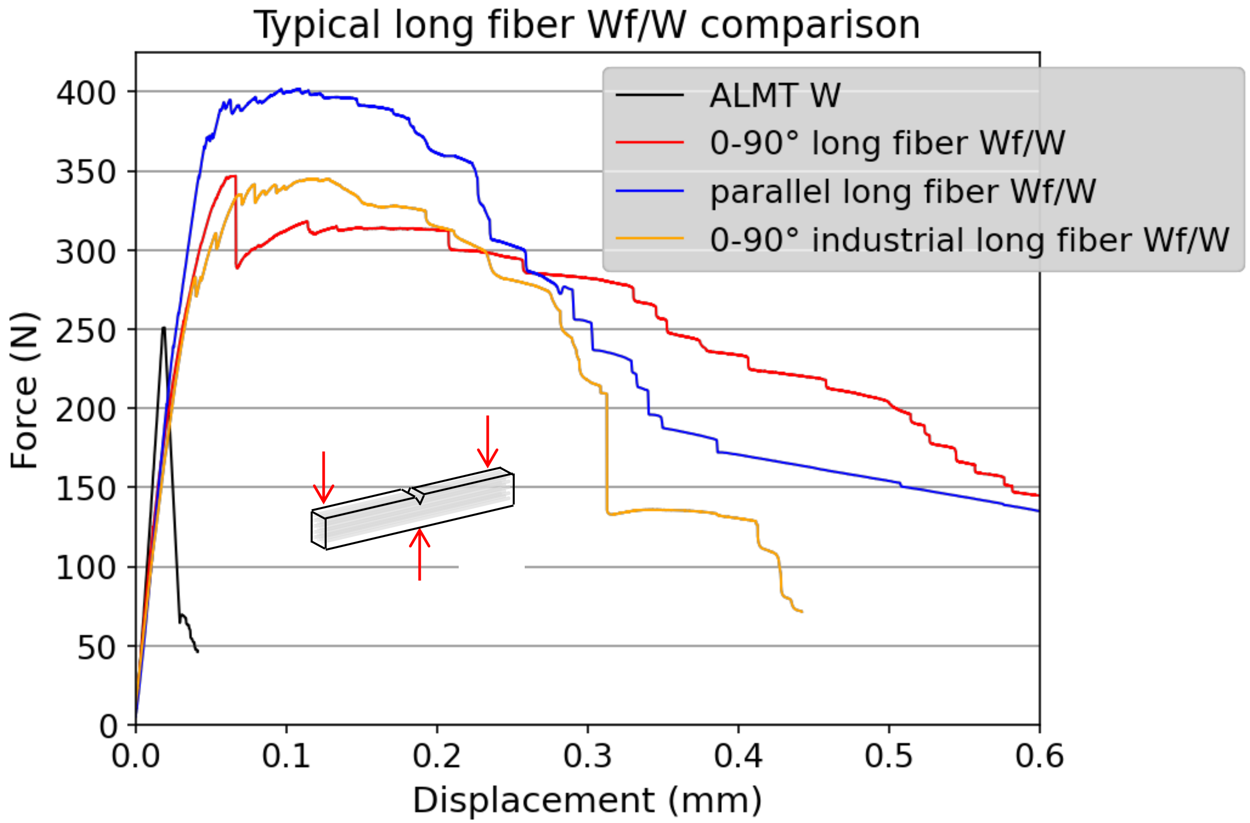
60 mm x 12 mm Wf/W
~91% relative density

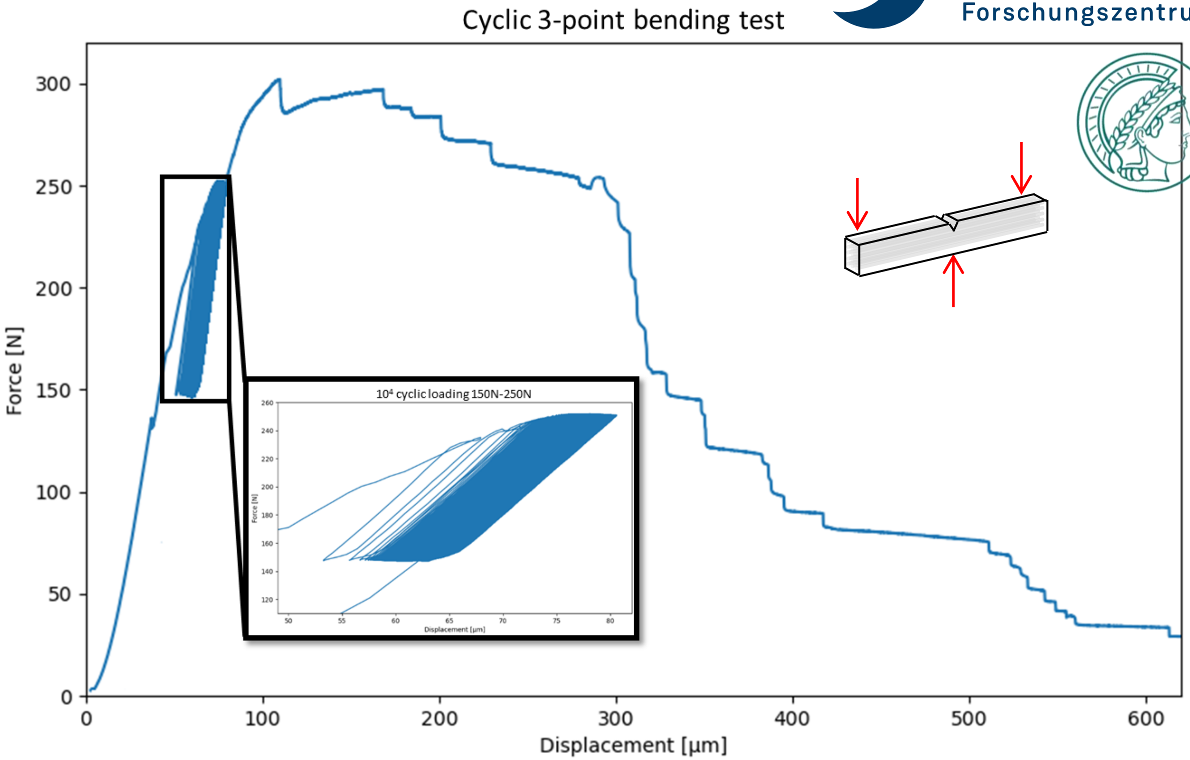


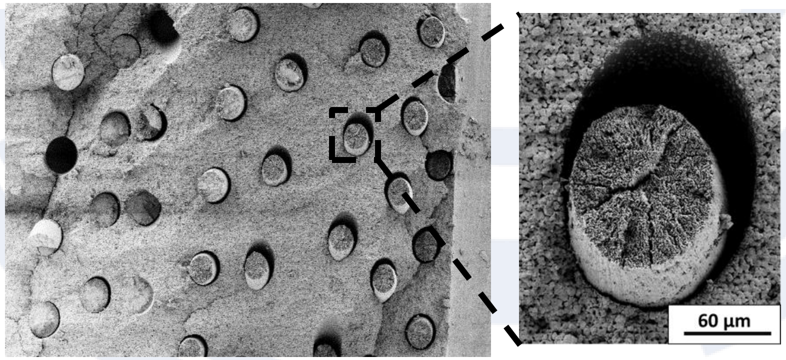


Flat tile mock-ups and monoblocks based on long fiber W_f/W are prepared for HHF tests

Mechanical tests





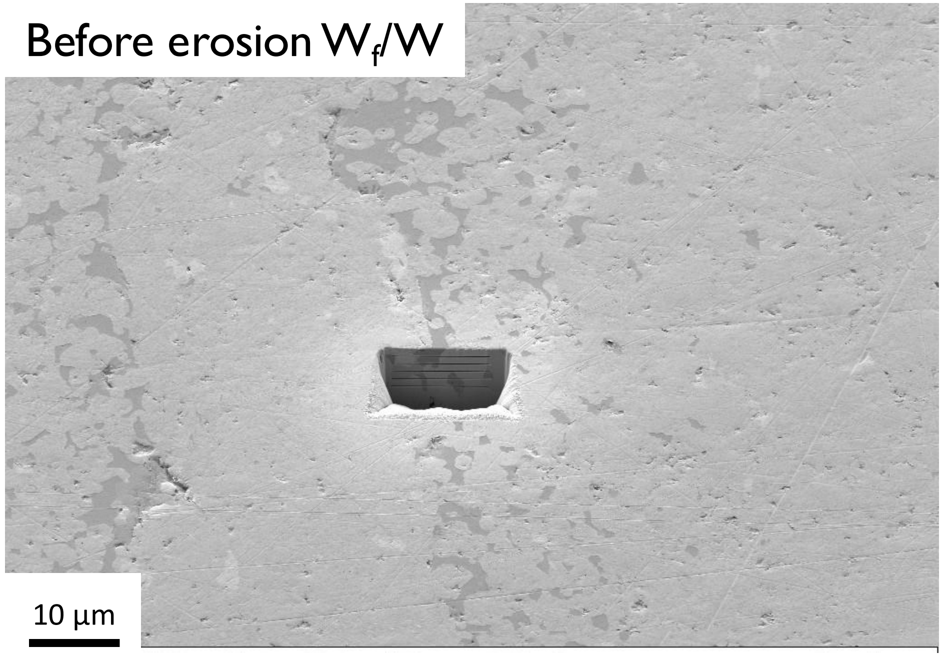


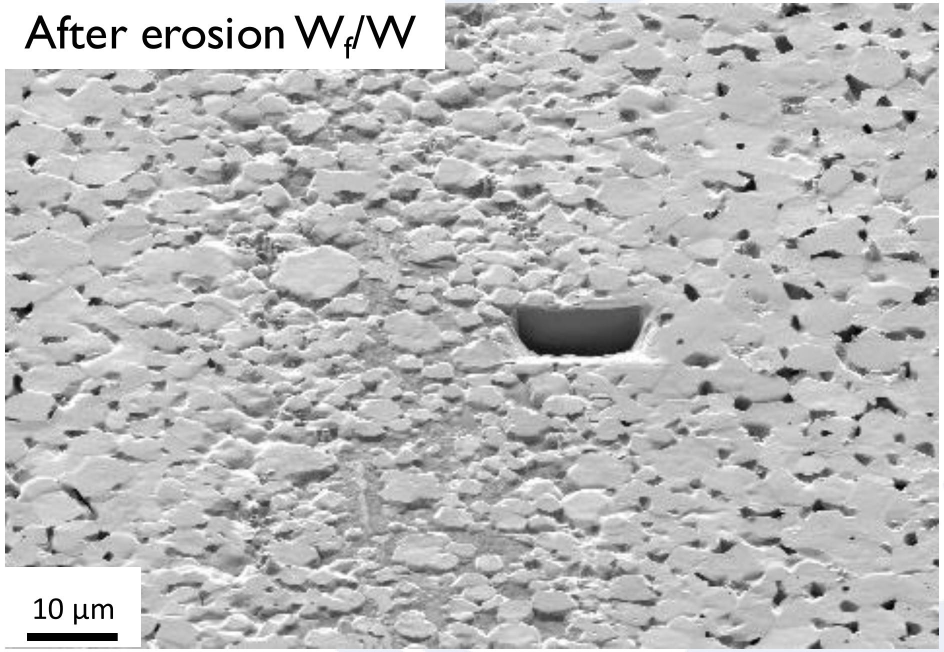
- Mechanical tests were performed for long fiber W_f/W with 0-90° fiber orientation, including cyclic tests
- Slightly lower maximum loading with significant pseudo ductility compared to parallel orientation design
- No degradation of mechanical properties after cyclic loading

Plasma erosion

- Neon plasma, 98-117 eV, flux: 1x $\times 10^{21}$ Ne^+ $m^{-2}s^{-1}$, total fluence of 3 $\times 10^{24}$ Ne^+ m^{-2}, ~90ºC in PSI-2

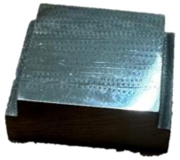
	Mass loss	Depth loss
Reference W	~2.85mg	~2.4 μm
L-Wf/W	~3.06mg	~2.2 μm



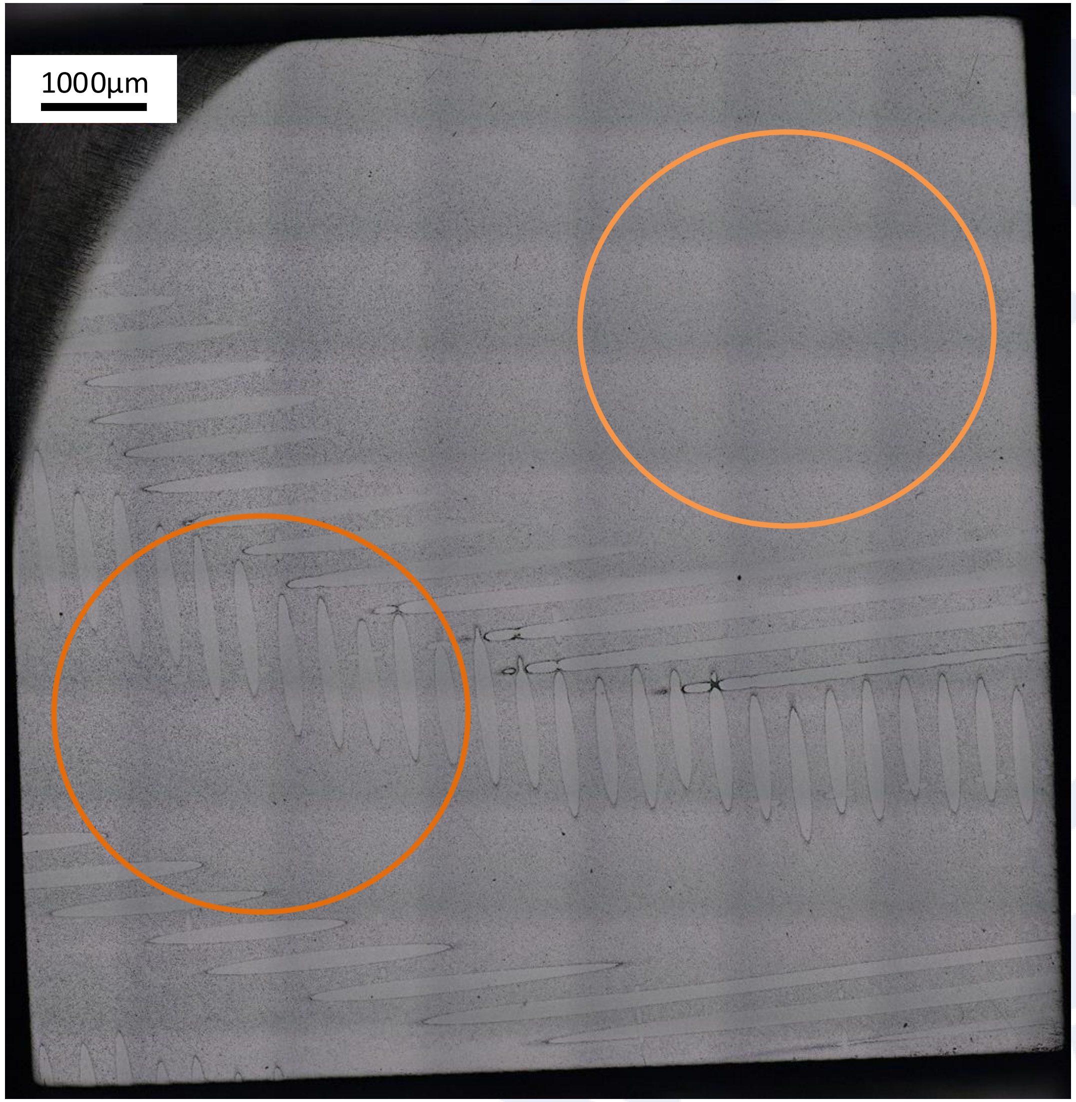


Comparable erosion property to Pure W

Fuel retention



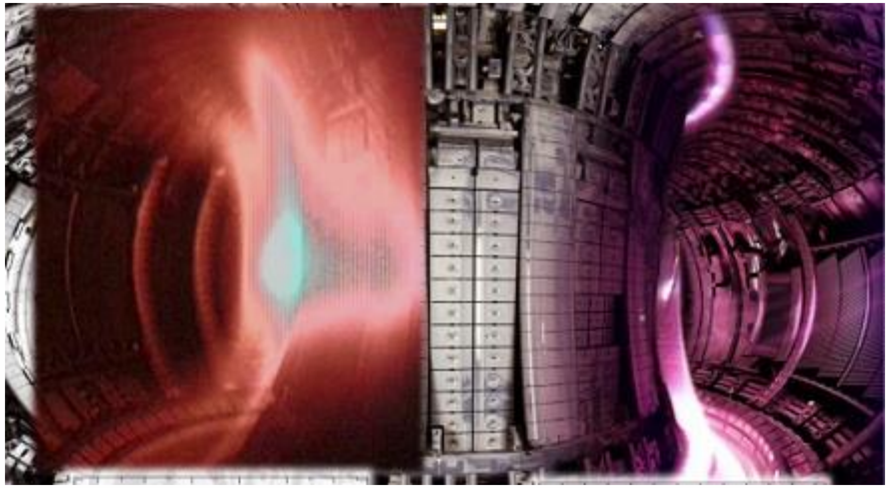
- D plasma exposure was applied. Bias ~95V, Flux:~2.45×10^{21} $m^{-2}s^{-1}$; the total fluence ~$5 \times 10^{25} D^+ m^{-2}$. During the exposure, the temperature was ~275 °C.
- NRA experiments on different regions
- Two points are tested, one on the region without fibers, and the other at the region with fiber/interfaces
- Later, together with TDS results, these results will be helpful to understand whether we have different retention behavior for W_f/W compared to pure W



DIFFER with Collaborators

- **The effect of mitigated thermal transients on Eurofer-97**

Disruption loading for EUROfer in FW



Max thermal load when accompanied by vertical displacement is 300 GW/m^2, with mitigated loads around 10-100x lower

Events last between 1-4 ms. FEA modelling predicts vaporisation of the coolant and temperature rise of EUROfer below W armour to ~**950˚C**

ITER expected to experience around 2500 disruptions over its 30 year lifetime

Predictions for EU-DEMO and STEP unclear at this stage

Research question: How will EUROfer evolve under transient loading behaviour (recrystallization, formation of precipitates etc)?

UK Atomic Energy Authority

IAC Interface Analysis Centre
Materials research for Energy, Engineering and the Environment

Nuclear Energy Futures
EPSRC Centre for Doctoral Training

University of BRISTOL

SOUTH WEST NUCLEAR HUB

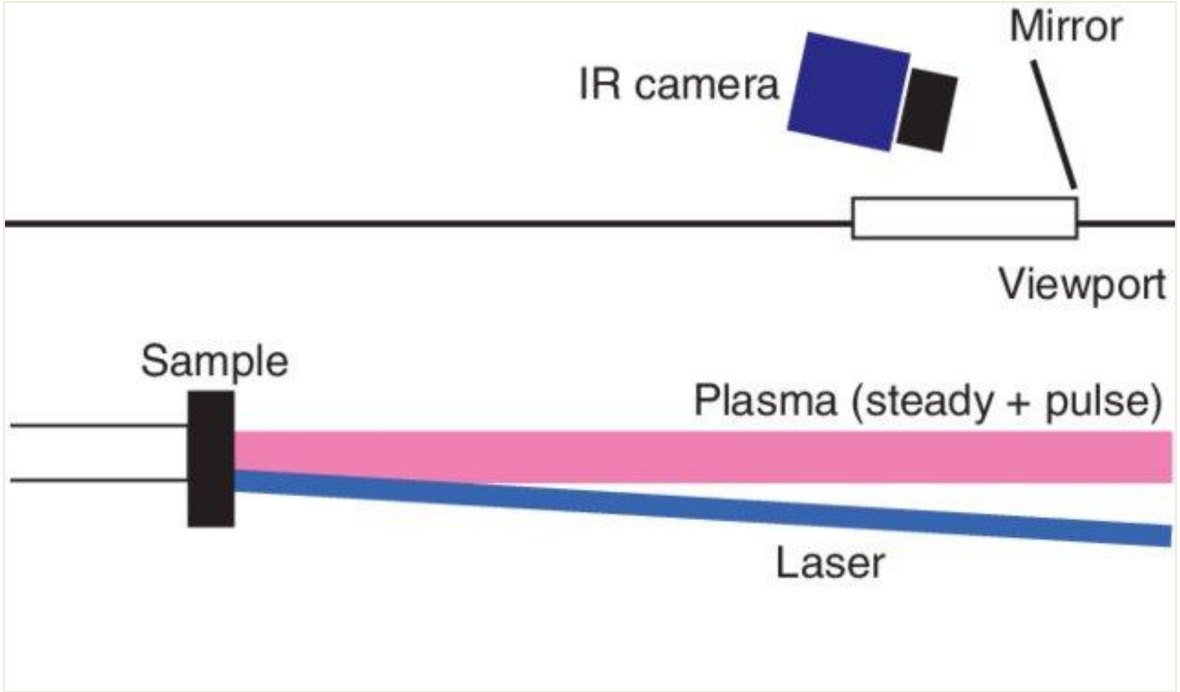
Experimental Conditions

Used Magnum PSI's steady state plasma to replicate regular fusion operating temperatures (~500˚C)

The YAG laser to simulate mitigated thermal transients (ΔT=450-500˚C)

Vary pulse length between 0.5-3ms and number of exposures (1, 100, 1000)

Used both Argon plasma and Deuterium plasma



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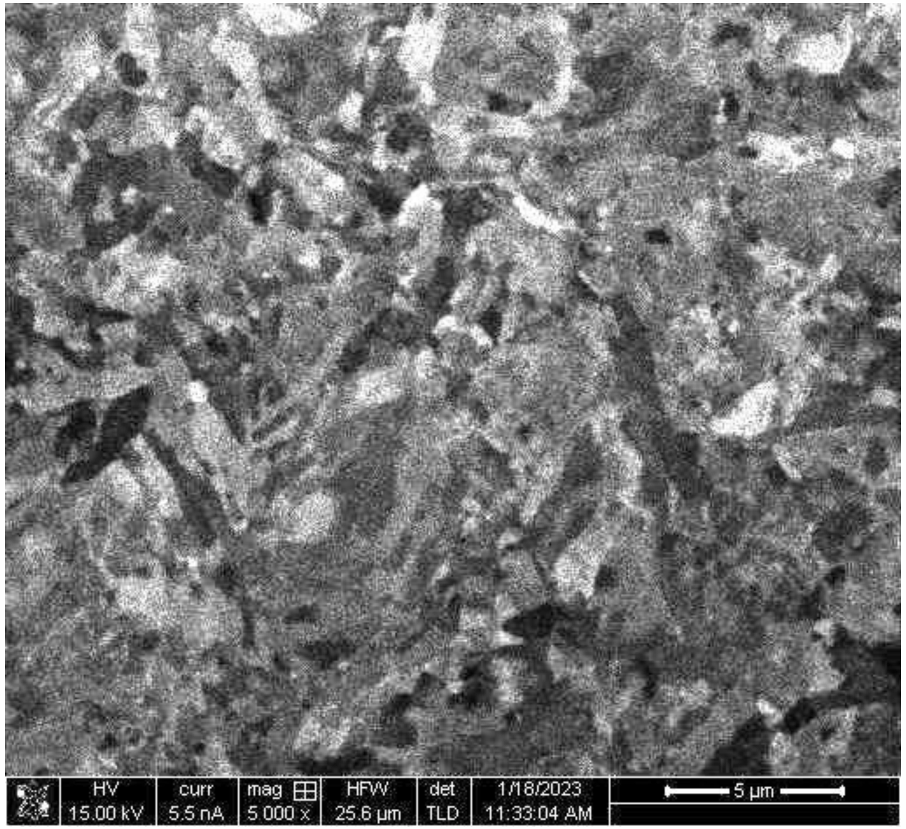
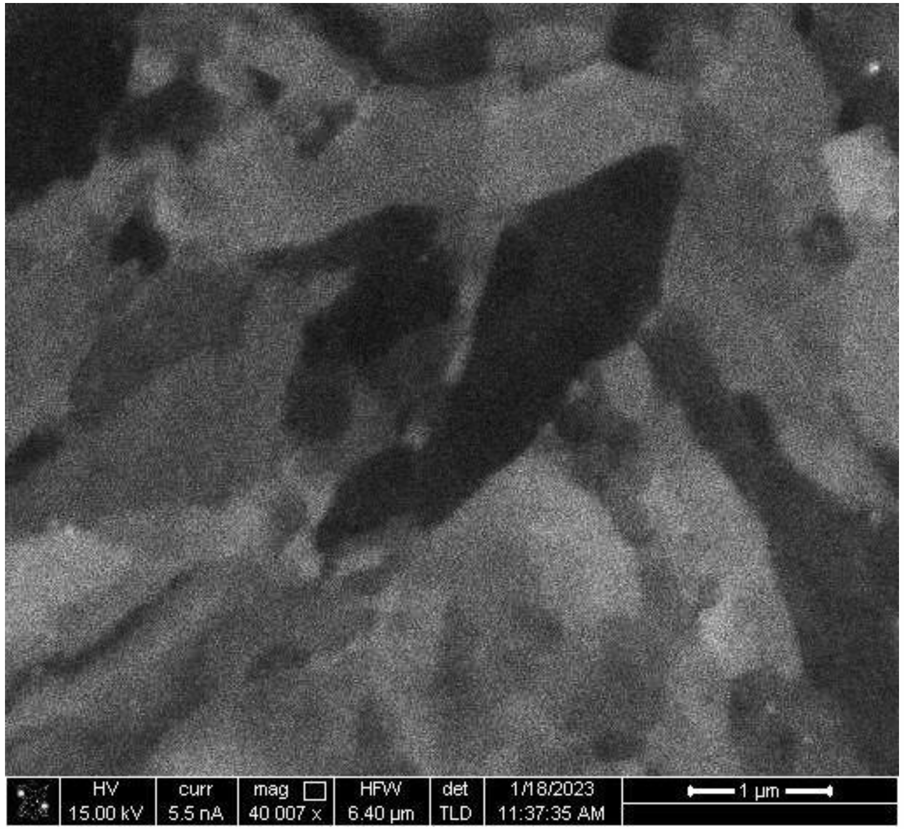
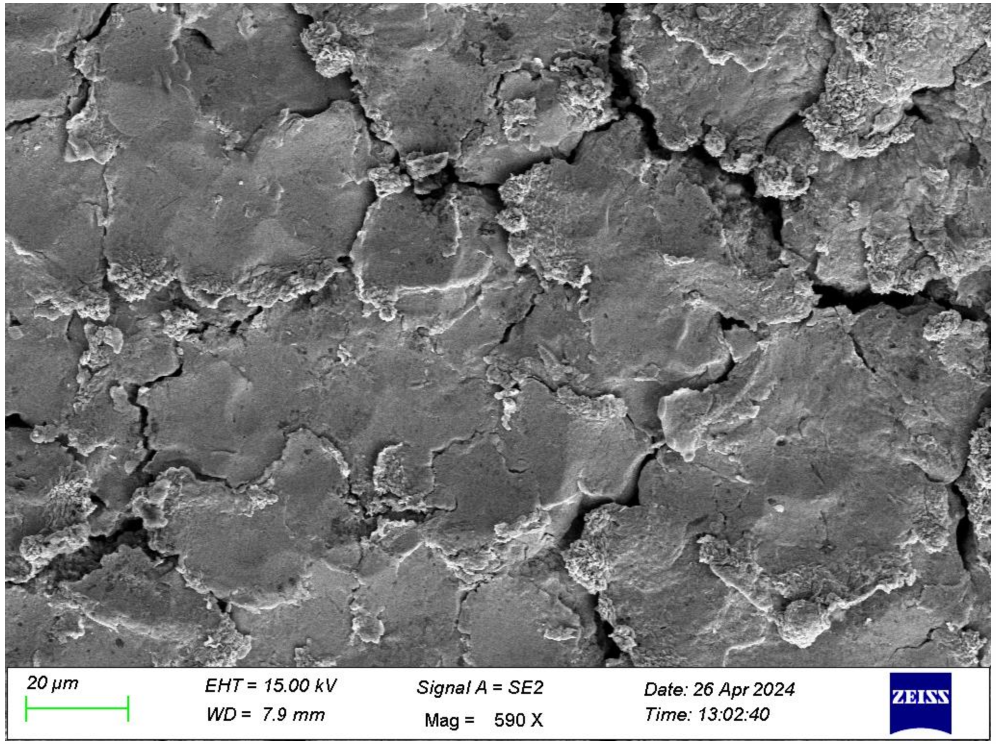
SEM images of as- received Eurofer-97 microstructure



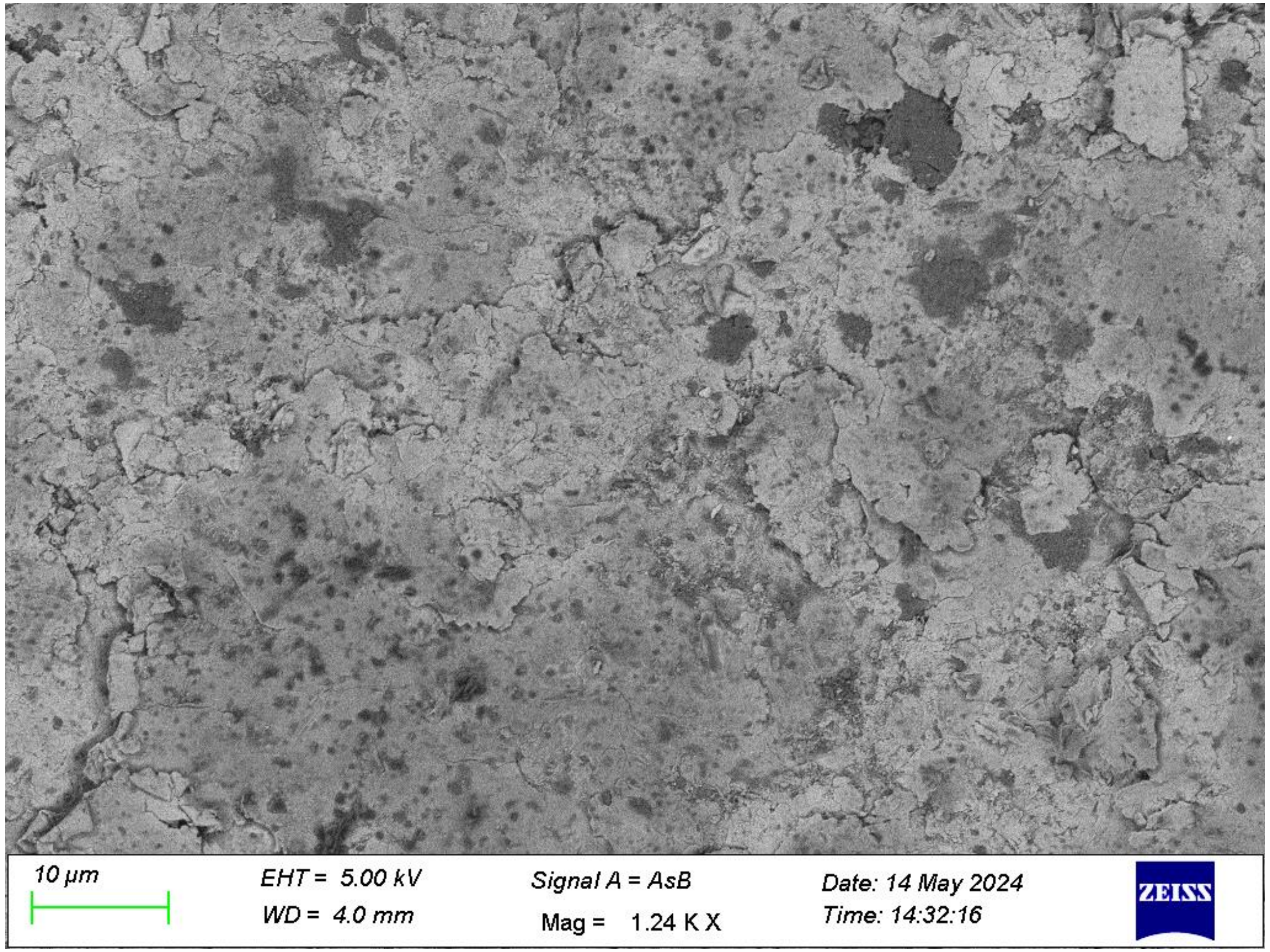


Original Ferritic-Martensitic structure

Plasma exposed material



Surface becomes more ferritic and flakey



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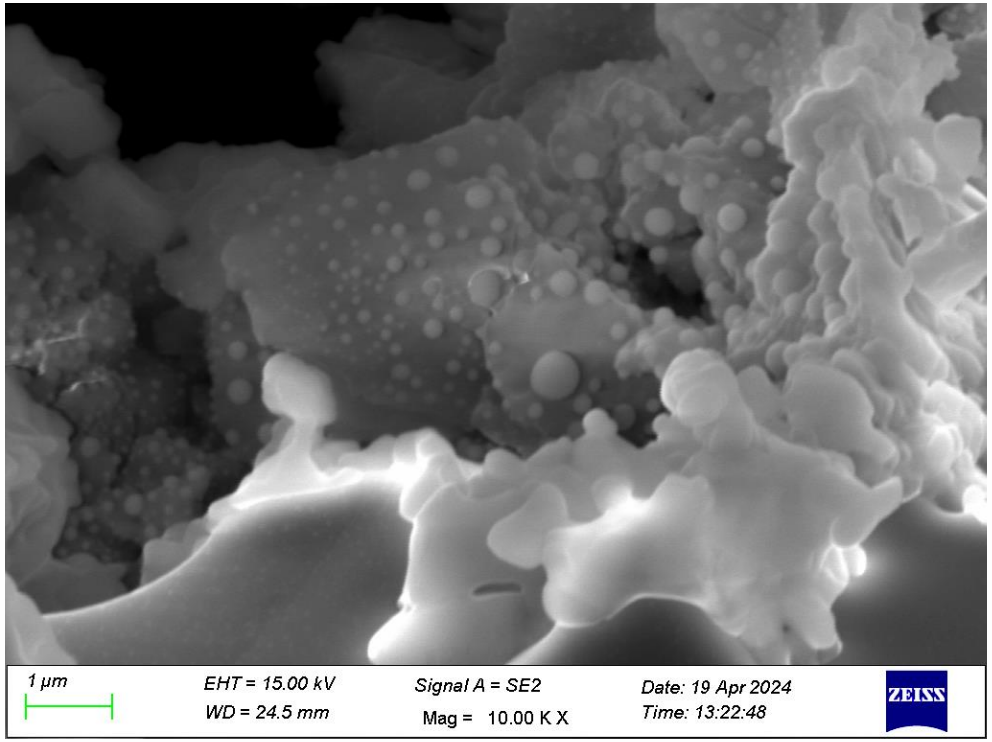
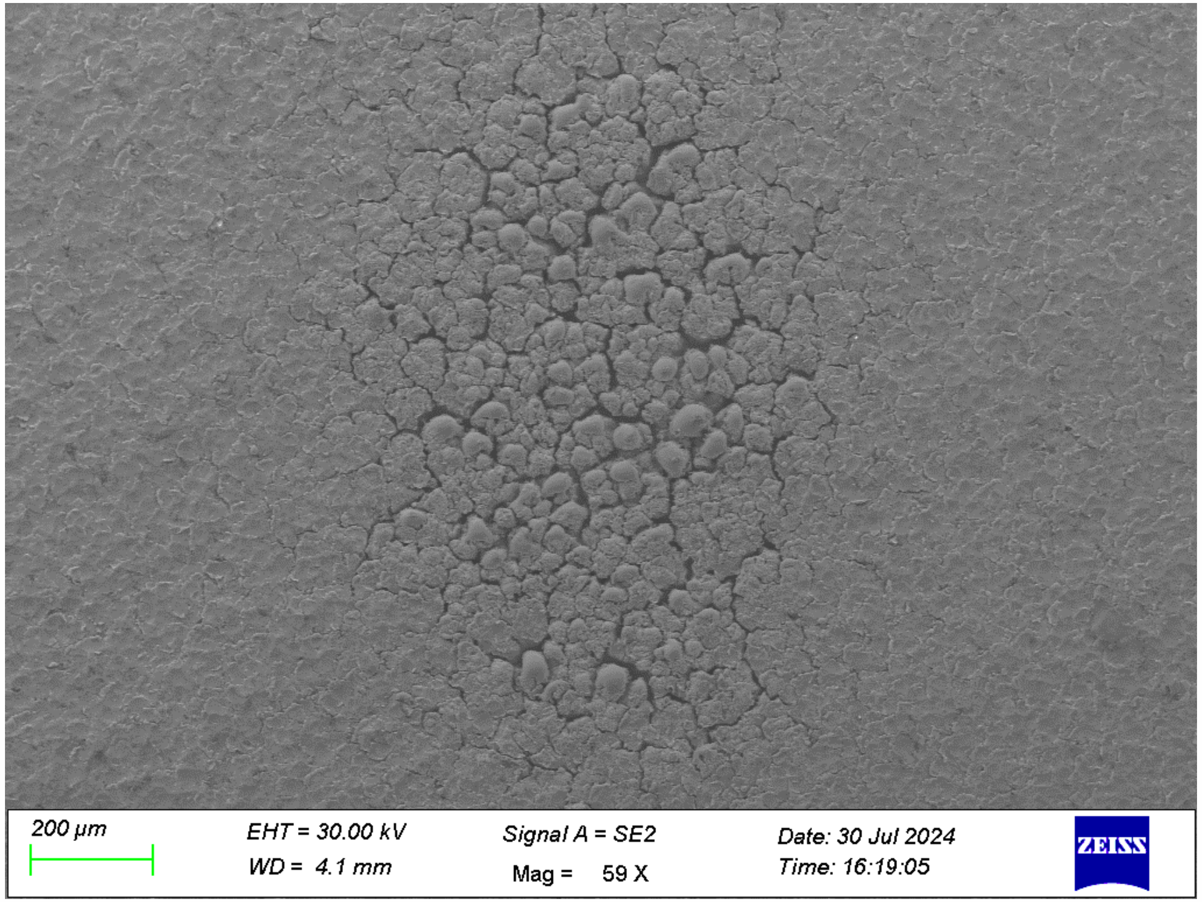
1ms pulse





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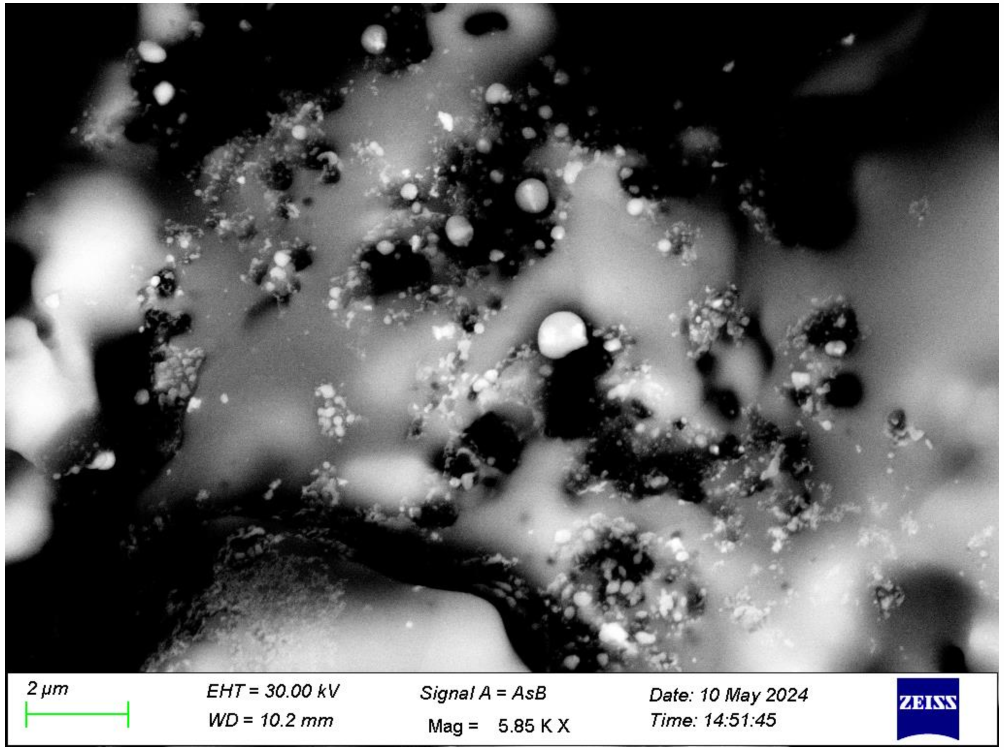
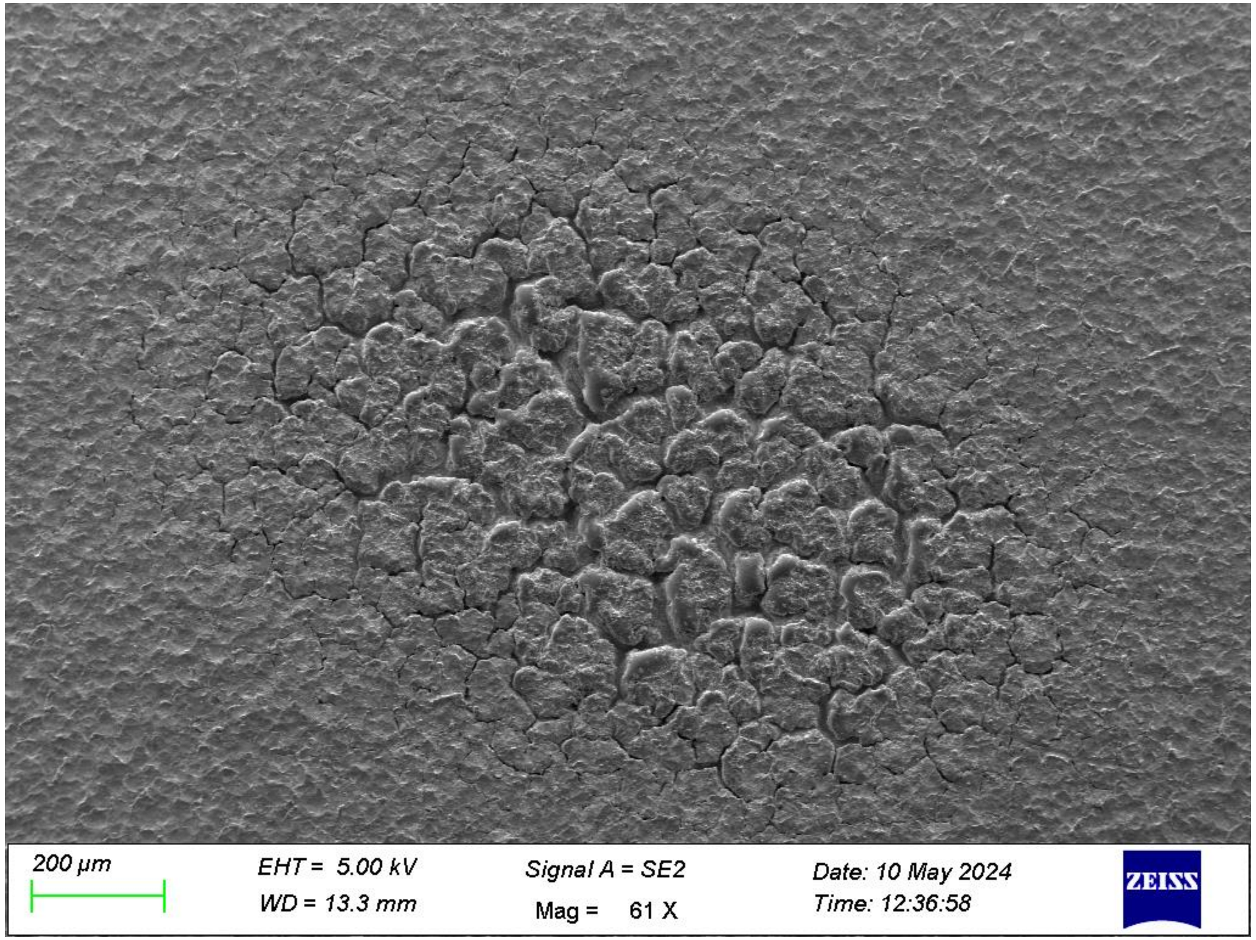
Argon, 1000 pulses, 950˚C

Deuterium plasma- 1000 pulses, 950˚C





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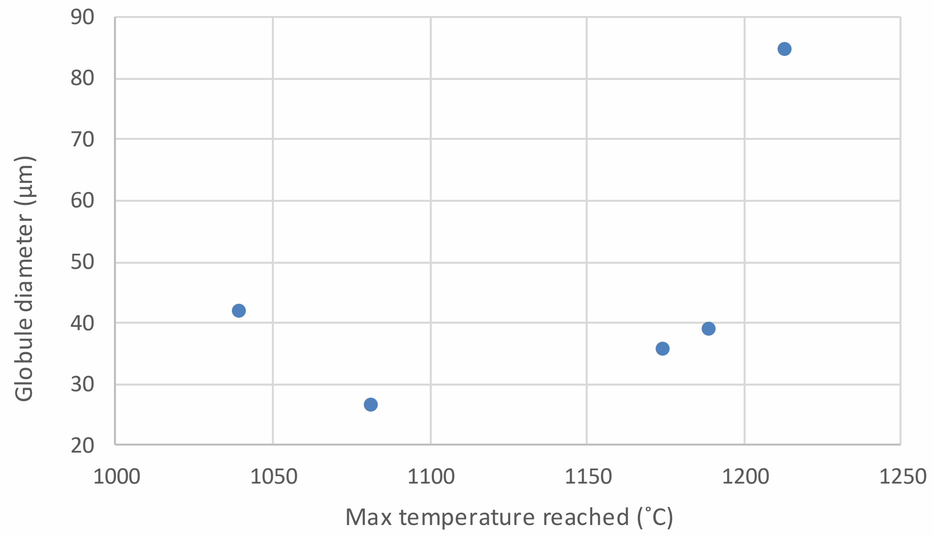
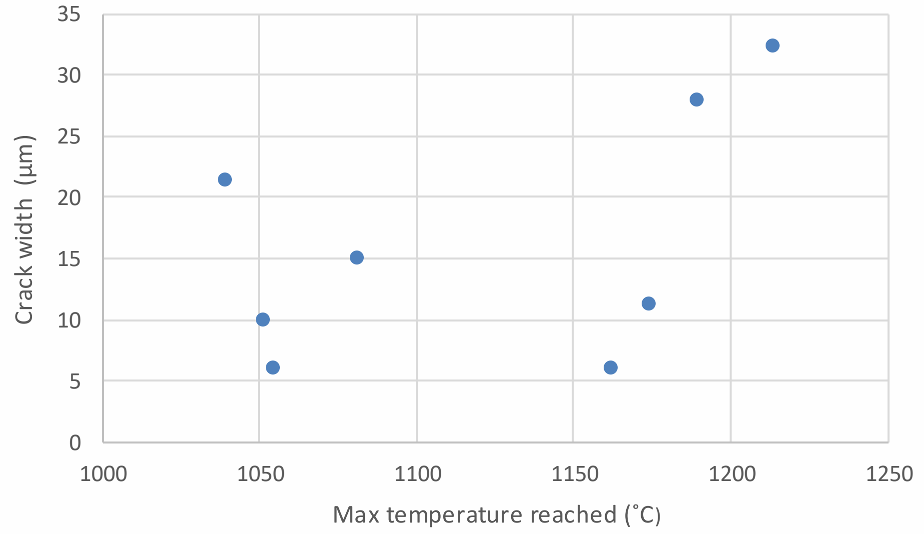
Next Steps and conclusions

See overall melt damage on surface, more interesting is to evaluate microstructural changes under surface (more representative)

Further cross sectional EDX, EBSD and imaging of samples

Second Magnum experiment with three different thicknesses of tungsten coating is being planned for early 2025. This experiment will also investigate three joining methods for tungsten. This is a collaboration with the team at Oxford University. Modelling for target parameters is underway.





SCK-CEN D.Teretnyev

- Prepare all to start the irradiation of latest KLST samples sent by Yiran Mao. The task is completed – samples are assembled and irradiation device is ready to start in the next cycle (in end of DEC).
- Preparing for PIE for tungsten fibres irradiated at 4 different conditions. We have extracted the fibers and now are sorting them, which is quite tricky due to very small size of the samples.

MPG Riesch

- Gladis Test on Advanced Materials und Tests and Giraffe / W Wires

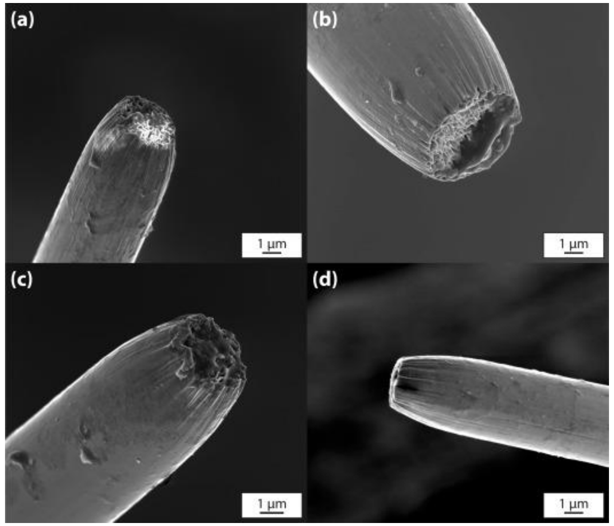
Influence of impurities on the mechanical properties of tungsten

Literature indicates that tungsten becomes brittle as a result of irradiation damage

We could not reproduce this in our tests on thin wires

Possible reasons:

- The strongly deformed microstructure generally prevents embrittlement
- The DBTT is increased, but is still below room temperature
- Change of composition through transmutation
- The embrittlement from the reactor experiments is due to carbon contamination



(a) 0.0 dpa
(b) 0.3 dpa
(c) 1.0 dpa
(d) 9.0 dpa

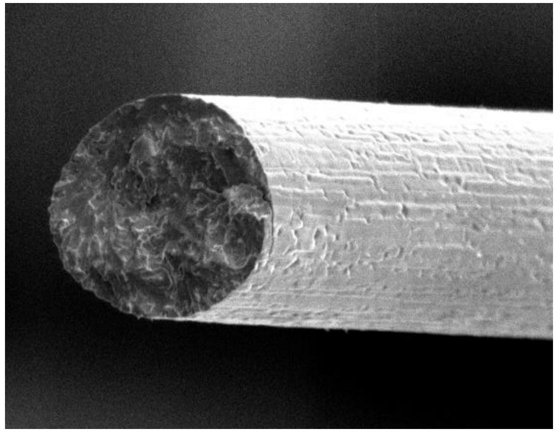
Influence of impurities on the mechanical properties of tungsten

Experimental verification by targeted implantation of impurities with subsequent mechanical testing

protium, deuterium	→ Fusion fuel
helium	→ Fusion ash
nitrogen, neon	→ Seeding for radiation cooling
carbon	→ Data from fission reactor experiments

➔ Tensile test after implantation

➔ Determination of fracture surface using SEM



Ductile fracture surface without carbon implantation (up)
Brittle fracture surface with carbon implantation (down)

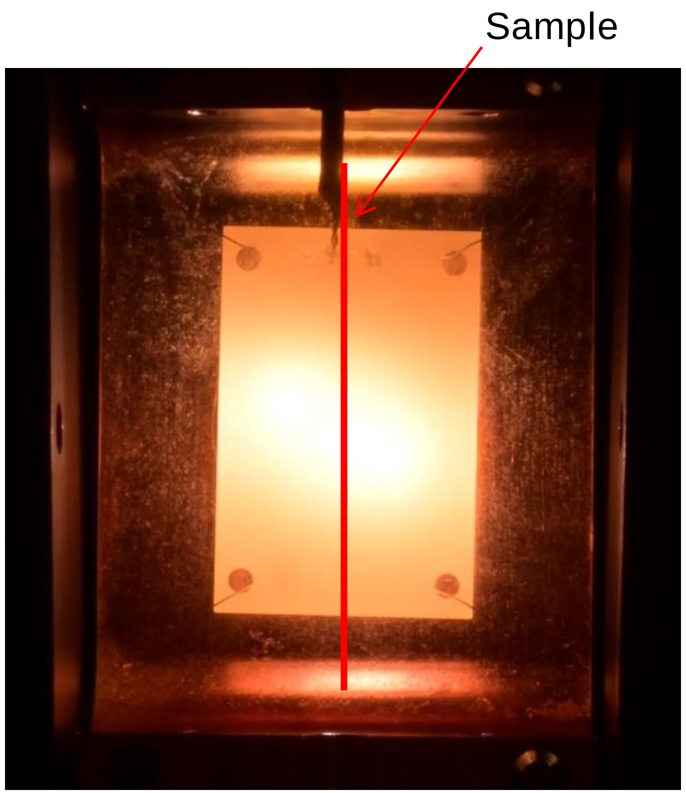
Influence of impurities on the mechanical properties of tungsten

Thermal influence during and after implantation

- During implantation, the temperature can be controlled to some extent by ion energy and current
  - Temperature can only be determined by calculation

- Use of dedicated sample heating system
  - Can only be used after implantation
  - Temperatures up to 1200°C have been carried out and up to 1600°C are planned

- Additional experiments planned with carbon diffusion from the outside
  - Coating of the sample with a carbon film
  - Subsequent heat treatment in the sample heater



ROBERT LÜRBKE | IPP

Test operation of one of the two heating plates at 1000°C

Performed tests

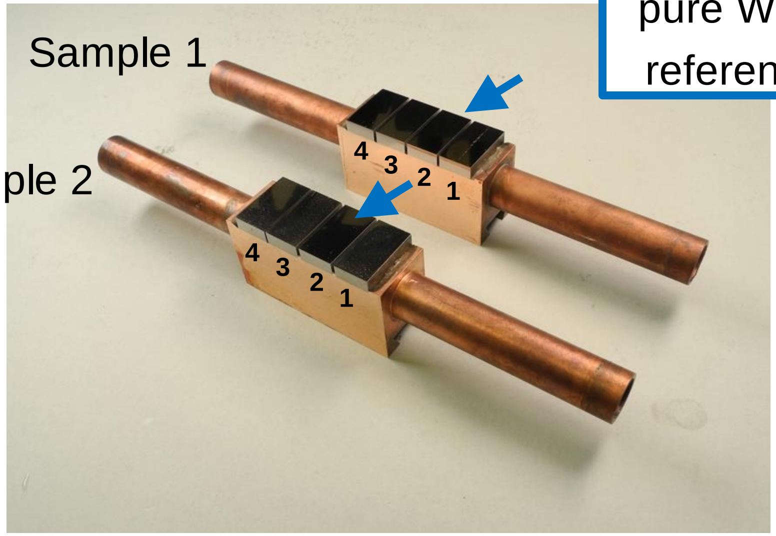
cold water cooling, T_{in}= 15 °C, p_{stat} = 10 bar, 12 m/s

Sample 1

1. Screening up to 12 MW/m^2
2. Cyclic loading: 100 pulses @ 10 MW/m^2 , 10 sec.
3. Cyclic loading: 100 pulses @ 15 MW/m^2 , 10 sec.
   after 30 cycles damage in tile 1, after shielding finalizing of 100 cycles possible

Sample 2

1. Screening up to 12 MW/m^2
2. Cyclic loading: 9 pulses @ 10 MW/m^2 , 10 sec.
   after 9 pulses damage in tile 3 and 4 → change mock-up position and shielding of tile 3 and 4
3. Screening up to 12 MW/m^2
4. Cyclic loading: 100 pulses @ 10 MW/m^2 , 10 sec.
5. Cyclic loading: 25 pulses @ 15 MW/m^2 , 10 sec
   stop due to damage increase in W_f/W tile (tile 1)



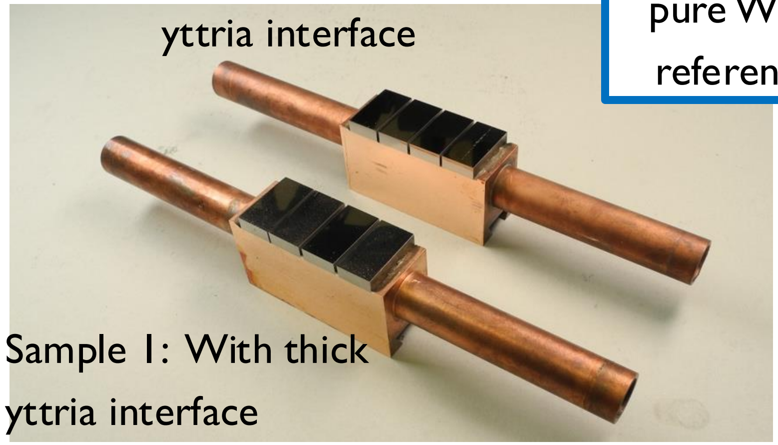
Long-fibre reinforced W fibre-reinforced tungsten composites produced by powder metallurgy; fibre orientaion 0°/90°

JÜLICH FORSCHUNGSZENTRUM

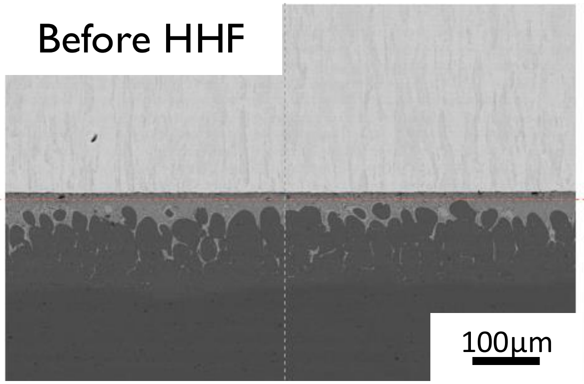
HHF on flat tile mock-ups

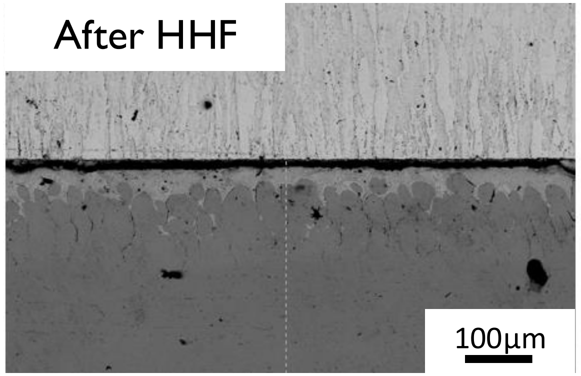
Sample 2: With thin yttria interface

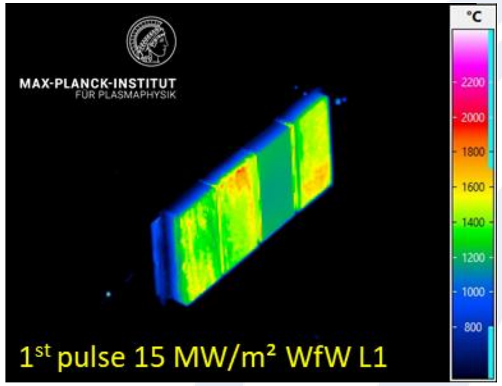
pure W as reference

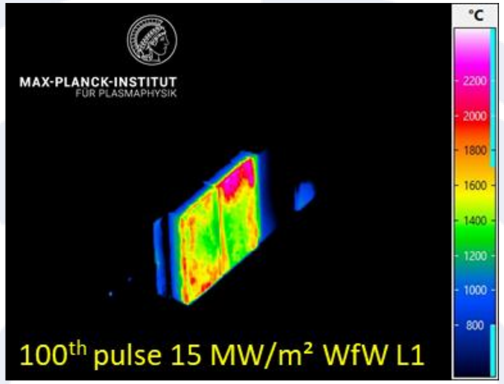


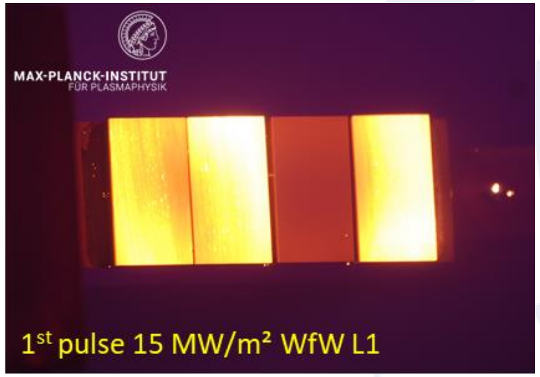
Sample 1: With thick yttria interface

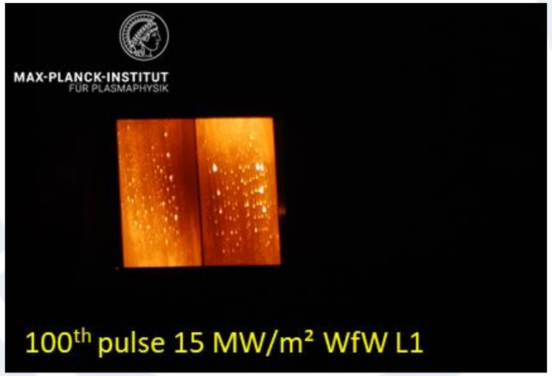












Shielding of damaged tile 1

- W_f/W flat tiles with can survive after HHF with 15MW/m^2 for 100 pulses
- Joining with the heatsink could be the bottle neck of the component, but cracking and decomposition of the yttria is also observed

JÜLICH Forschungszentrum

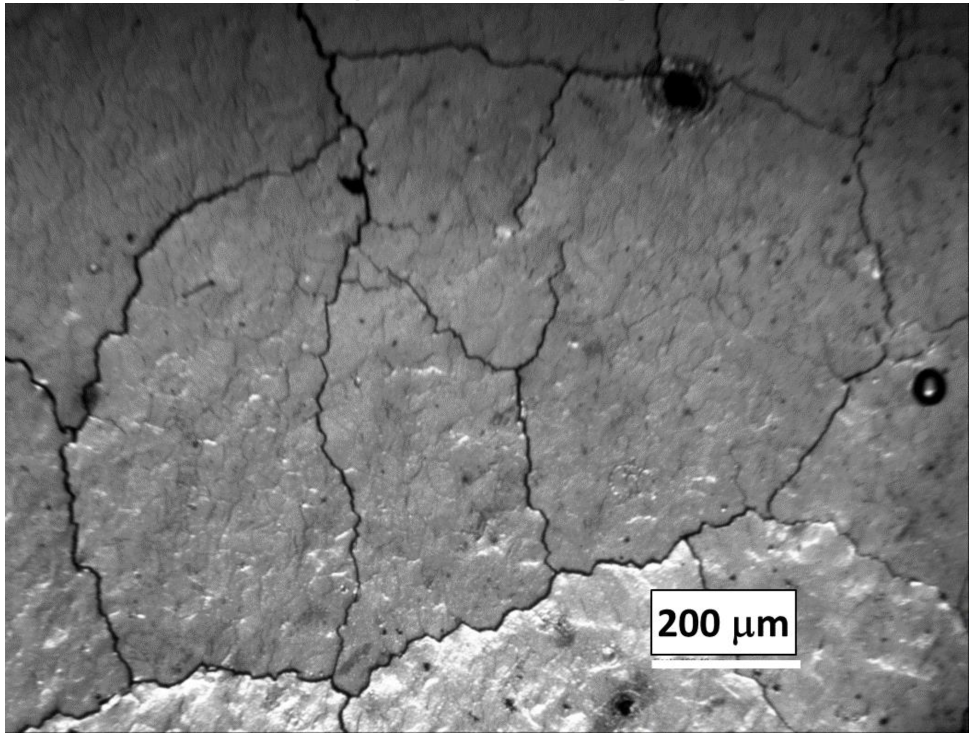
PWIE-SP A.A3.T-T004-D004

Investigation of advanced materials and coatings under ELM-like/disruption transient loading and subsequent analysis (KIPT)

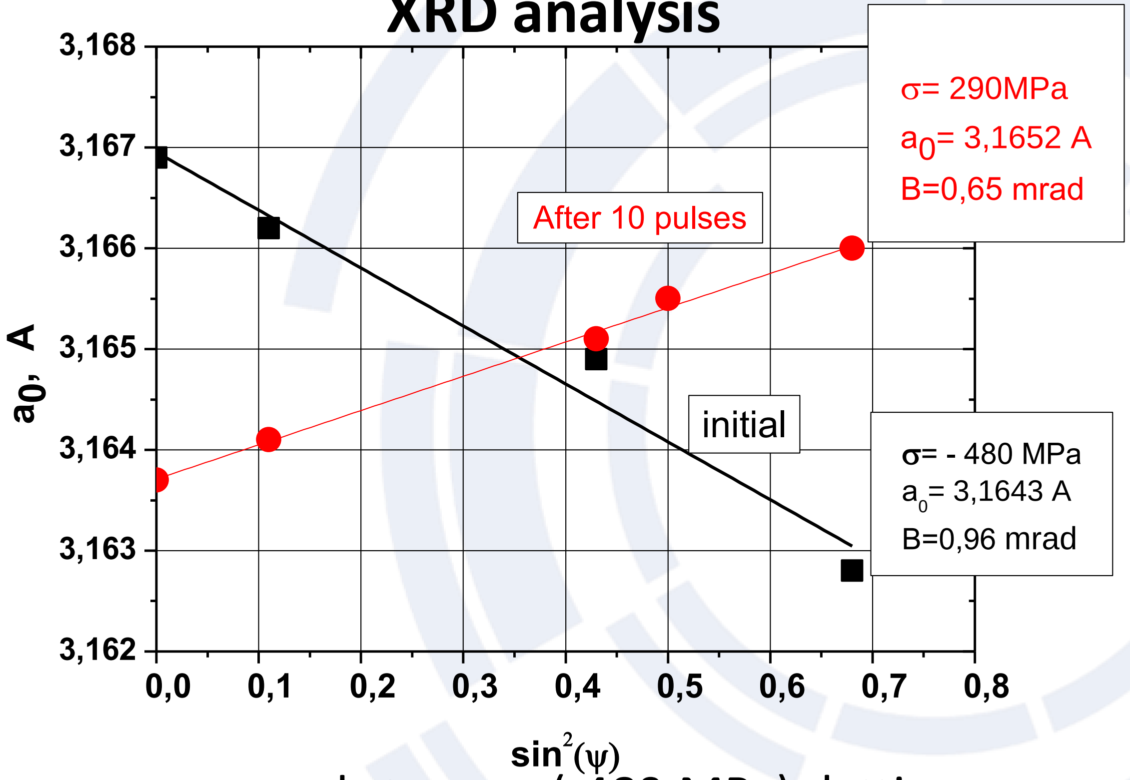
Surface modifications of advanced W materials

IGP tungsten with Transversal grain

Optical image



XRD analysis

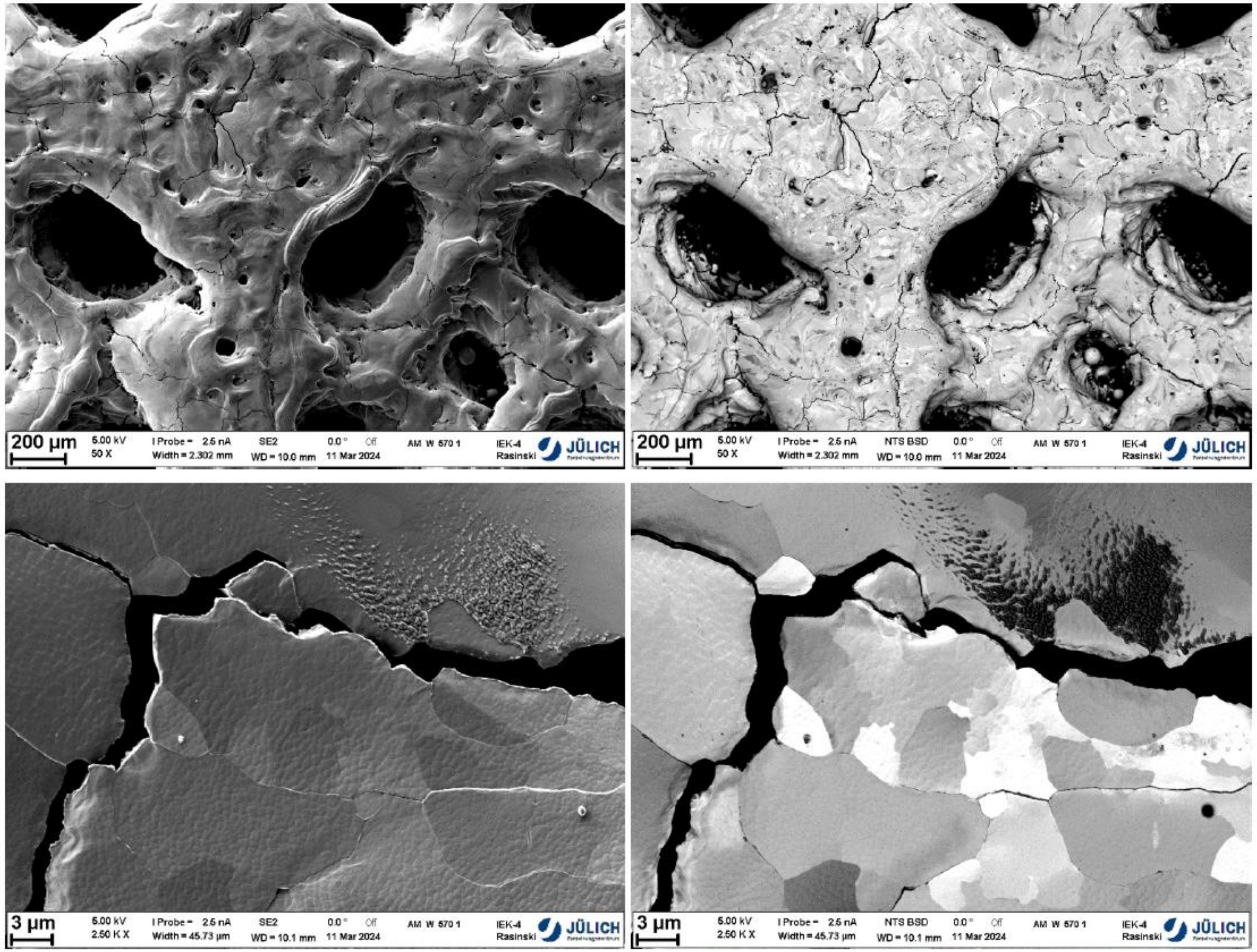


- After QSPA exposure: T=RT, 10 pulses, 0.9 MJ/m^2
- Surface melting, cracking (large and intergranular cracks), pores.

- Before: compressed stresses (-480 MPa); lattice parameter is smaller than reference value (indicating exceed vacancies)
- After: tensile stresses (290 MPa); lattice parameter close to the reference value; width of the XRD line decreased (indicating annealing of line defects)

Surface modifications of advanced W materials

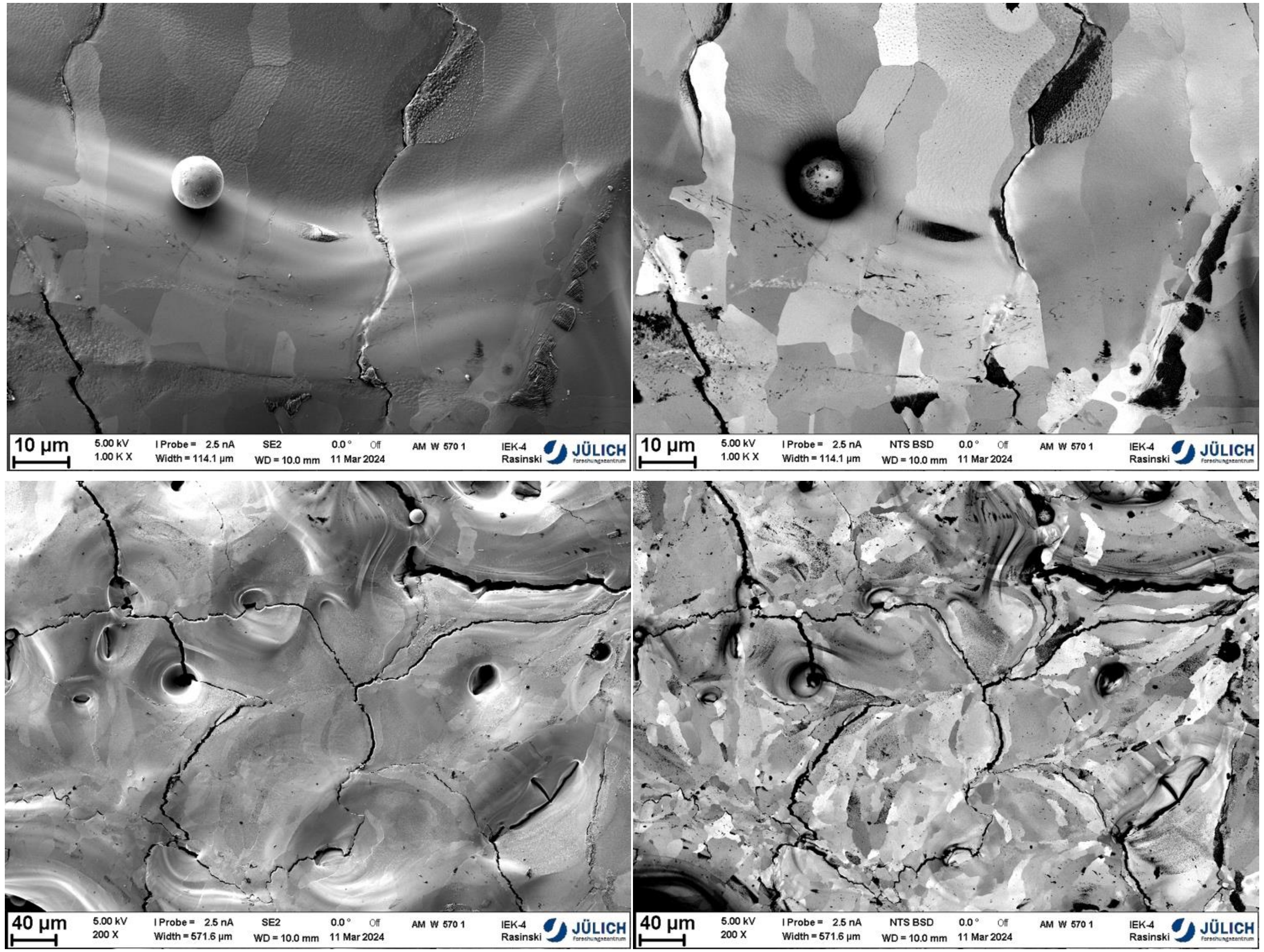
Latticed AM W



- 5 pulses of QSPA Kh-50 hydrogen plasma (τ_{pulse}=0.25 ms), heat loads above the W melting threshold, T_{base}=500 C
- Arithmetic mean roughness Ra = 84.8 [µm]
- *Next steps: FIB cuts and metallographic cross-sections*

Surface modifications of advanced W materials

Latticed AM W



- 5 pulses of QSPA Kh-50 hydrogen plasma (τ_{pulse}=0.25 ms), heat loads above the W melting threshold, T_{base}=500 C

SUMMARY: Analysis of surface modification of fusion relevant materials, caused by repetitive transient plasma pulses leading to W melting, has been performed for QSPA exposed samples.

WP PWIE SPA 4

Results 2024

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

High Temperature performance of Armour Materials: Recrystallization and Melting

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
A.Durif	CEA	6	D001
W. Pantleon	DTU	7	D002
S. Ratynskaia	VR	13	D003 (S.Ratynskaia, P.Tolias, L.V. Ignitchouk F. Castello)
I. Garkusha	KIPT	30	D004
M. Rasinski	FZJ	4	D005 (M. Rasinski, A. Kreter, M. Vogel)
S. Ratynskaia	VR	7,84	D006 (2023 Transfer)
Total		67,84	

Deliverables:

Deliverable ID	Deliverable Title
D001	Assessment of plasma impact on material properties linked to ITER relevant PFUs (CEA)
D002	Annealing of chosen tungsten-based materials and quantification of recrystallization kinetics (DTU)
D003	Development of MEMENTO and MEMENTO + GEANT 4 including RE - Damage (VR)
D004	Influence of plasma pre irradiation with heat loads near surface recrystallization on surface damaging with heat loads above the melting threshold (KIPT)
D005	Analysis of PSI-2 exposed materials, focusing on funding the relevant regime for fuzz formation in AUG He campaign (FZJ)
D006	Development and validation of the MEMOS-U code (link with WPTE – WEST/AUG) (VR) (2023 Transfer)

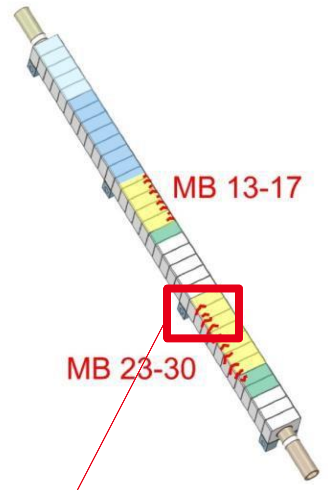
KIPT Collaborators have resumed operation

CEA A.Durif et al

- Investigation related to the presence of recrystallization and melting droplet on WEST divertor (WEST phase I)   (already reported)
- Study related to the monoblock leading edge crack initiation and propagation (WEST Phase I) (extra study)

Crack initiation and propagation studies in WEST

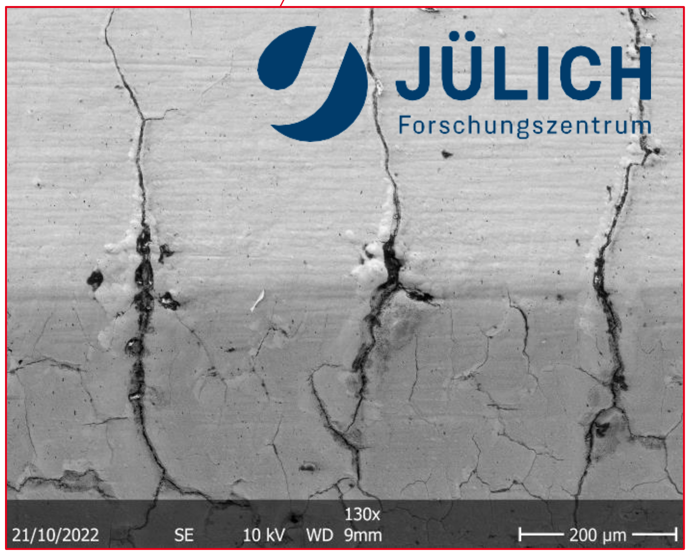
WEST Phase 1



Top

Leading edge →

side

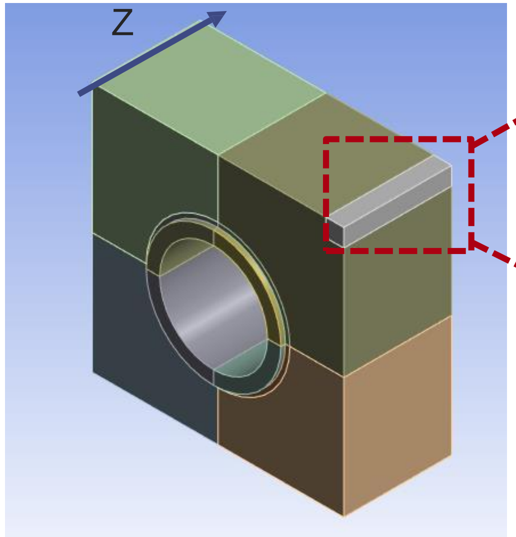


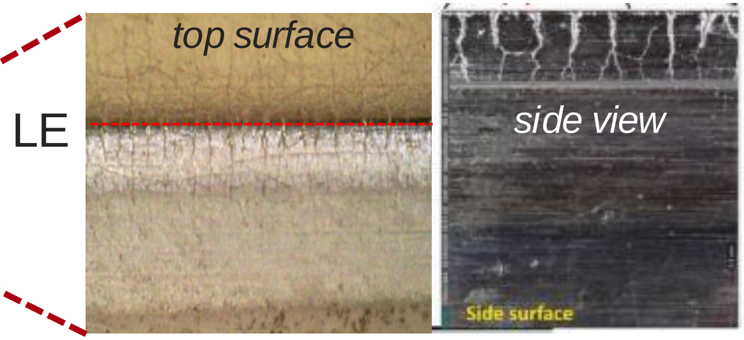
Questions tackled in this talk:

- How do these cracks could initiate and propagate ?

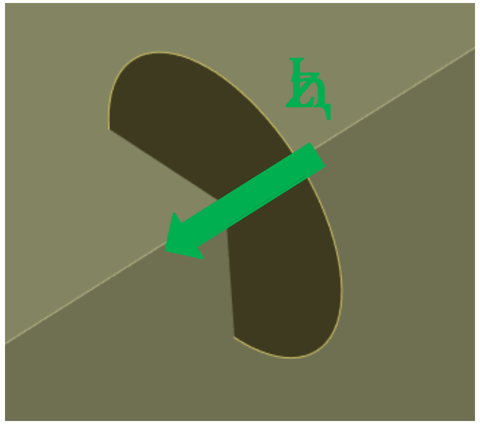
Leading edge cracking : Failure mode

Leading edge (LE) cracks

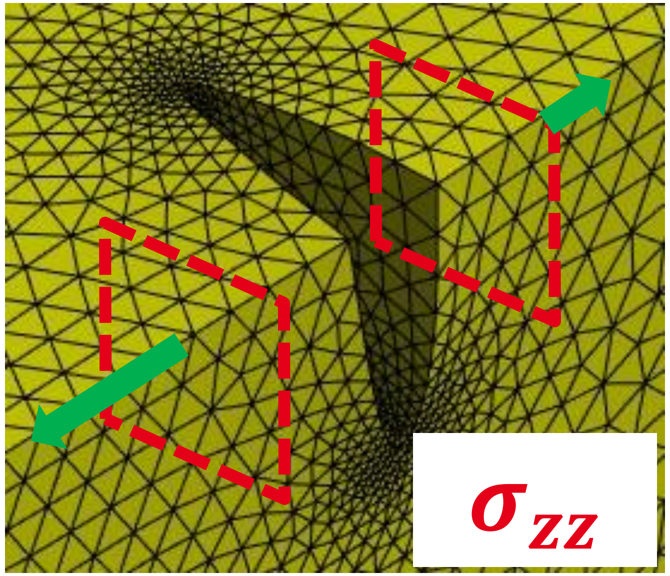




Cracking mode I (stress on Z axis σ_{zz})

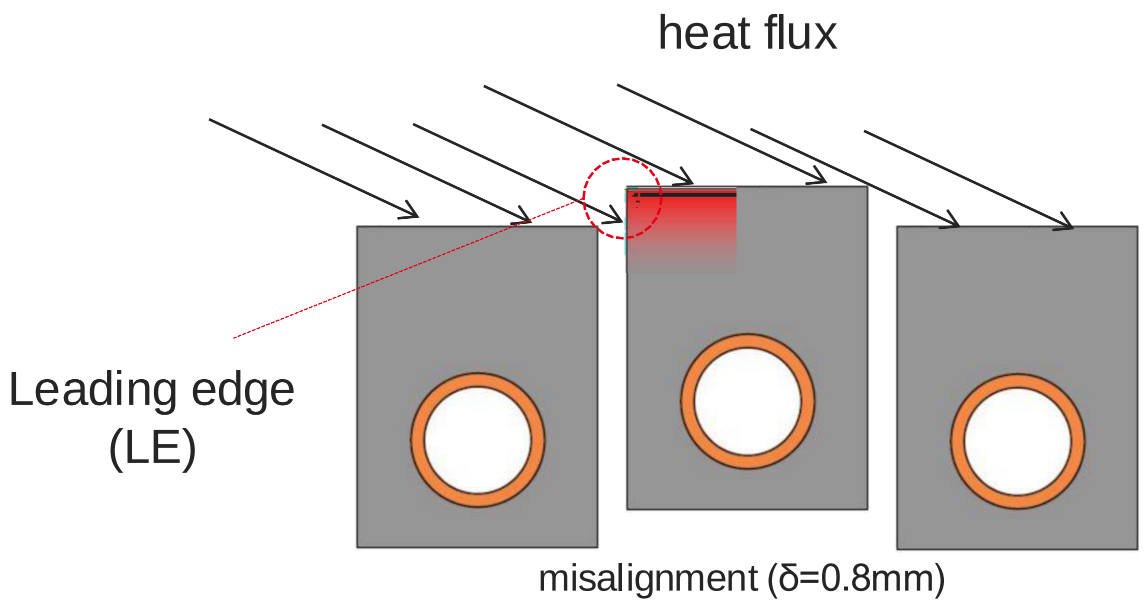


crack defined as circular interface (crack length = disc radius)



Normal stress leads to crack initiation and propagation

Numerical assumptions



- Two types of heat flux studied :
  - Quasi steady state on misaligned monoblock : heat flux of 70 MW/m² during 5s (WEST C4 exp. camp.) – *reported here*
  - Disruption : heat flux of 600 MW/m² during 3ms

- Fracture mechanics model: elastic approach (cooling phase)

Brittle crack initiation :

$$(\sigma_{zz}) \geq \sigma_{YS}$$

DBTT $\in [200{,}600]°C$

Propagation :

$$\mathrm{J}, \mathrm{K} \geq \mathrm{J}_c, \mathrm{K}_{Ic}$$

Fracture toughness (mode I) → K_{Ic}

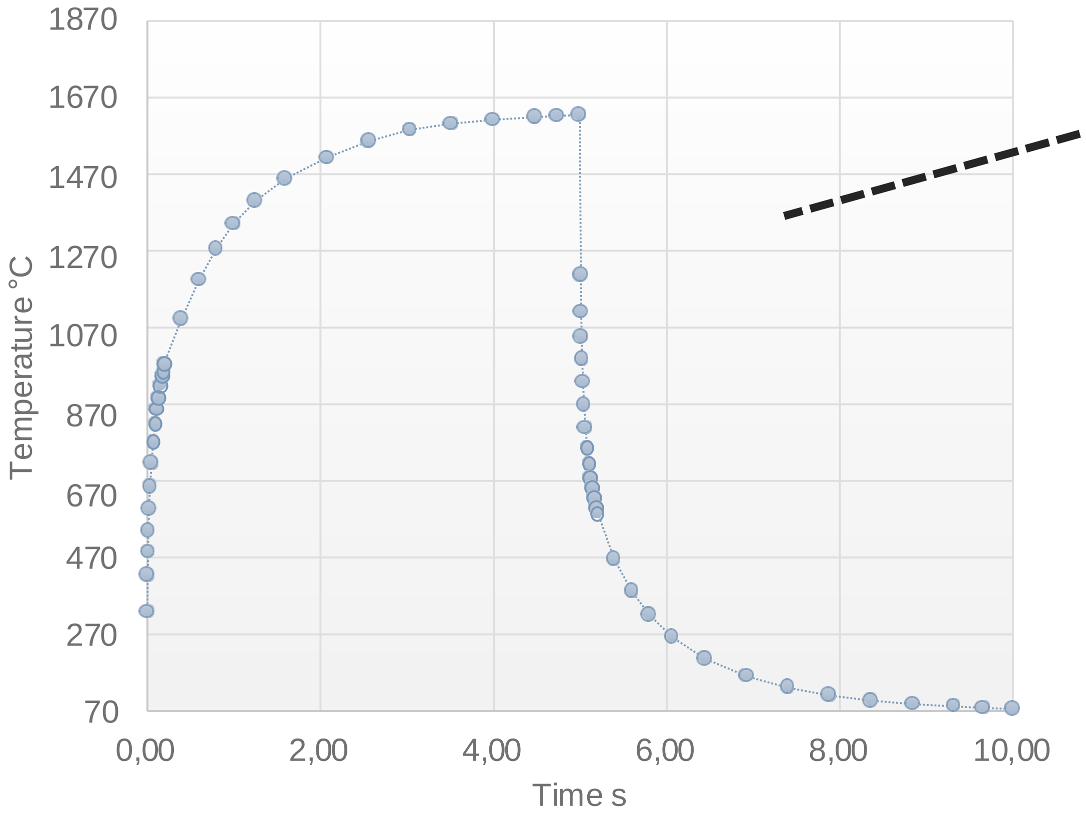
Critical J-integral → J_c

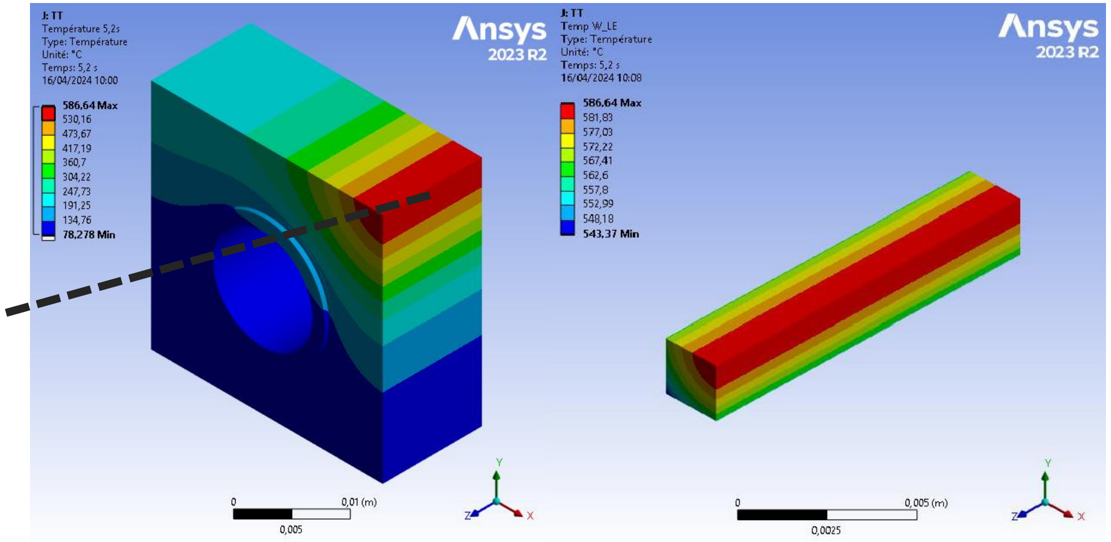
Ys: Yield Stress *DBTT: Ductile to Brittle transition temperature*

Thermal response (70MW/m² / 5s)

Standard heat loading in C3-C4

- Leading edge temperature evolution

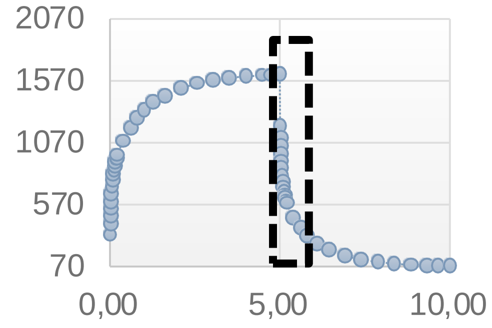


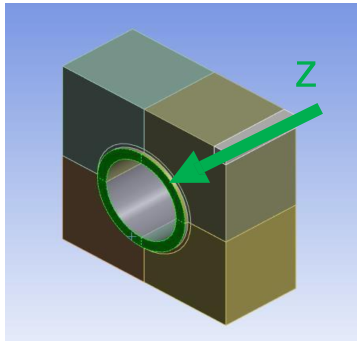


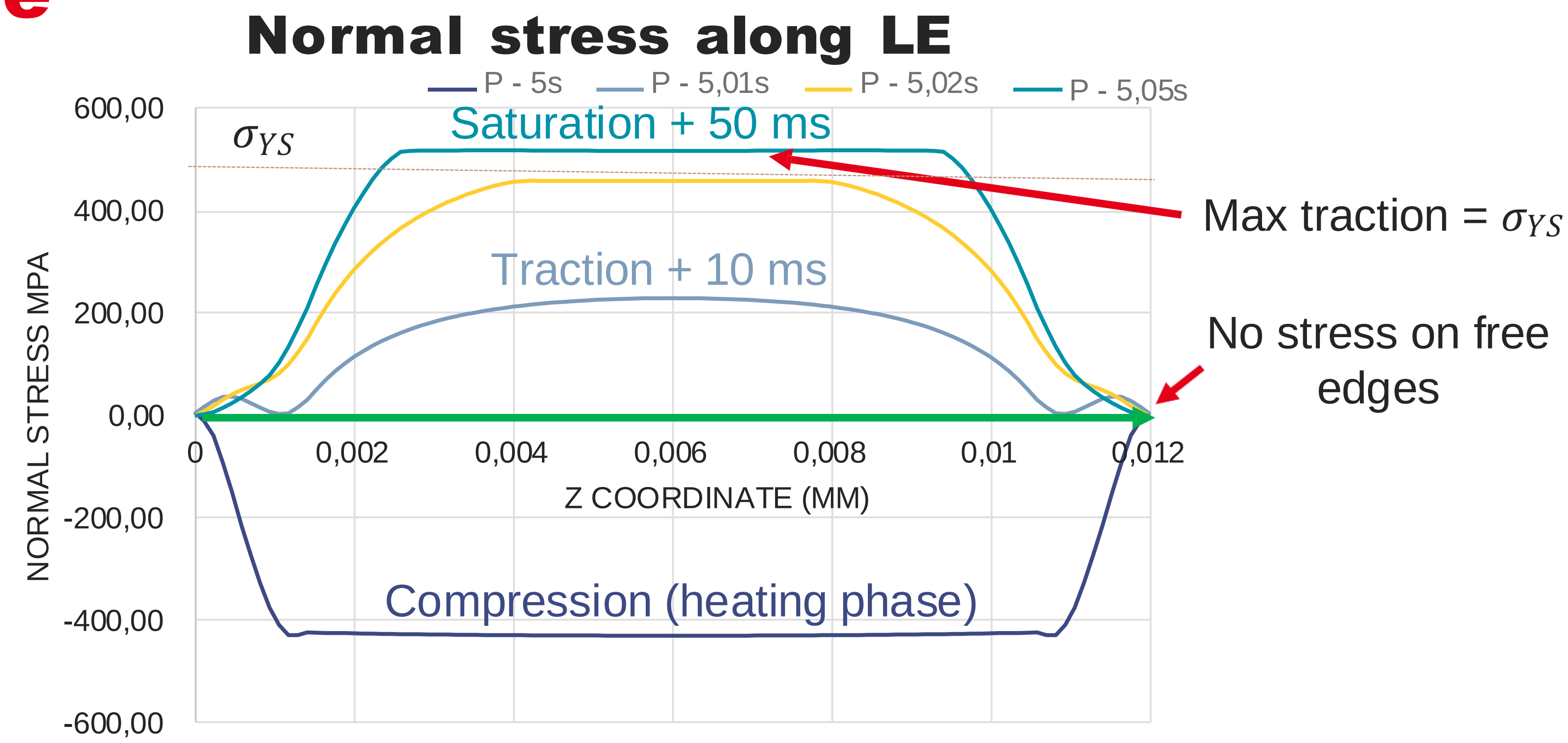
Max temperature:

$1622°C$

Abrupt tensile stress increase during the beginning of the cooling phase



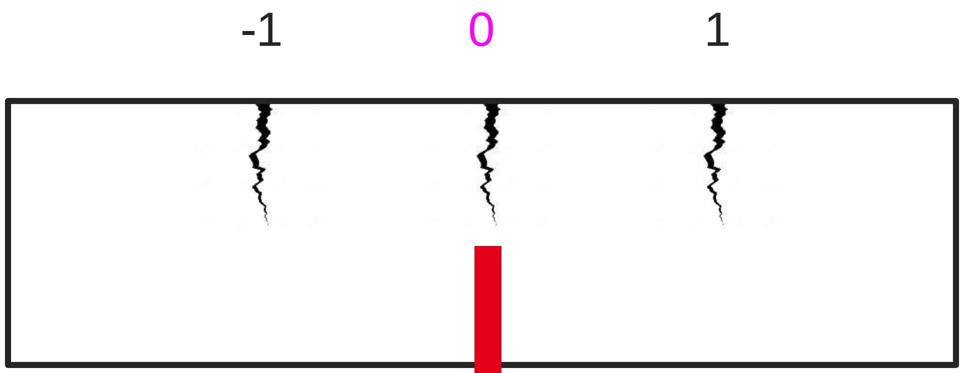




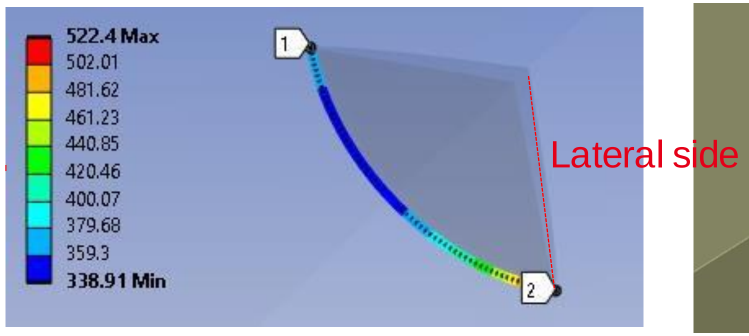
- Cooling induces strong tensile stress at the leading edge → Need to be considered
- 0,05s after the start of the cooling phase, tensile stress reachs the material yield stress along the leading egde (>50% of the total length)
- **Numerical assumption: Stress field obtained at $t = 5.05s$** (T~870°C > DBTT) is considered as intial stress in the crack propagation modelling

Numerical outputs

Cracks are indexed regarding how away they are from the center of the LE



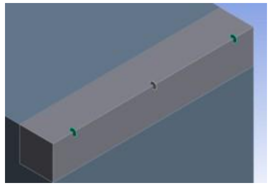
Maximum of J-integral profile is estimated



Crack tip

$$J_{max0} = 522,4 J/m^2$$

Propagation area for quasi steady state heat flux (70 MW/m²)

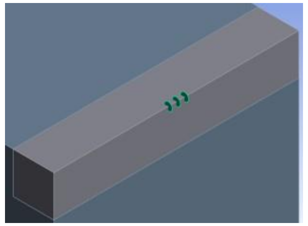


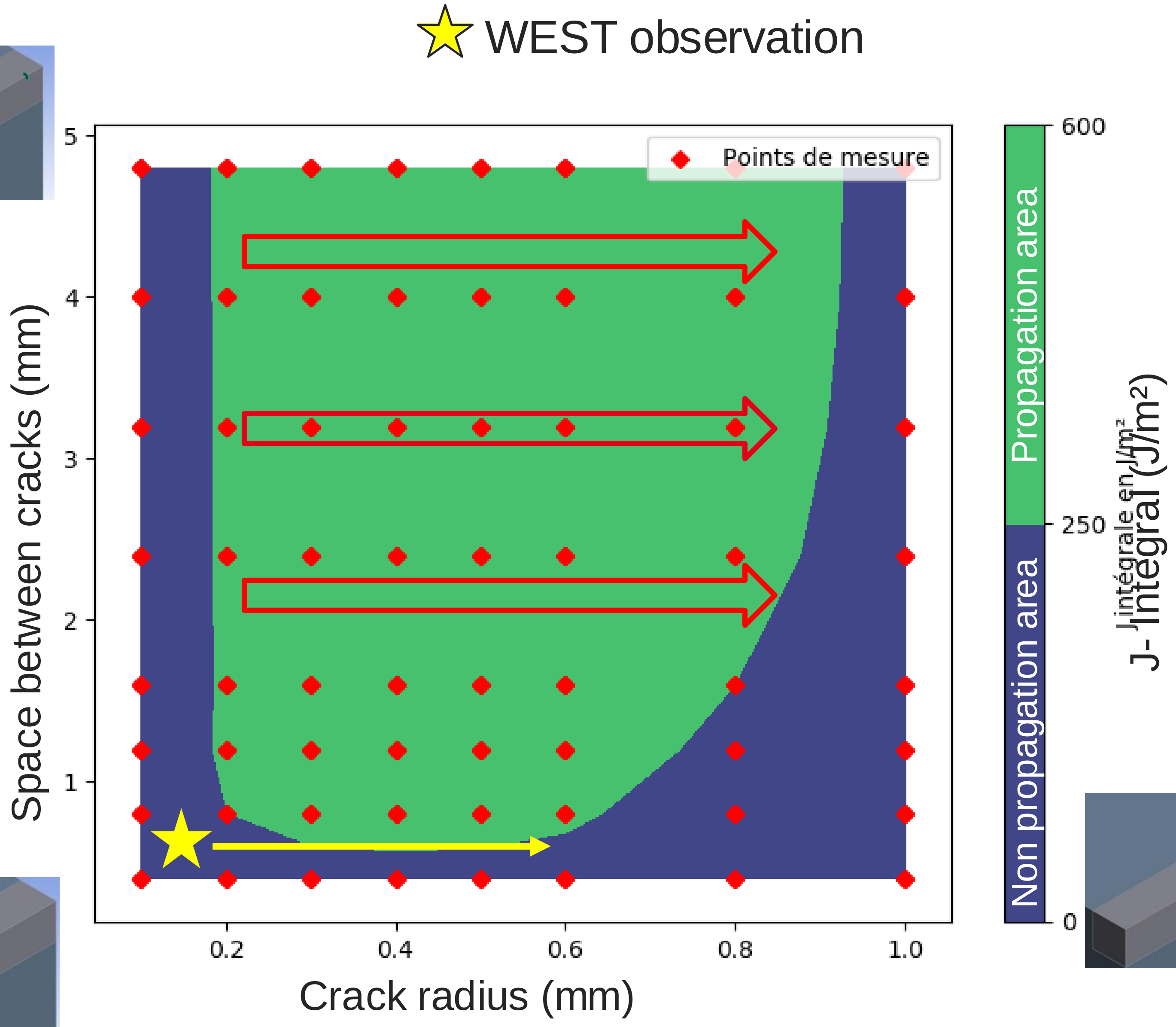
Crack profile :

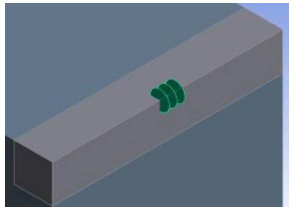
[[6mm-d, r], [6mm, r], [6mm+d, r]]

r and d varying parameters

- For pre-existing cracks (r>0,2mm) steady-state could leads to propagation toward the right part of the graph
- Small cracks (< 0.2 mm) cannot propagate in quasi steady state
- Could disruption lead to crack initiation? (study on-going, first output is yes)



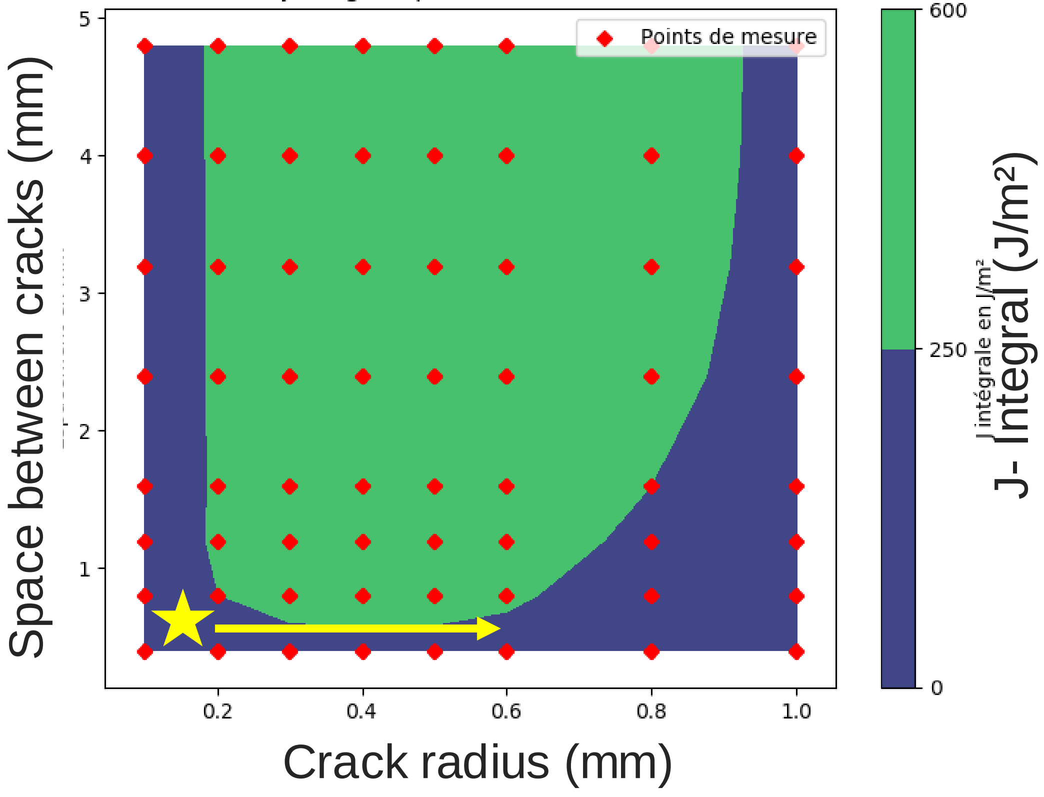




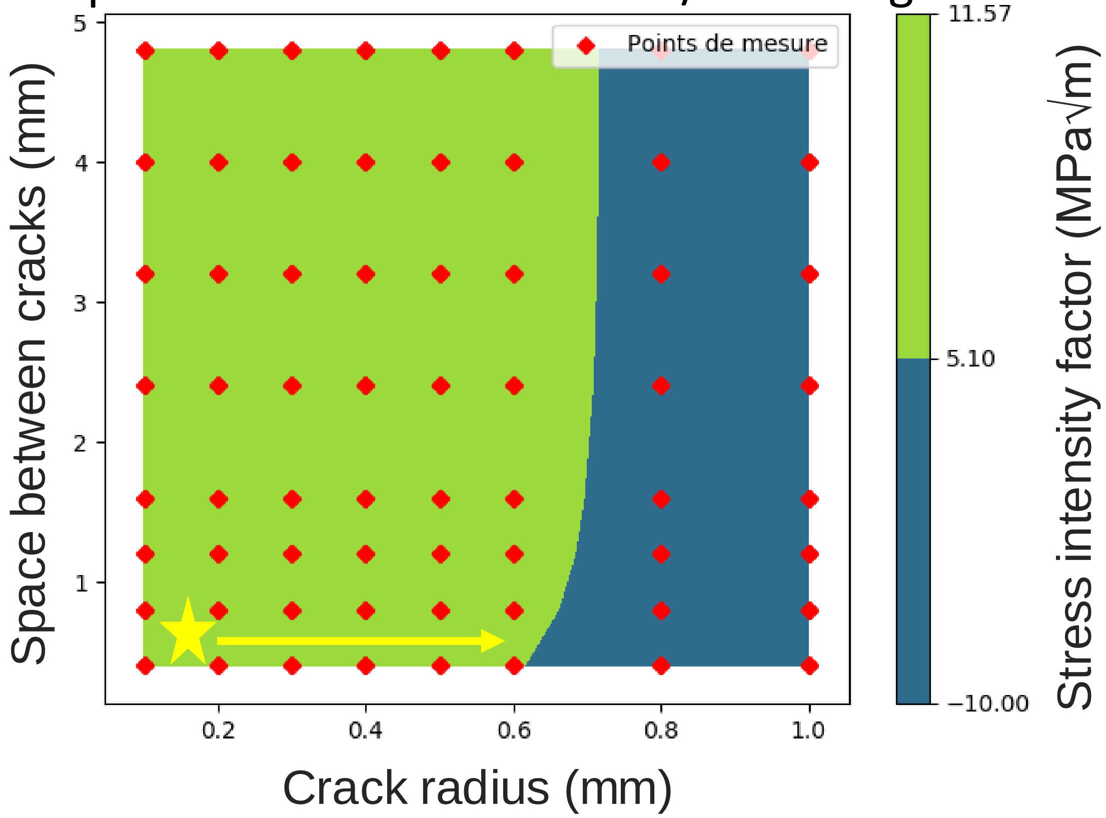
Instead of steady-state, disruption could initiate cracks and propagate it

☆ WEST observation

Quasi steady state (70 MW/m² during 5s



Disruption : heat flux of 600 MW/m² during 3ms



- Quasi steady state: No crack initiation but higher propagation depth
- Disruption: crack initiation, propagation depth limited

Conclusions

- Overview of the WEST leading edge monoblocks cracking have been done (Phase I) based on optical images analysis and post-mortem (data statistically representative)

- Numerical methodology developed to assess cracks propagation at the leading edge

- Small cracks r<0,2mm : no propagation in steady-state ⟶ crack initiation suspected under disruption

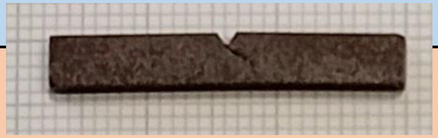
- Larger cracks r>0,2mm : pre-existing cracks steady-state could lead to propagate

DTU W. Pantleon et al

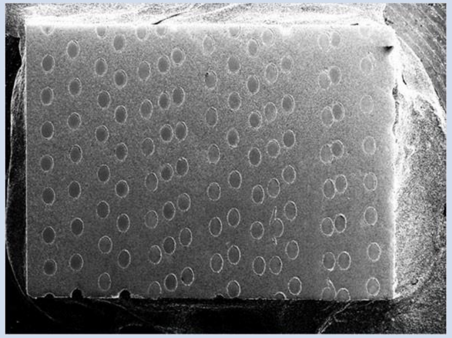
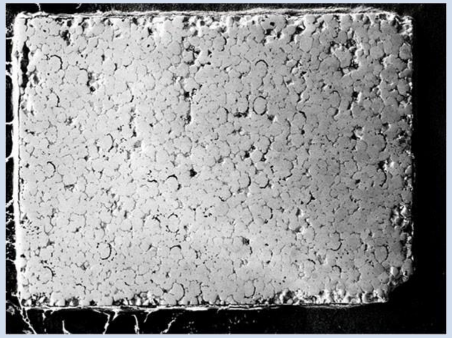
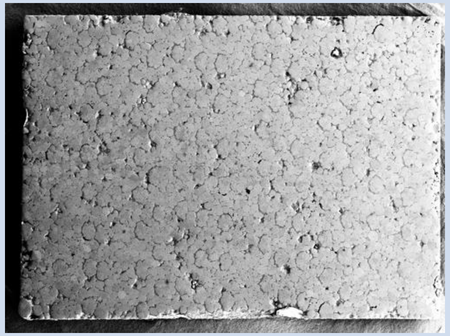
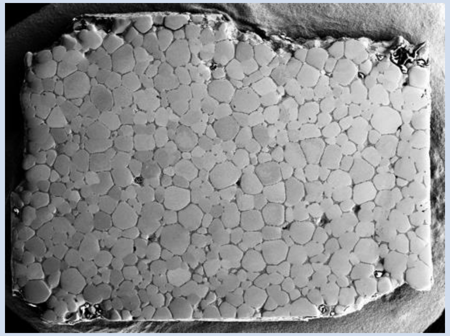
- High temperature performance of armour materials: recrystallization and melting – DTU 2024

Tungsten fiber-reinforced tungsten W_f/W

- Multi fiber composites from Yiran Mao
- Powder metallurgical route
- Two single edge notch bending specimens 27x4x3 mm^3 (three point bending test specimens)

Spec.	Fibers	Alignment	Matrix	Interlayer	State	
A	Conti-nuous	Parallel in layers	Dense	Yttria	Bend to fracture	
B	Short	Random	Porous	No	Slightly bended	

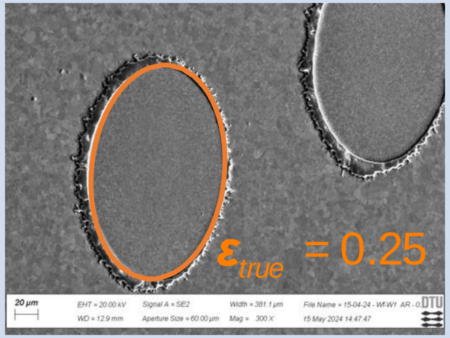
W_f/W continuous fibers – Light optical microscopy

As-received		Annealing for 1 week at 1450 °C	
 notch side	Note fiber elongation from manu-facturing / bending		Grain growth in matrix
Annealing for 3 days at 1450 °C		**Annealing for 2 weeks at 1450 °C**	
	Grain growth in matrix		Grain growth eliminated fibers completely

W_f/W continuous fibers – Scanning electron microscopy

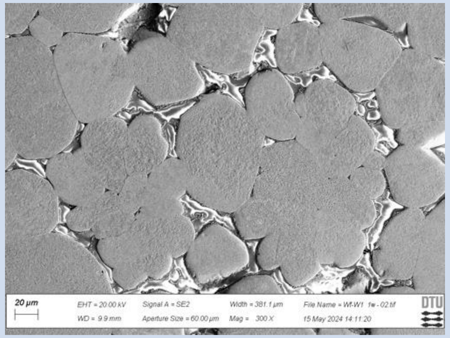
As-received

notch side



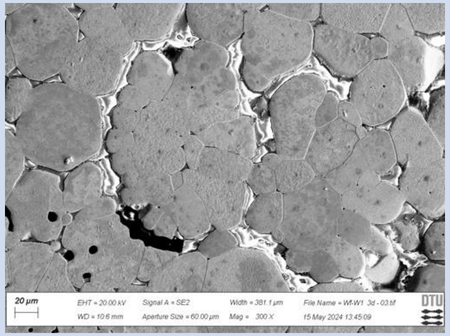
Note fiber elongation from manu-facturing / bending

Annealing for 1 week at 1450 °C



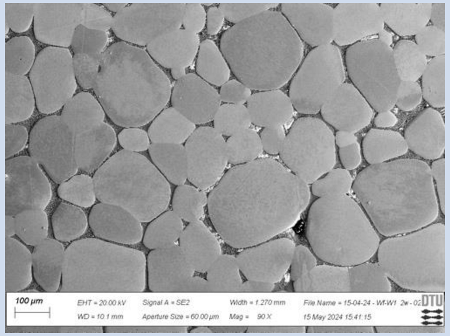
Fiber hardly to be identified, grain growth in matrix

Annealing for 3 days at 1450 °C



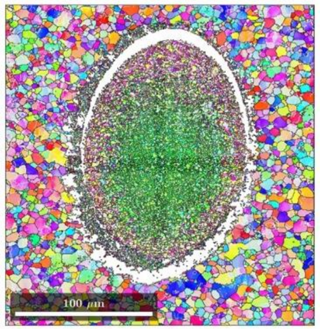
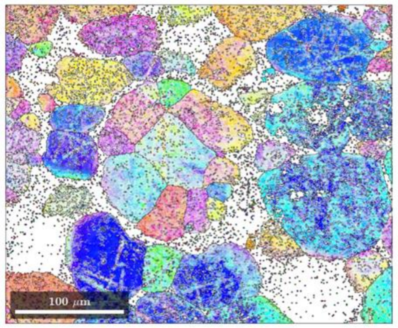
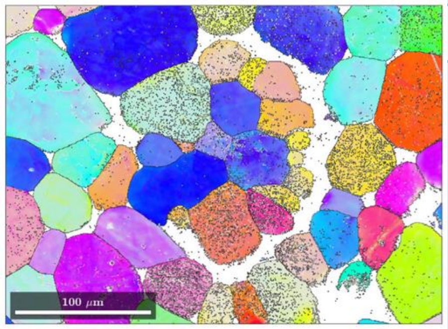
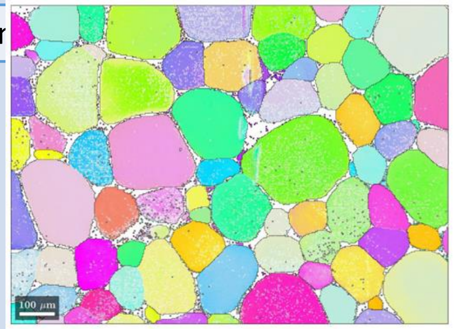
Recrystal-lized fiber, grain growth in matrix

Annealing for 2 weeks at 1450 °C

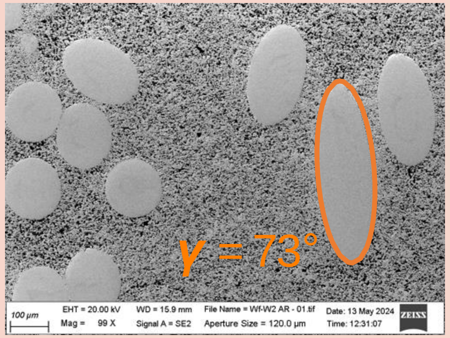
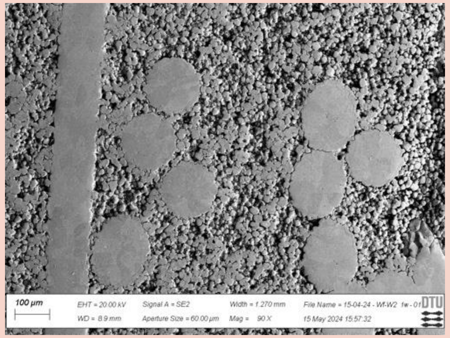
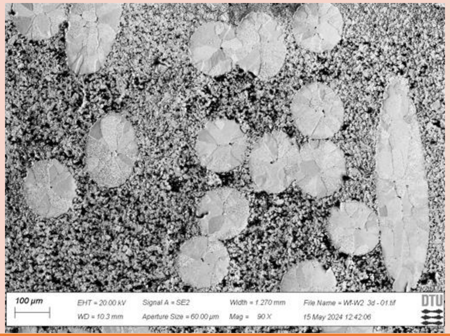
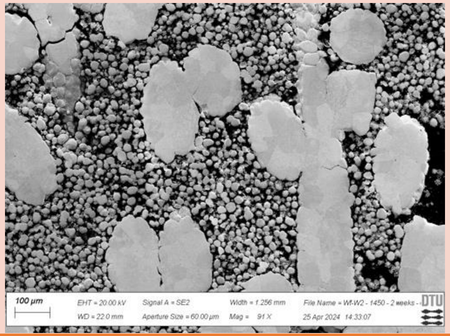


Grain growth eliminated fibers completely (Note scale bar)

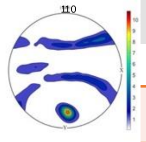
W_f/W continuous fibers – EBSD

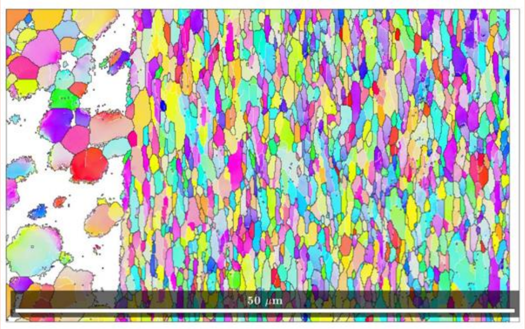
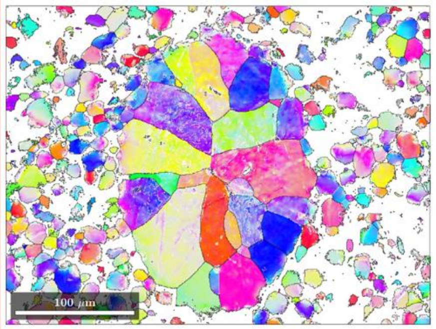
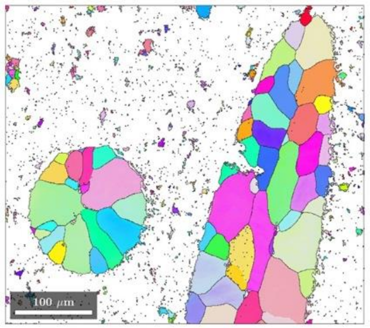
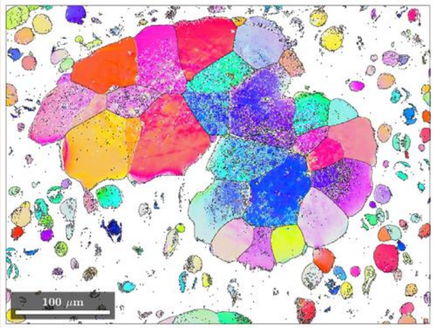
As-received		Annealing for 1 week at 1450 °C	
	Note fiber elongation from manu-facturing / bending, <110> aligned along fiber, but rim		Fiber hardly to be identified, grain growth in matrix
An		Anr	
	Recrystal-lized fiber, grain growth in matrix, <110> alignment along fiber lost		Grain growth eliminated fibers completely (Note scale bar)

W_f/W short fibers – Scanning electron microscopy

As-received		Annealing for 1 week at 1450 °C	
	Note hetero-geneity on macroscopic scale and porous matrix		Recrystal-lized fibers, matrix coarsens slightly
Annealing for 3 days at 1450 °C		Annealing for 2 weeks at 1450 °C	
	Recrystal-lized fibers, matrix almost unaffected		Recrystal-lized fibers, matrix coarser, larger open volume, disintegrate s

W_f/W short fibers – EBSD



As-received		Annealing for 1 week at 1450 °C	
	Close up of part of a fiber with neighboring porous matrix		Recrystal-lized fibers, matrix partially resolved, slightly coarser
Annealing for 3 days at 1450 °C		**Annealing for 2 weeks at 1450 °C**	
	Recrystal-lized fibers, matrix on this scale not resolved		Recrystal-lized fibers, matrix only partially resolved, coarser; larger open volume

Conclusions 2024

Powder metallurgical W_f/W from JÜLICH Forschungszentrum

- Elongated fibers from manufacturing/bending
- Annealing at 1450 °C: fiber recrystallization after 3 d
- Grain growth in bulk matrix, fibers dissolved after 2 w
- Porous matrix coarsens and looses coherence

Continuation

- Shorter annealing times (2 d, 1 d, 8 h)
- Annealing at 1350 °C

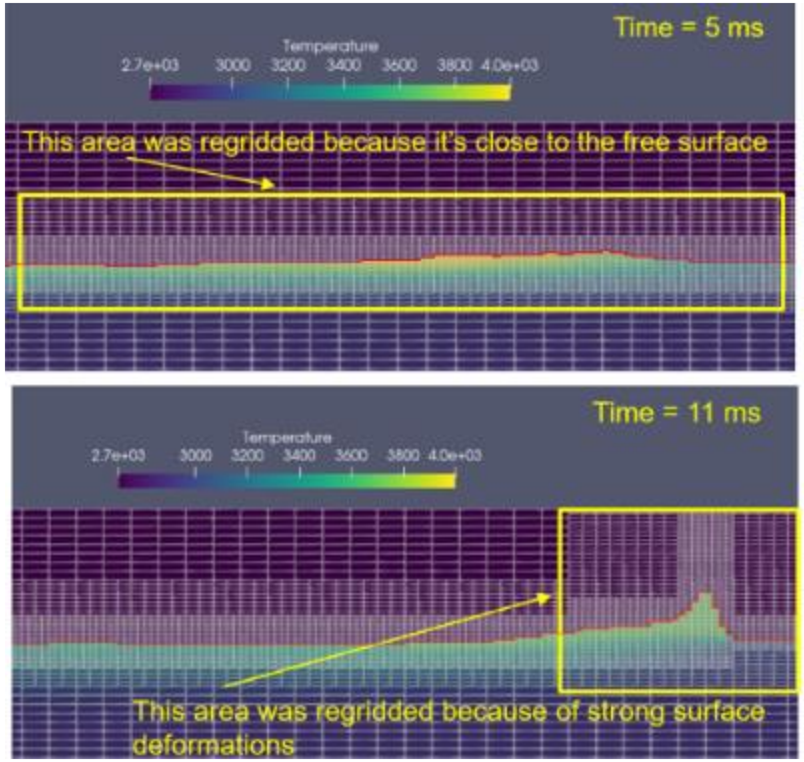
VR S.Ratynskaia

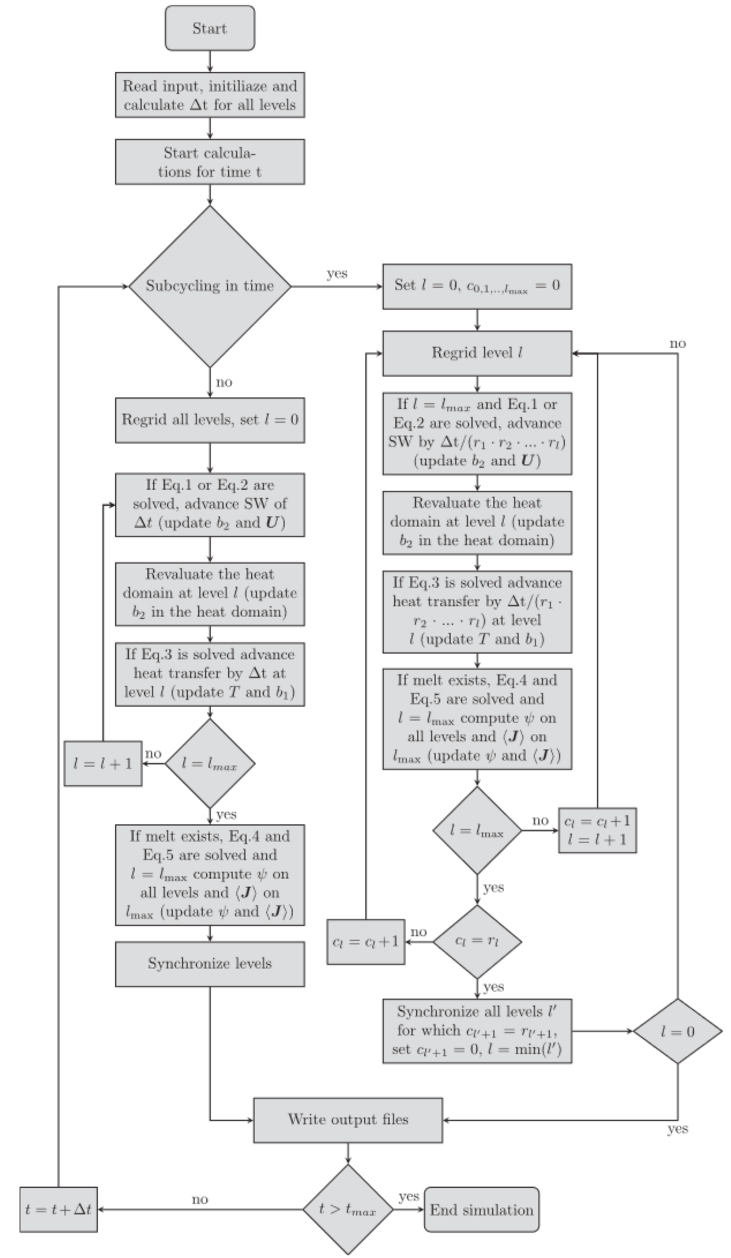
- Development of MEMENTO and MEMENTO/COMSOL + GEANT4 work flow for modelling of PFC damage

MEMENTO: documented implementations

MEMENTO numerical implementations are published in ful
future reference for the code

"The MEMENTO code for modelling of macroscopic melt motion in fus
Castello, S. Ratynskaia, P. Tolias, L. Brandt, *Fusion Engineer. Design* **26** 1





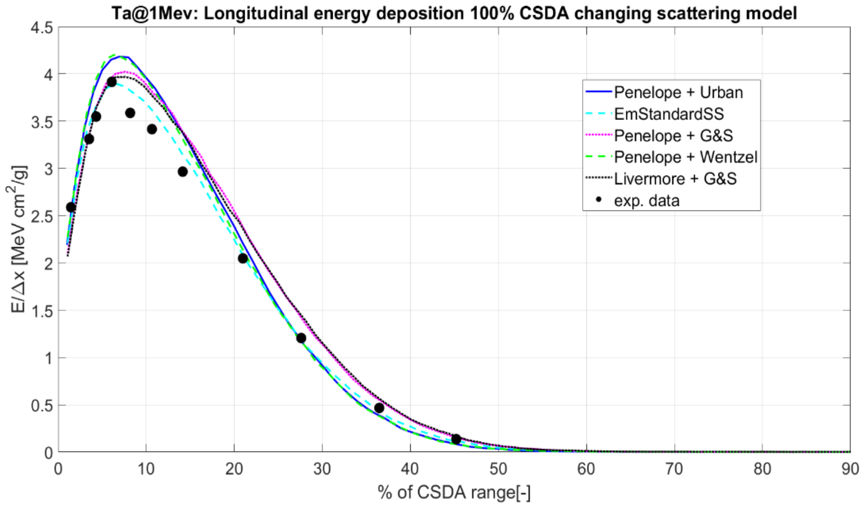
MC simulations of electron transport in matter

Geant4 has vast physics list choices but it is to be defined by the user

→validation of the relevant physics libraries and scattering implementations of Geant4

- Need to find the most accurate and computationally cost effective combination of physics libraries and scattering implementations for MeV electrons incident into tungsten (high Z) and into graphite/BN (low Z).
- **Extensive comparison of Geant4 simulations with:**

  - precision calorimetry experiments (normal incidence, keV and MeV range)
  - electron backscattering experiments from thick or thin targets (normal and oblique incidence, keV and MeV)
  - electron transmission experiments from thin targets (normal incidence, keV range)
  - Bremsstrahlung efficiency measurements from thick or thin targets and photoneutron yield measurements.



An example for Ta (Z=73)

GEANT4 physics model benchmarking against experimental data for energy deposition by 1 MeV electrons normally impacting bulk Tantalum.

[G. J. Lockwood et al., IEEE Trans. Nucl. Sci., 6, 326-330 (12 1973)]

Manuscript to be submitted 2025

Modelling of *brittle* materials with *no liquid phase*: C and BN

Modelling the brittle failure of graphite induced by the controlled impact of REs in DIII-D,
S. Ratynskaia *et al*, EUROfusion pinboard No **38821**
Submitted to Nuclear Fusion (2024)

KORC *(RE striking positions & momenta)* → MC particle transport code **Geant4** *(volumetric energy deposition)* → FEM multiphysics software **COMSOL** *(thermoelastic response)*

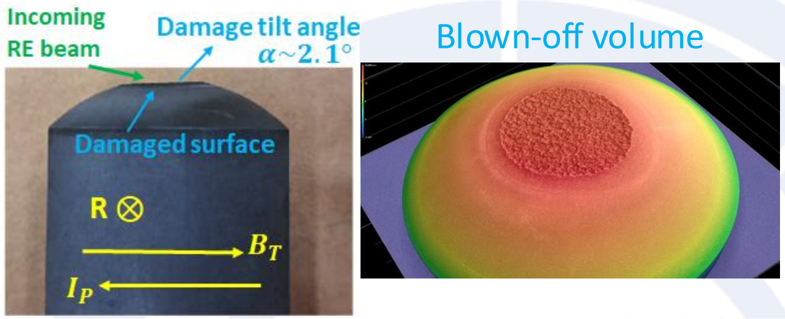
Constrains: measured conducted energy, damage topology, explosion time & blown-off material volume

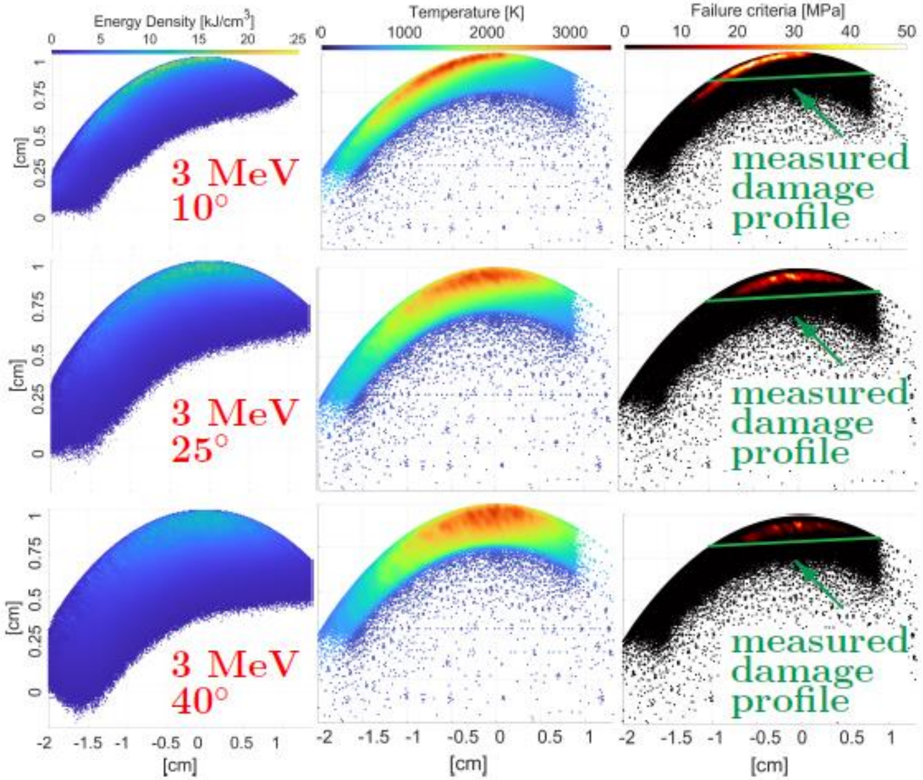
Local failure criterion: the principal stresses are compared with the ultimate or compressive strengths, depending on their sign.

The model is capable distinguish between different RE impact scenarios and to identify RE parameters which provide the best match to the observations.

Ongoing work: **BN tiles in WEST** – see next slide

Controlled DIII-D experiment

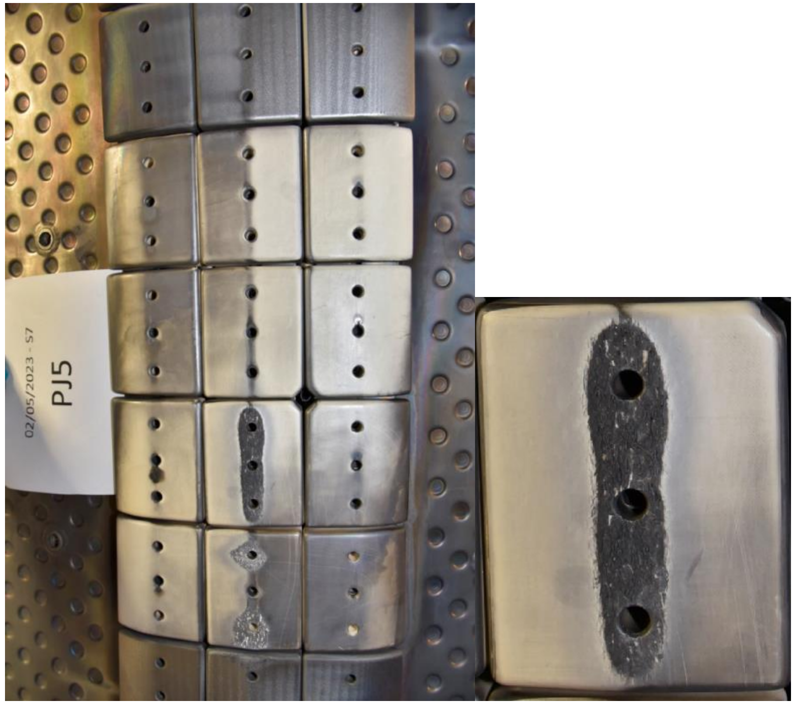




Modelling of brittle materials: BN tiles damage in WEST

- The same model to simulate BN tiles damage by REs in WEST **[in connection with WPTE]**

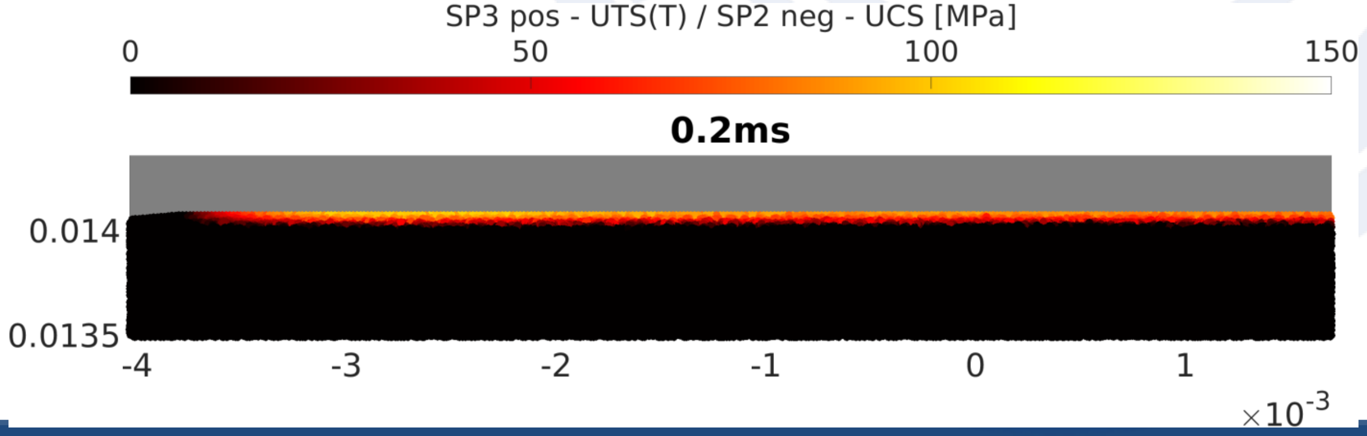
Mismatch with IR-recovered surface temperature data indicate larger angle RE impacts than originally specified as empirical input –
the RE loading needs to be re-visited to complete the task



First round of runaway experiments on Boron nitride tiles (2023)
C. Reux 'WEST runaway damage' ,
50th EPS satellite meeting on runaway damage, July 2024, Spain

Results for 10 MeV REs impacts and loading 3.5 kJ to the tile

Brittle failure (colored region) : 55 µm at 0.2 ms

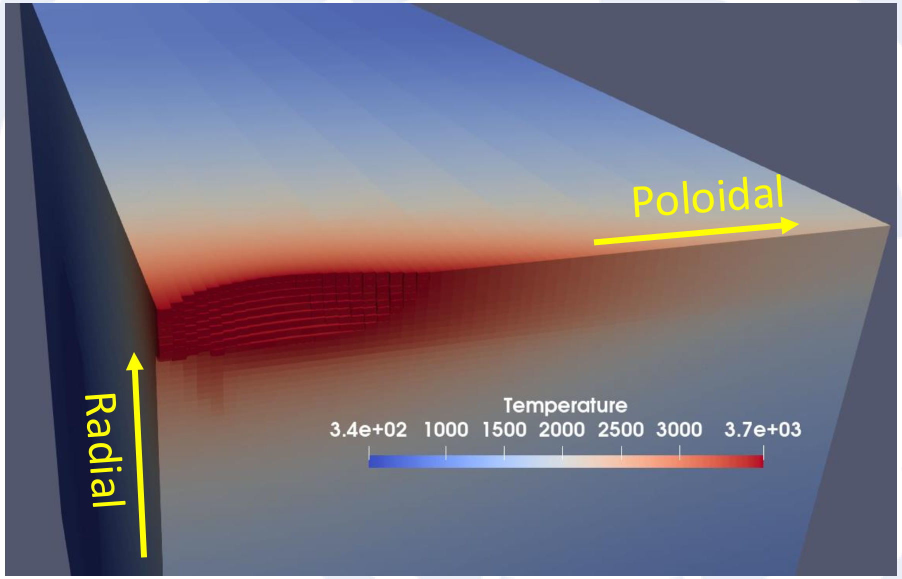


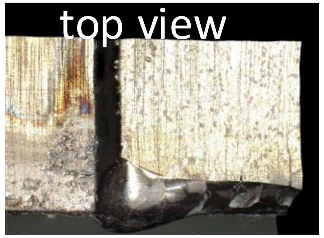
Design and modelling gap melting in WEST

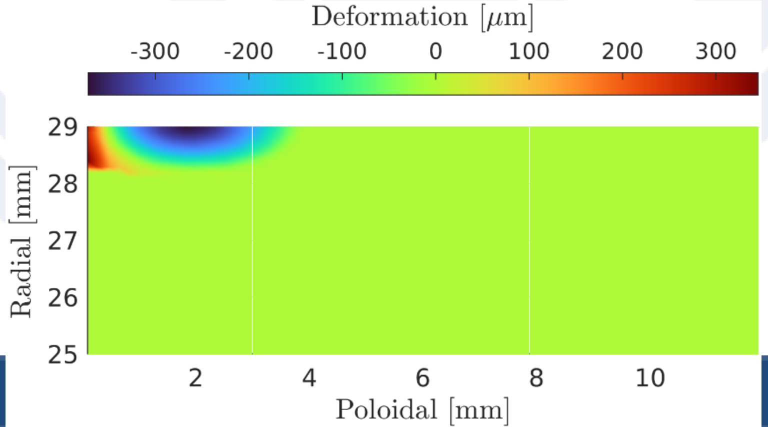
[in connection with WPTE]

Melt across gap experiments in WEST (shifted from 2023 to 2024, carried out spring 2024) – final heat flux received, MEMENTO simulations are completed

- Even though different from the AUG exposure of the gap sample, where ELM-induced melting was transient, this new experiment confirmed the same picture - resolidification preventing gap wetting and melt infiltration.
- The reason is that both experiments featured the same melt dynamics regime characterized by very shallow and very slow pools.

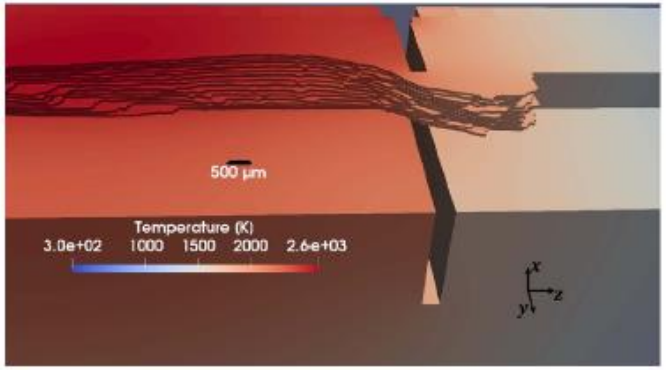




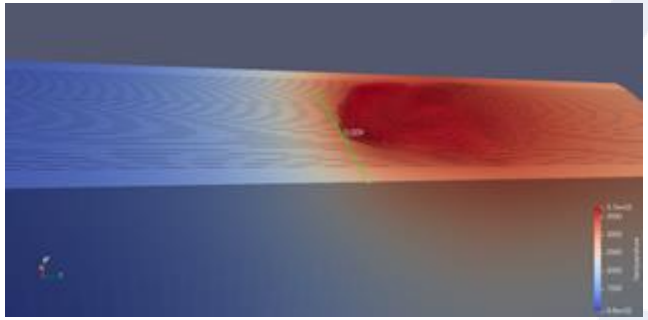


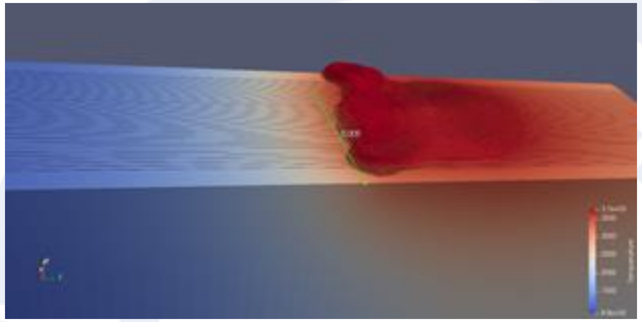
Design new sustained tungsten melt bridging experiments in AUG

[in connection with WPTE]



Ratynskaia et al *NF* **64,** 036012 (2024)





Predictive MEMENTO modelling of the progression of deformation profile during exposure to an AUG ELMing H-mode discharge. The Sample is at 11^{o} angle to B field – this design allows for shallow melting (initially transient but sustained upon the gap crossing) without the formation of dynamic leading edges (that complicate theory-modelling comparison).

EXPERIMENT:

samples are ready, first exposure on 10th December 2024!

FZJ M.Rasinski et al

- Analysis of PSI-2 exposed materials, focusing on funding the relevant regime for fuzz formation in AUG He campaign

Plans for 2024

Achived in 2023

Comparison between linear devices (PSI-2) and tokamak (AUG) environment for fuzz formation

- Check previous exposures in PSI-2 with simultaneous plasma and laser loading
- Check best conditions to reproduce AUG He fuzz
  - From existing exposures
  - New PSI-2 exposures (2 exposure finished)

Plans for 2024

- Finish all exposures in He plasma (additional 2-3)
- Find best conditions to reproduce AUG He fuzz.

- Based on the above:
- Experiment: **94%D + 5%He + 1%Ne plus laser**, in PSI-2 on W to be performed

(since no scheduled He campaing in ITER, the above would be most relevant exposure for normal ITER opperation)

PSI-2 He exposure - Fuzz formation

Base Temperature ~ 900 °C
Ion Flux ~ 6 - 8 × 10^{21} $m^{-2}s^{-1}$
Fluence ~ 1 × 10^{25} m^{-2}
Energy ~ 160 eV

Laser

200 MW/m^2 and 400 MW/m^2 0,5 ms, 25 Hz
Temperature 1100 – 1700 °C
(600 °C increase during the laser shot)

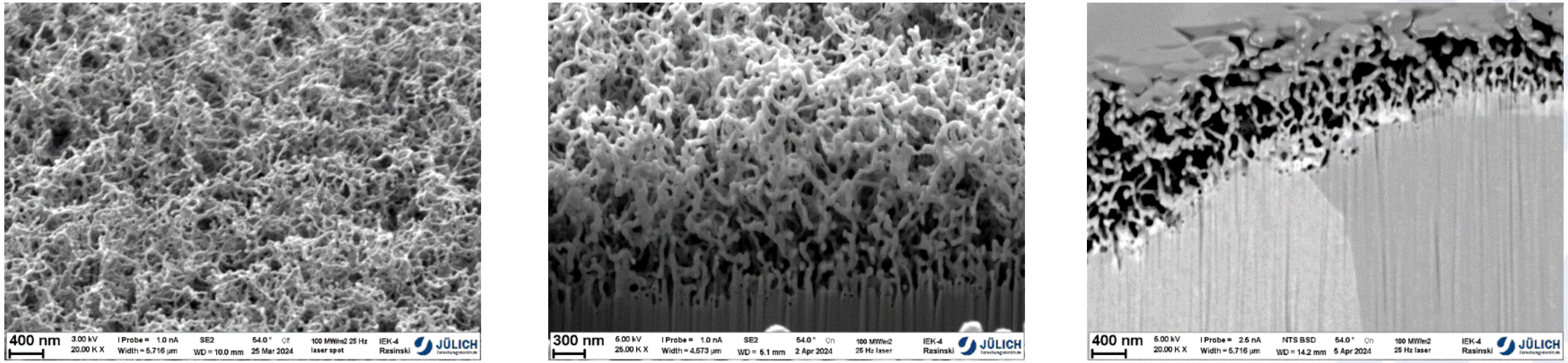
Laser

100 MW/m^2 0,5 ms, 25 Hz and 200 Hz
40 MW/m^2 0,5 ms, 200 Hz

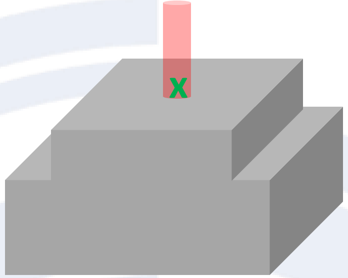
PSI26 - P3-045
M. Rasinski NME 2023

Results 2024

100 MW/m² 25 Hz - in the laser spot



SEM images of the surface and FIB prepared cross-section of the W sample exposed to He plasma with ***100 MW/m² 25 Hz*** *laser loading*



PSI-2 He exposure - Fuzz formation

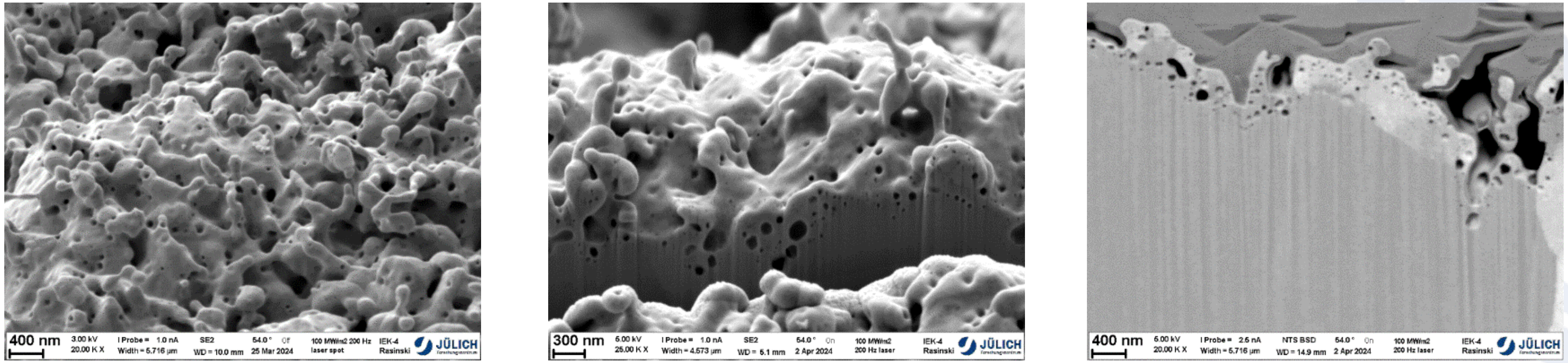
Base Temperature ~ 900 °C

Ion Flux ~ 6 - 8 × 10^{21} $m^{-2}s^{-1}$

Fluence ~ 1 × 10^{25} m^{-2}

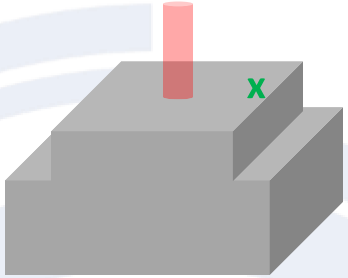
Energy ~ 160 eV

100 MW/m² 200 Hz - in the laser spot



SEM images of the surface and FIB prepared cross-section of the W sample exposed to He plasma with ***100 MW/m² 200 Hz*** *laser loading*

Results 2024



PSI-2 He exposure - Fuzz formation

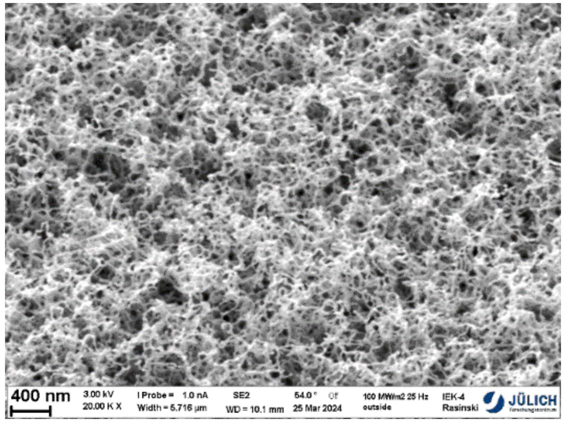
Base Temperature ~ 900 °C

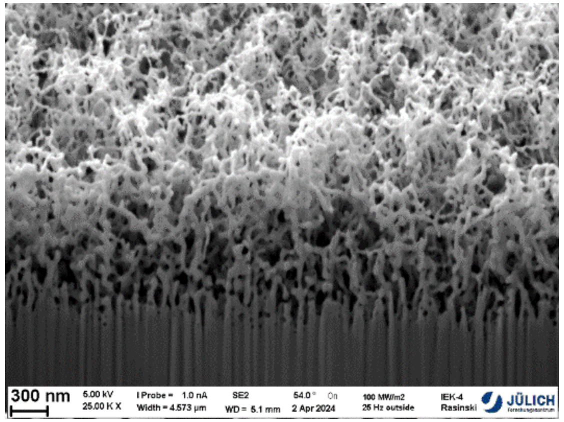
Ion Flux ~ $6 - 8 \times 10^{21}\ m^{-2}s^{-1}$

Fluence ~ $1 \times 10^{25}\ m^{-2}$

Energy ~ 160 eV

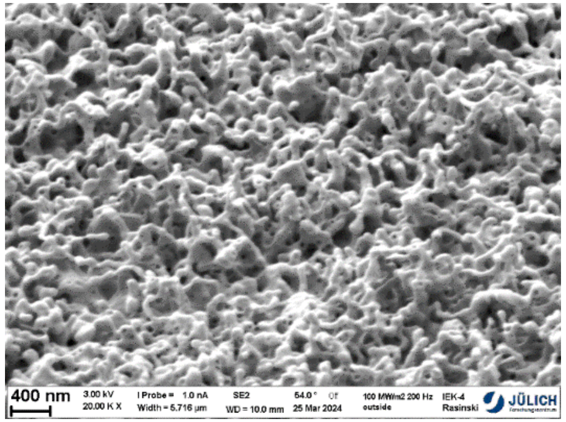
100 MW/m² 25 Hz - outside laser spot

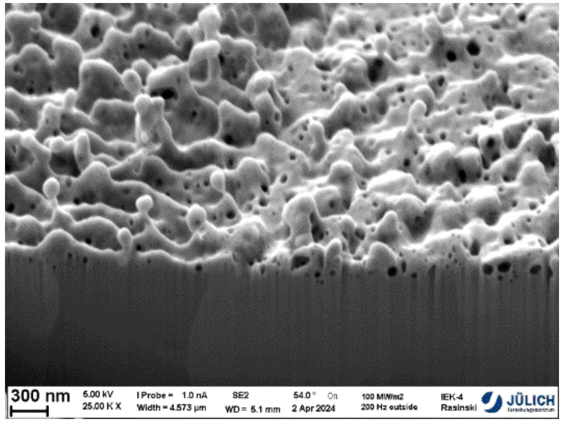




*SEM images of the surface and FIB prepared cross-section of the W sample exposed to He plasma with **100 MW/m² 25 Hz** laser loading*

100 MW/m² 200 Hz - outside laser spot

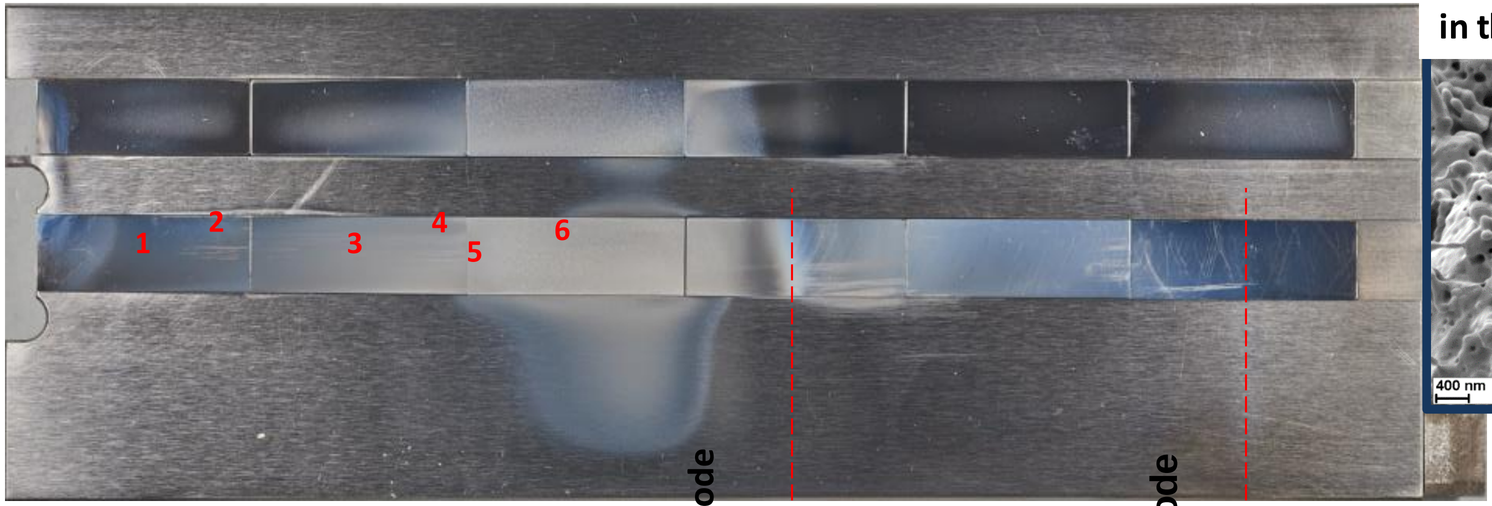




*SEM images of the surface and FIB prepared cross-section of the W sample exposed to He plasma with **100 MW/m² 200 Hz** laser loading*

Results AUG He

PSI-2

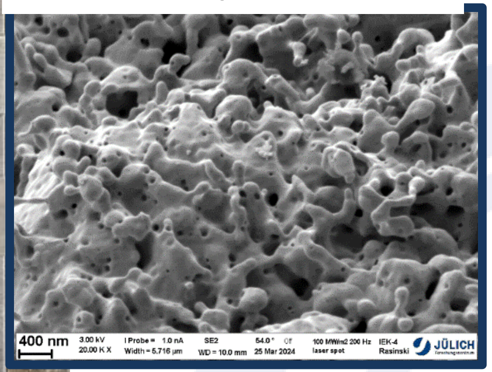


Φ_i ~ 2-4 x 10^{24} He/m^2

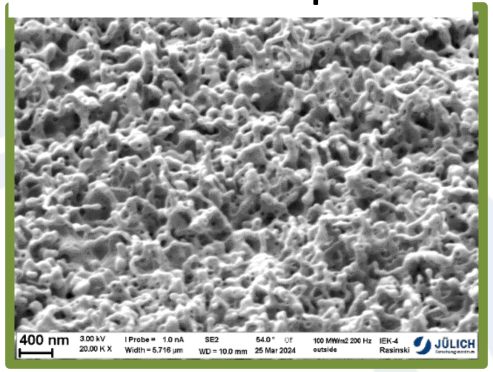
H-mode

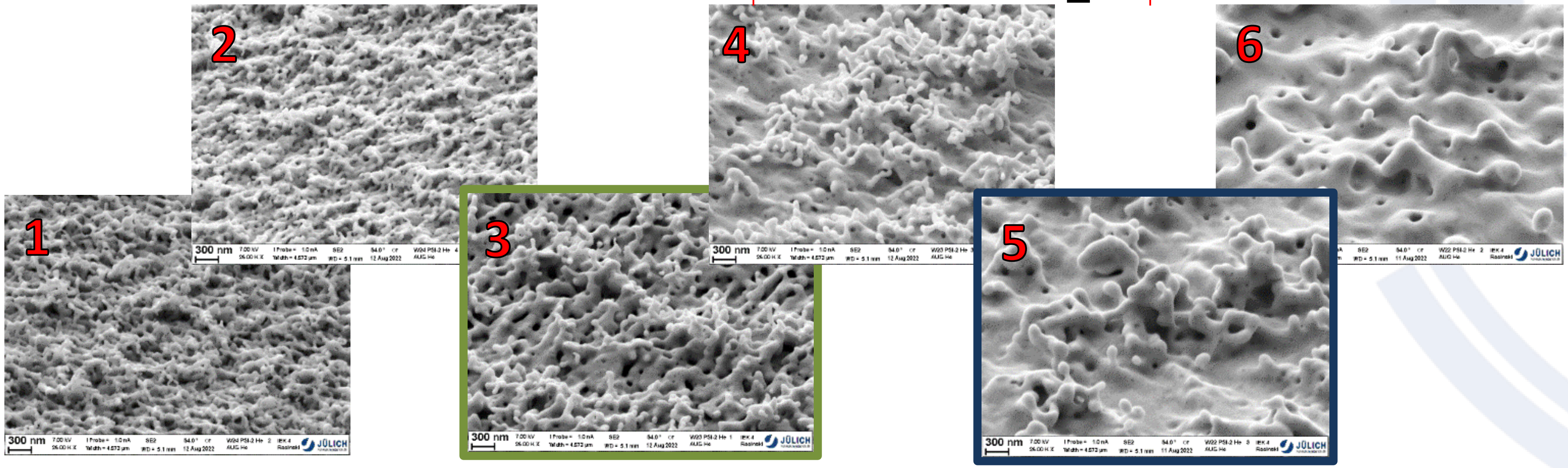
L-mode

100 MW/m^2 200 Hz
in the laser spot



100 MW/m^2 200 Hz
outside the laser spot





- Different exposure temperature (due to laser loading in the laser spot and outside laser) leads to formation of different fuzz structures in PSI-2.
- **Revealed structures fits with good agreements with surface morphology of W exposed in AUG He campaign. Locations above H-mode strike line exhibited different surface temperature.**

Conclusions

- Fuzz formation during AUG He campaign very non-uniform and strongly dependent on surface temperature
- Relatively good agreement between PSI-2 and AUG He W fuzz morphology for samples exposed to high frequency laser loading in PSI-2
- Linear device can be a good proxy for mimicking the fuzz formation in tokamaks. Fuzz structures and bubble formation present after AUG He might be reproducible by simultaneous laser and plasma loading
- Visible recrystallization of W in the laser spot position. Small grains still present beneath the fuzz – He effect on retarded recrystallization

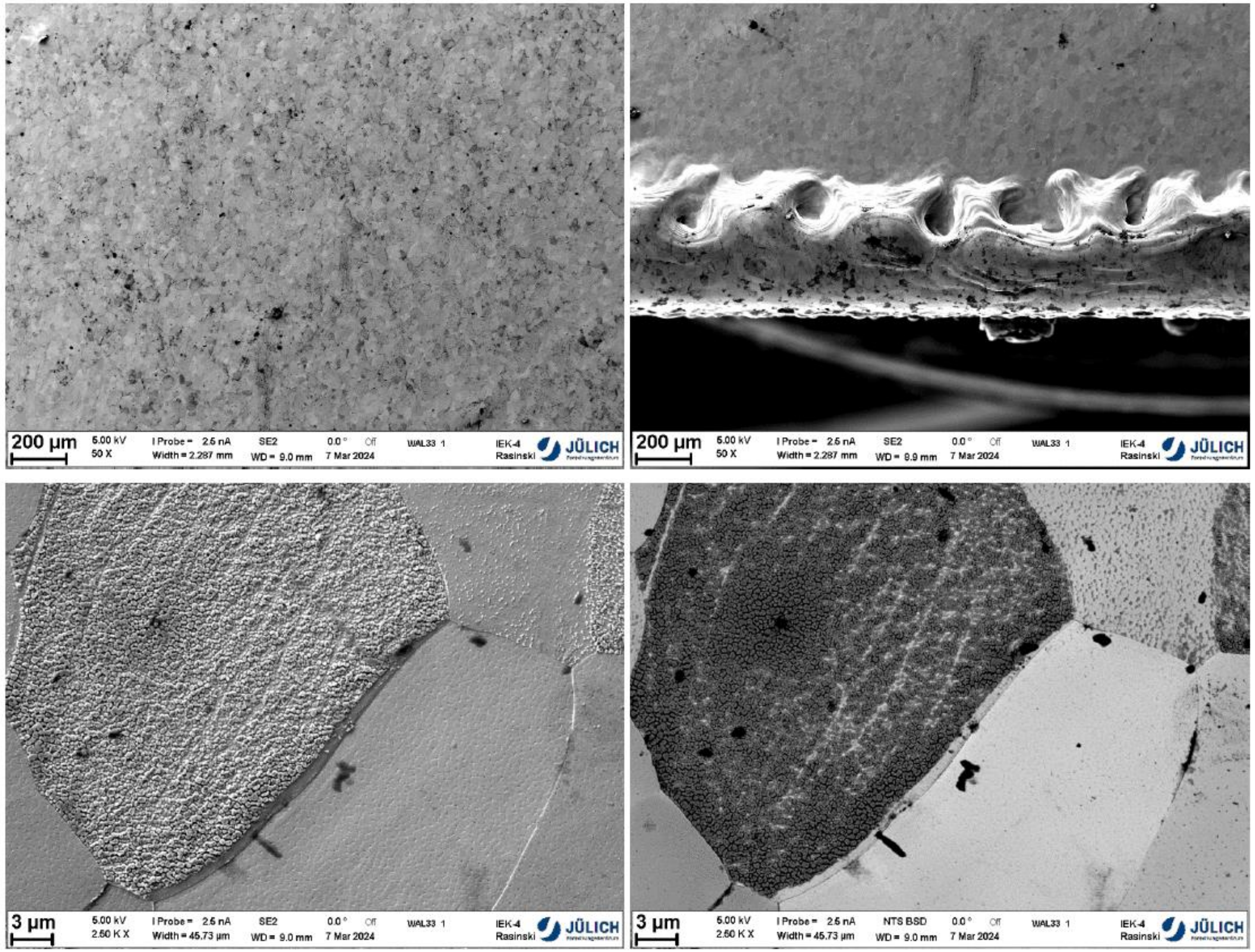
- **Expose to mixed plasma 94% D + 5% He + 1% Ne plus laser loading to be finished in 2024**

PWIE-SP A.A4.T-T004-D004

Influence of plasma pre irradiation with heat loads near surface recrystallization on surface damaging with heat loads above the melting threshold (KIPT)

Analysis of re-melted W layers

Solid W



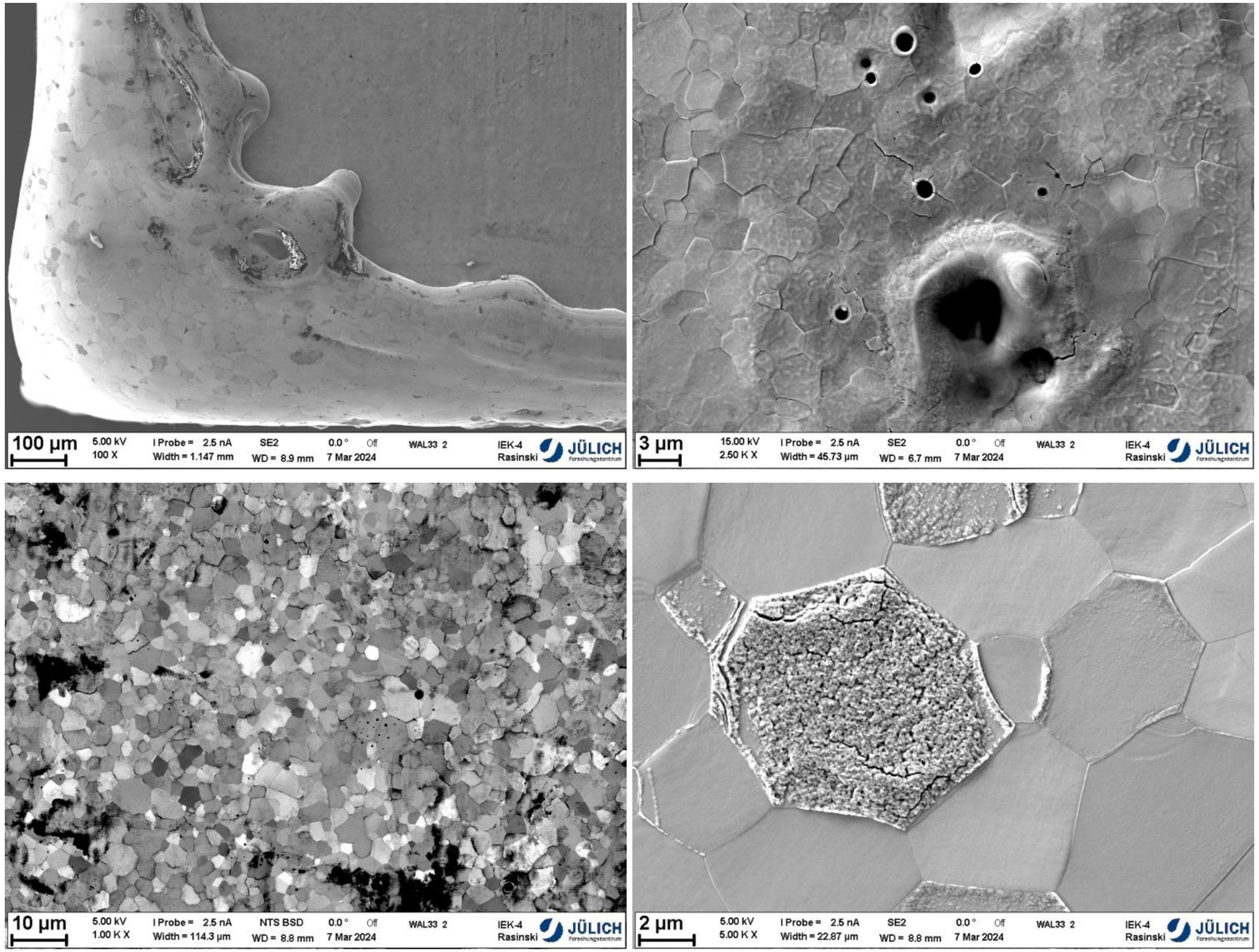
- 5 pulses of QSPA Kh-50 hydrogen plasma (τ_{pulse}=0.25 ms), heat loads above the W melting threshold, T_{base}=500 C

- Arithmetic mean roughness Ra = 0.32 [µm]
- Melt layer velocity V_m ~ 1 m/s
- Wavelength λ_m ~ 0.3 mm
- $\lambda_{K\text{-}H}$ ~ 0.08 mm; $\lambda_{R\text{-}T}$ ~ 0.3 mm
- Rayleigh-Taylor & Kelvin- Helmholtz Instabilities could lead to the formation of protuberances
- Cellular structure evolved into DUST???

V.A. Makhlai, et al., Phys. Scr. 2020, 014047.

Analysis of re-melted W layers

Solid W

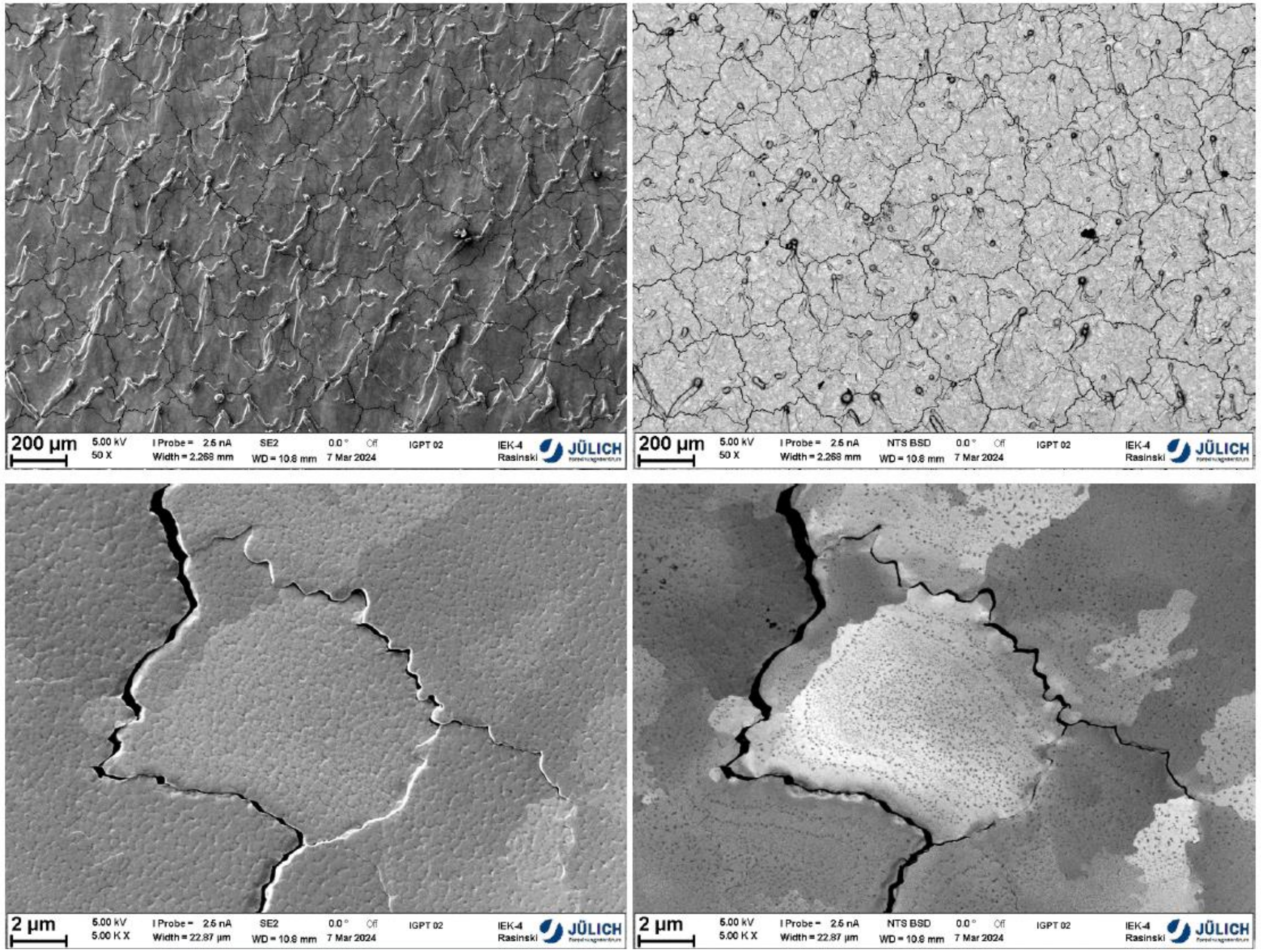


- 5 pulses of QSPA Kh-50 hydrogen plasma (τ_{pulse}=0.25 ms), heat loads above the W melting threshold, T_{base}=500 C

- Melt layer velocity V_m ~ 1 m/s
- Rayleigh-Taylor & Kelvin-Helmholtz Instabilities could lead to the formation of protuberances
- Surface modification
- Cellular structure evolved into DUST???

Analysis of re-melted W layers

IGP tungsten with Transversal grain



- Helium exposure with 10 MPC plasma pulse. Short pulse duration (τ_{pulse}=20 µs), heat loads above the W melting threshold, Tbase=RT
- Arithmetic mean roughness Ra = 4.73 [µm]
- *An additional temperature and surface tension gradient (T and σ) led to the formation of a pronounced pattern along the cell edges during the solidification of the liquid layer*

SUMMARY: SEM studies of exposed solid and lattice tungsten samples have shown crack formation, which contributes to the development of the surface profile. FIB cuts and metallographic cross-sections are planned in collaboration with FZJ.

WP PWIE SPA 5

Results 2024

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Compass-U

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
Renaud Dejarnac	IPP.CR	16	D001 (J.Mtejicek, A.Rednyk,R.Dejarnac,P.Vondracek,J.Caloud,K.Patocka,M.Durovec,M.Bousek,J.Klecka,D.Kirhetov)
Daniel Alegre	CIEMAT	2	D002 (D. Alegre, S. Shick, D. Tafalla, P. Fernández-Mayo, T., Hernández, A. De Castro and E. Oyarzabal)
Pavel Veis	CU	4	D003
Thomas Morgan	DIFFER	2	D004
Laura Laguardia	ENEA	2	D005 (Iafrati, Pedroni, Ghezzi, De Angeli)
Marius Wirtz	FZJ	1	D006
Elzbieta Fortuna-Zalesna	IPPLM	6	D007
Total			

Device	Beneficiary	Days	Related Deliverable
OLMAT	CIEMAT	4	D002
MAGNUM-PSI	DIFFER	2	D004
PSI-2	FZJ	2	D006
JUDITH-2	FZJ	8	D006

Deliverables:

Deliverable ID:	Deliverable Title:
D001	Comprehensive pre-characterization of the 9 candidate W materials
D002	Fast transient simulation on COMPASS-U W armor by a CW laser at OLMAT
D003	Nanocracking detection studies on sxposed materials from PSI-2, Magnum, OLMAT, JUDITH
D004	ELM-like loading effects on different W grades
D005	Post Mortem Analysis , and TDS
D006	Studies on Materials supplied for COMPASS U in on HHF
D007	Comparative Microscopy studies on samples exposed in PSI-2, MAGNUM, JUDITH & OLMAT

IPP Prague

- **Aim:** Comprehensive characterization for downselection of W materials for PFCs of COMPASS-U
- Specifically in PWIE: heat flux performance & material evolution of microstructure and surface condition

- W materials from 9 suppliers (Admat, ALMT, AT&M, Bango Alloy, Inkosas, Midwest Tungsten, Plansee, SMF, T&D)
- Comprehensive pre-characterization of basic properties already performed at IPP (microstructure, density, hardness, thermal conductivity, composition, tensile tests at 3 temperatures)
- For PWIE, 3 suppliers selected for follow-up characterization: ALMT, AT&M, Plansee

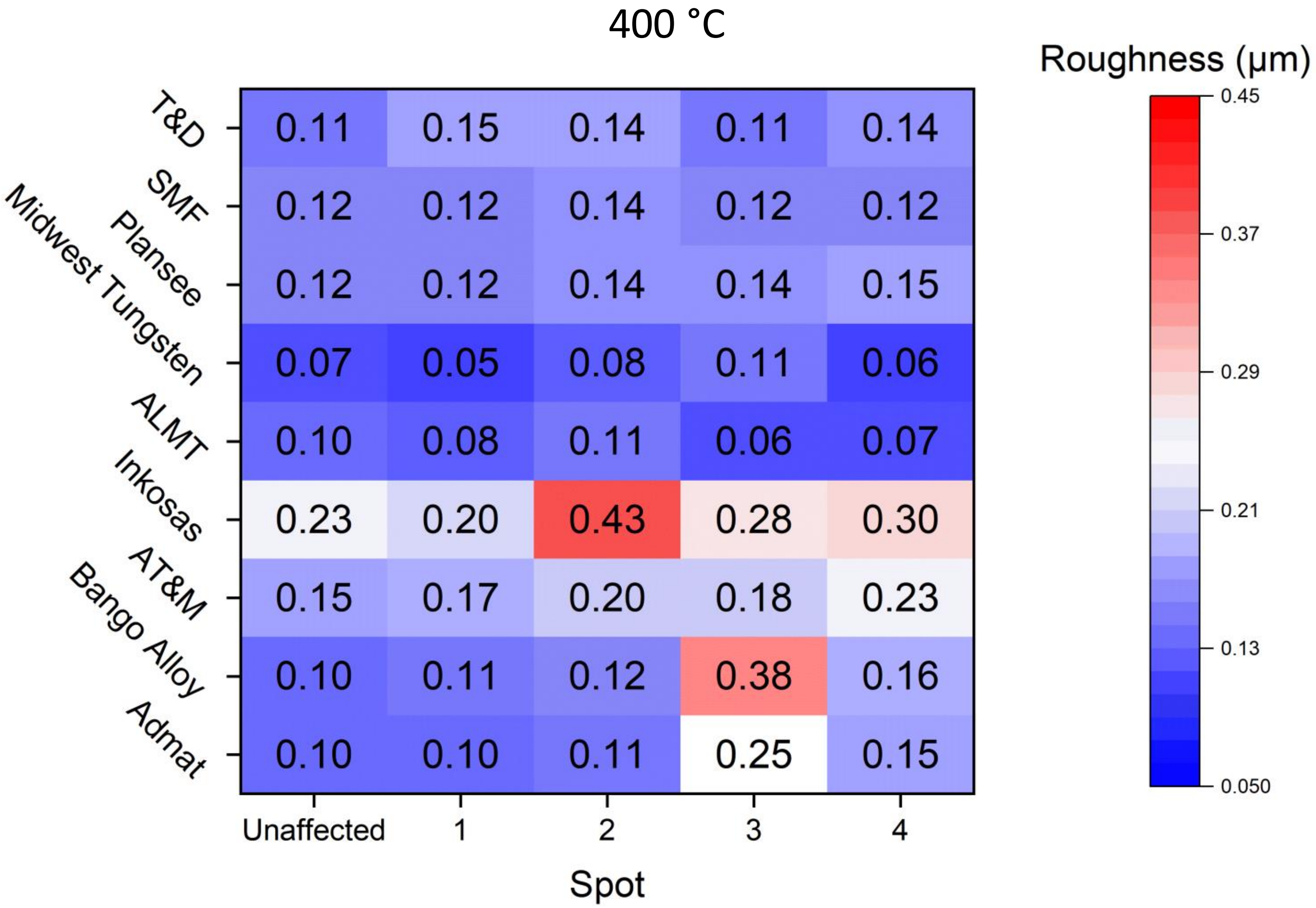
Thermal shock testing at PSI-2

- Low and high pulse number thermal shock test at PSI-2 (no plasma)
- Low pulse number thermal shock tests at T_{base} = RT, 400 and 1000 °C with the laser at PSI-2

Spot	L (GW/m^2)	Δt (ms)	F_{HF} ($MW/m^2s^{½}$)	number
1	0.19	1	6	100
2	0.38	1	12	100
3	0.38	1	12	1000
4	1.6	2	72	1

Low pulse number testing of W samples

- Samples from 9 different manufacturers
- 400 and 1000 °C base temperature
- Further post-mortem characterization at FZJ and IPP-Prague



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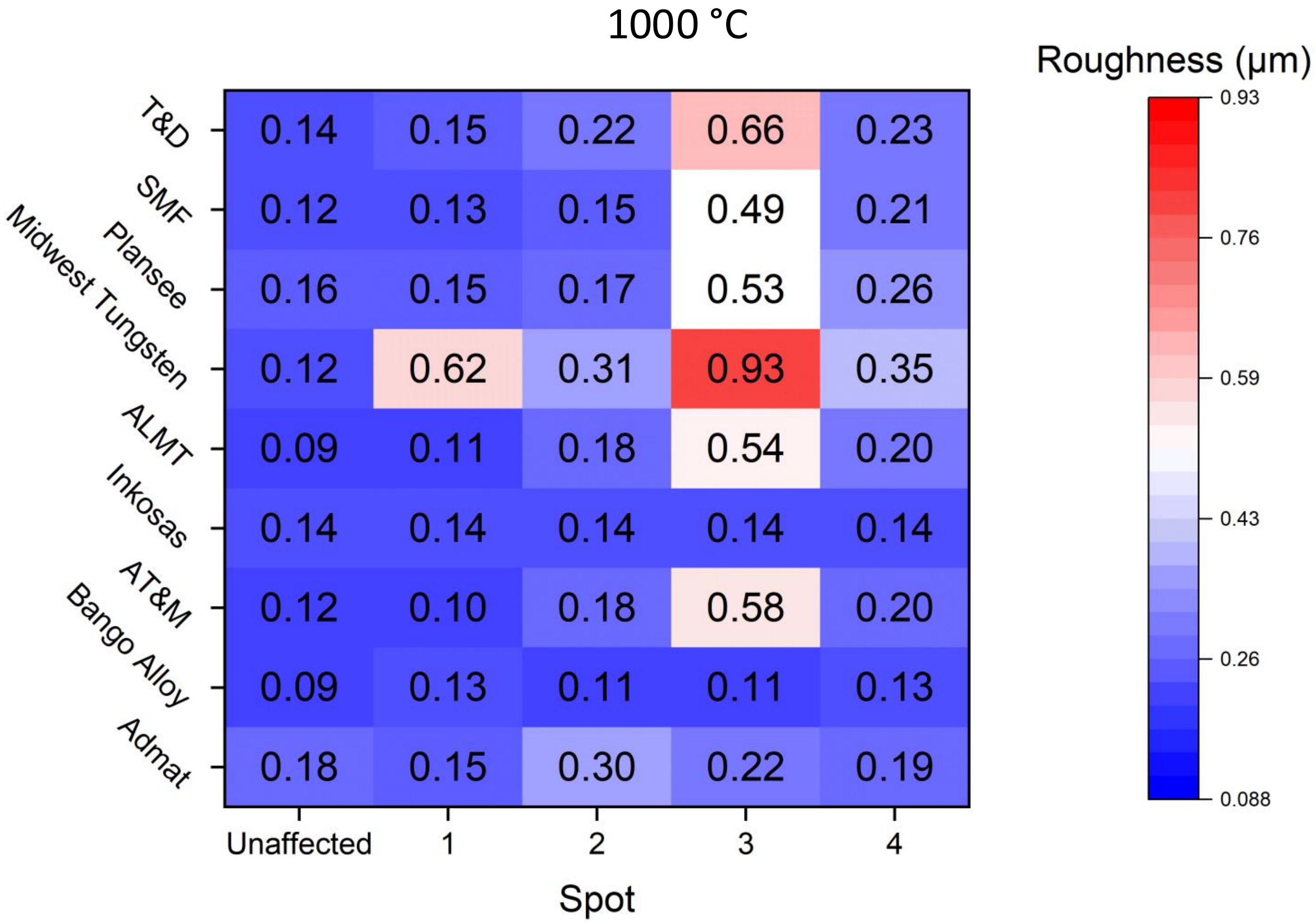


Thermal shock testing at PSI-2

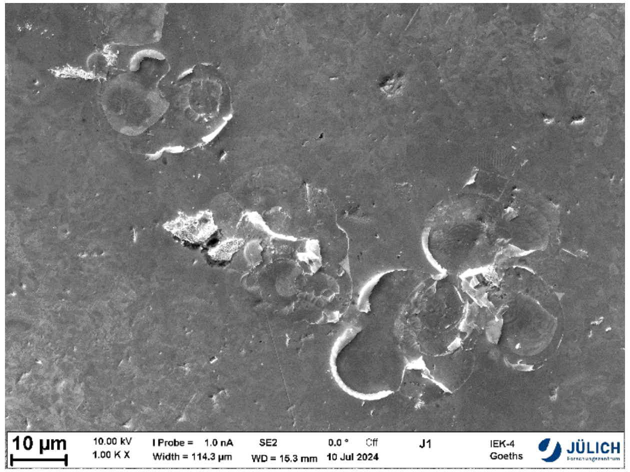
- Examples of surface changes (spot 3)

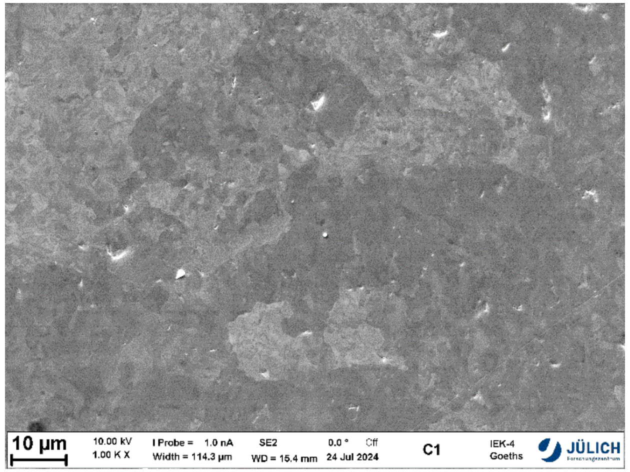
ALMT

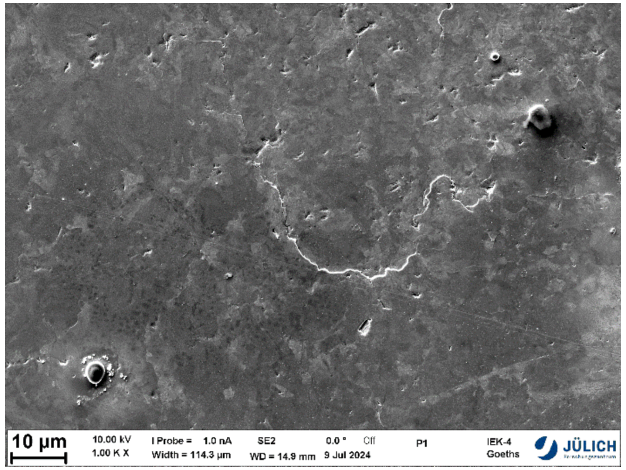
AT&M

Plansee

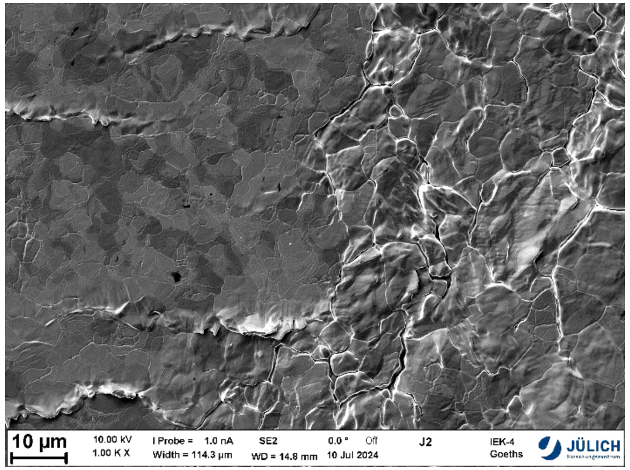
400 °C

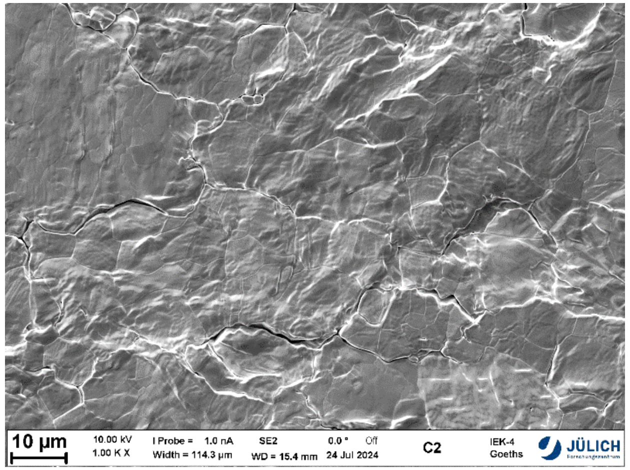


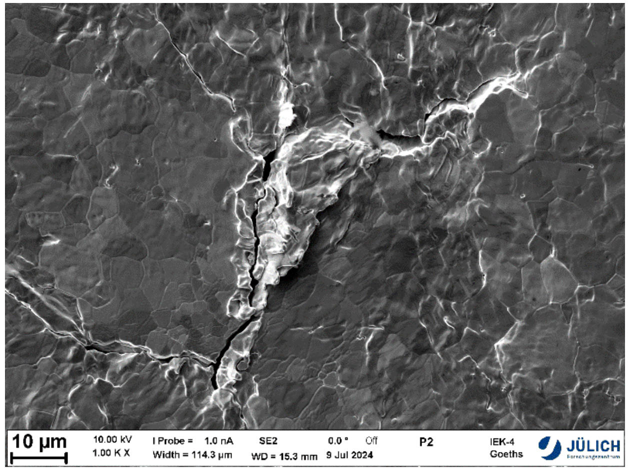




1000 °C

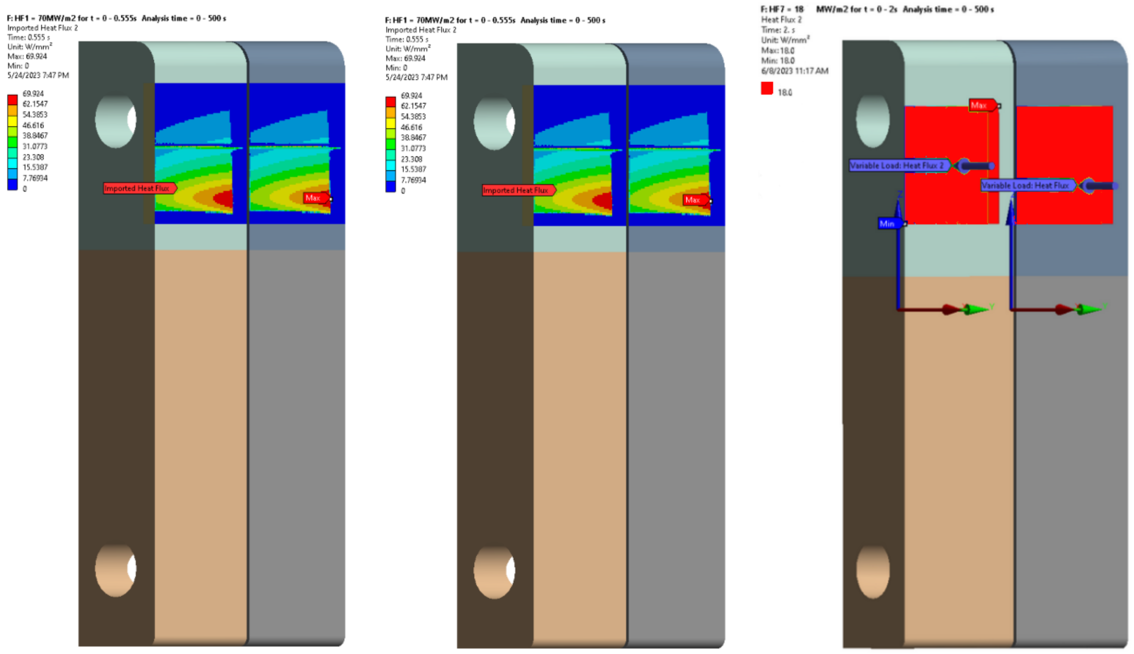




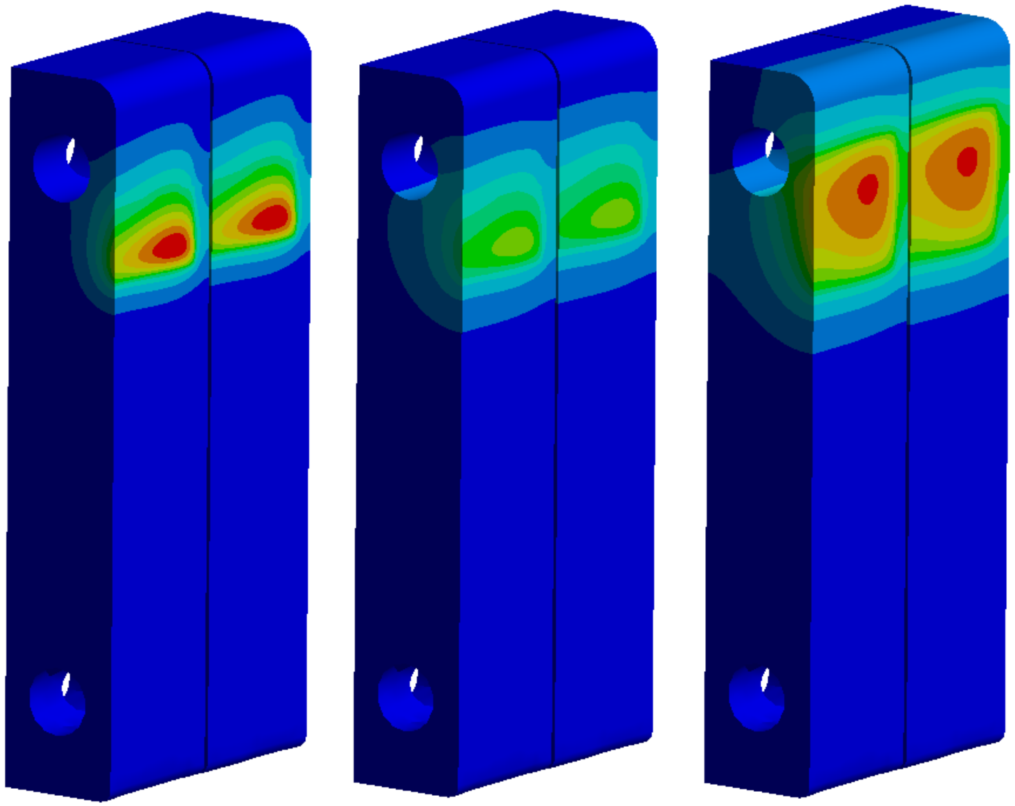


Heat flux testing at JUDITH-2

- ➢ COMPASS-U relevant spatially distributed heat fluxes on COMPASS-U OVT-like tungsten tiles
- ➢ Aim: to study cracking under HHF exposure in order to validate (or not) FEM predictions and design



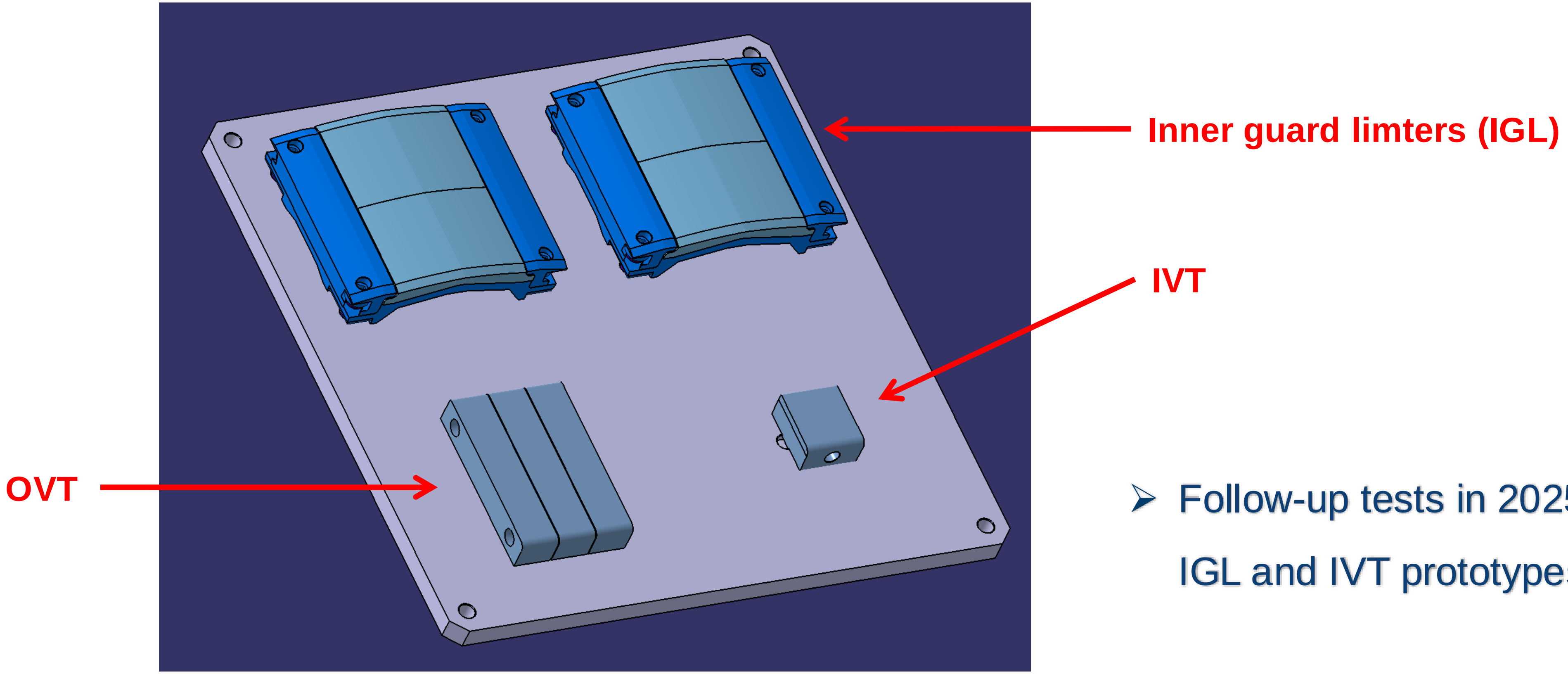
Foreseen heat flux profiles: Heat flux scenarios HF1 (70 MW/m² + 5mm Eich's profile), HF2 (35 MW/m² + 5mm Eich's profile) & HF3 (20 MW/m² + 30mm square profile),



Modelled temperature response to heat flux scenarios HF1, HF2 & HF3, from left to right.

Heat flux testing at JUDITH-2

- 3 OVT-like samples attached to a backplate, to include the effect of attachment on stresses within the tiles
- Samples prepared at IPP, sent to FZJ (Nov 2024)
- Test to be performed near the end of 2024

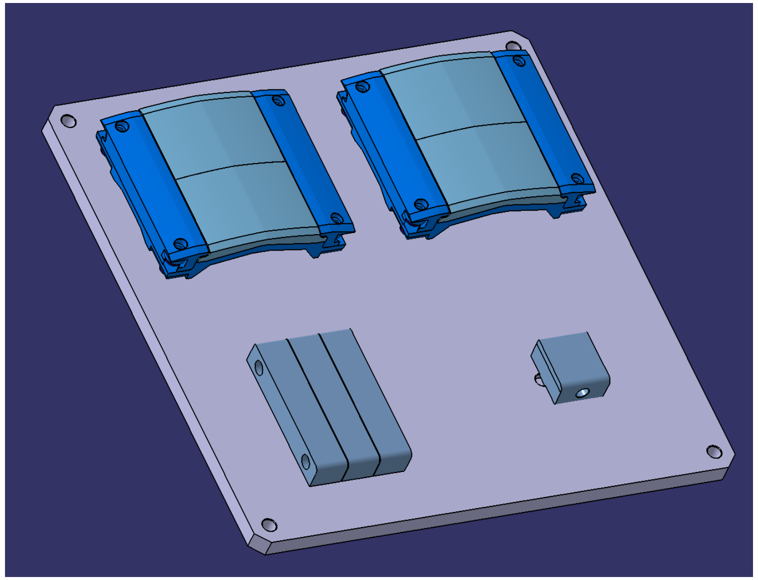


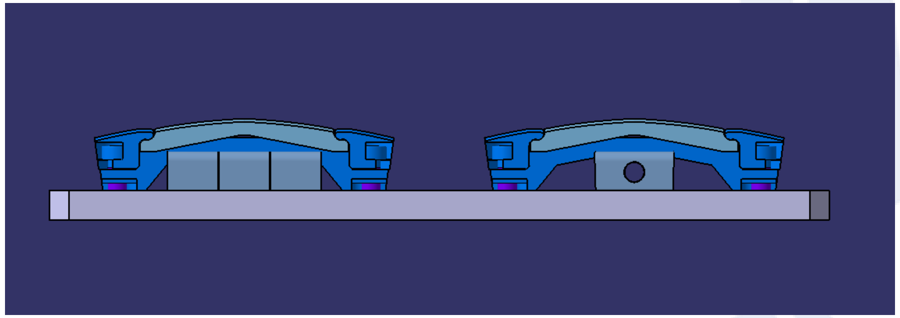
- Follow-up tests in 2025 including IGL and IVT prototypes scale 1

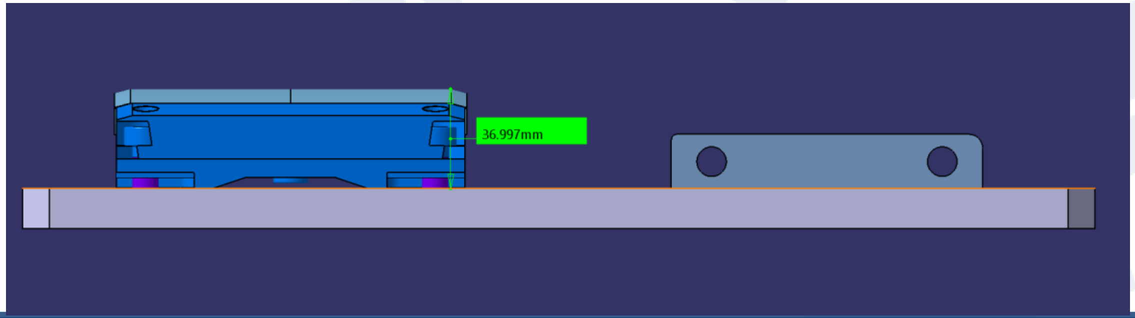
FZJ COMPASS-U activities

Aim of this proposal is the qualification of different materials and components for COMPASS-U (first wall and divertor) with regard to their stationary heat load and thermal shock resistance against ELM like loading conditions (1 ms, up to 0.38 GW/m^2). Qualification conditions and criteria (determined by characterization after HHF-tests) determined on reference tungsten are available.

A detailed pre- and post-mortem analysis of the tested materials and components is necessary and will be done in order to characterize the induced damages. Based on these results damage mechanism will be identified which will help to improve the materials/component to mitigated the damages and to improve the lifetime in a fusion device.



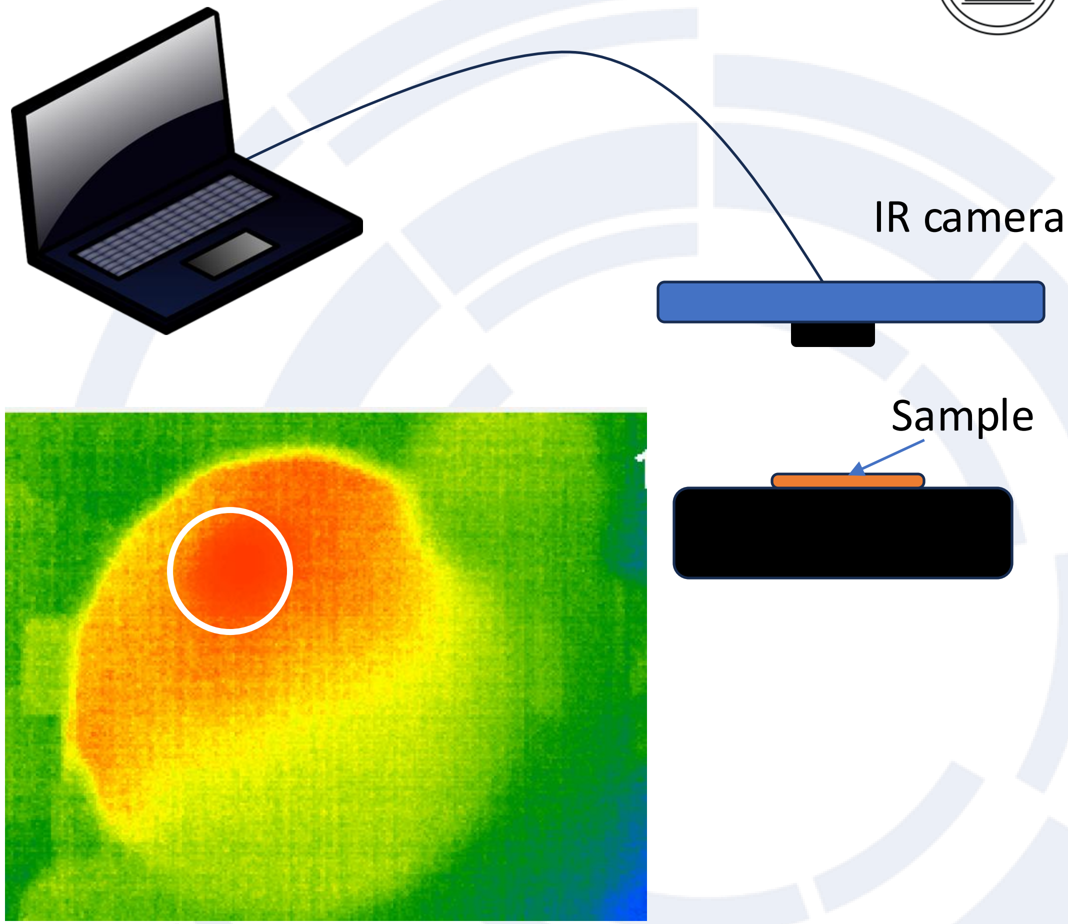




IR Camera for surface analysis – cracking detection

Comenius Univ. in Bratislava

- Study analyses the surface for cracks and indentation using IR camera.
- Seek thermal S314SPX IR camera was acquired to analyse the surface.
- Python program was developed to record images and videos.
- A CW IR laser operating at 1470nm was used to heat the surface.
- Preliminary tests after laser heating were done on materials with low thermal conductivity. (plastic, paper ..).
- Localized hotspots were observed at the indented positions in the image captured by the IR camera.
- Working currently on W/metallic samples.



Task for 2025
Nanocracking detection
Testing of the proposed nano cracking detection technique using real samples: Analysis of representative HHD Tungsten samples exposed in Magnum-PSI and/or Judith-2.

Deliverable: PWIE-SP A. S. T-T001-D003
Status: *done.*
Facilities: NA — or Modelling*: NA*
Linked WP or TSVV:

ENEA-CNR L. Laguardia, M. Iafrati, M. Pedroni

- Microstructure and mechanical properties of selected W materials after exposure, including comparative analysis

After exposure to steady-state and transient heat loads (PSI-2 and/or Magnum PSI) of the selected tungsten first wall COMPASS-U plasma-facing components, Post-characterization, devoted to the detection of fuel retention and surface microstructure modifications, will be performed by:

- Thermal Desorption Spectroscopy (TDS)
- Scanning Electron Microscopy (SEM)
- Atomic Force Microscopy (AFM)

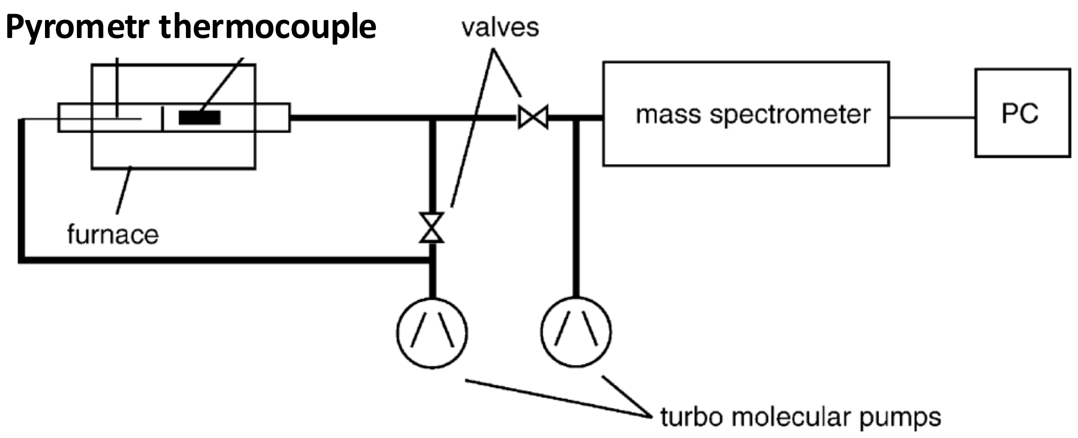
D005: Microstructure and mechanical properties of selected W materials after exposure, including comparative analysis

- After exposure to steady-state and transient heat loads (PSI-2 and/or Magnum PSI) of the selected tungsten first wall COMPASS-U plasma-facing components, Post-characterization, devoted to the detection of fuel retention and surface microstructure modifications, will be performed by:

- Thermal Desorption Spectroscopy (TDS)
- Scanning Electron Microscopy (SEM)
- Atomic Force Microscopy (AFM)

2024 Activity

- As soon we receive the exposed samples (we are waiting them before of the end of November), assess the W resistance to fuel retention by TDS analysis .



- It is a custom-built high vacuum system in which:
- direct currents are driven through the substrates which reach surface temperatures in the order of 2000 K.
- a Pfeiffer mass spectrometer is connected to the turbo molecular pump of the chamber.
- the samples temperature and the leak-rate of the gases from the samples are recorded simultaneously.
- the temperature measurement is performed through viewports of the vacuum vessel using a pyrometer and a type C thermocouple directly in contact with the sample.

WP PWIE SPA Outlook

A few comments

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General Remarks

- Continuation of SPA activities
- Full Establishment of SPA 5
  - Inclusion of Tasks at UKAEA

CIEMAT Outlook SPA 1

- **D003: Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures**

Experiments planned in 2025

OLMAT BEAM: fatigue studies in large holder

Repeat with more samples:

- New *PM-Wf/W* (if available)
- New *WCrY* alloys with/without spinodal structure. Being cut and polished.
- *Additive Manufactured AM-W* to check lower properties: Being polished.
- W/WC from JSI: agreed collaboration
- Study WCrY/CuCrZr joints by HIP-DB
- Study AM-W/CuCrZr joints by AM

Laser: disruption and long term fatigue

Disruptions with new laser fiber:

- Repeat WEST analysis: 300-800 MW/m^2 at borders.
- PM-Wf/W: 300-800 MW/m^2 at borders and surface
- Continue COMPASS-U testing

Prepare long term fatigue:

Simulate mitigated ELMs in DEMO: 0.1 MJ/m^2, 2 ms, 20 Hz. 5000 pulses in 1, years: ~$7 \cdot 10^8$ ELMs!

- 275 Hz limit in our laser, $8 \cdot 10^6$ pulses/day, ~100 days
- Equivalent F_{HF} at 2000 Hz: $6 \cdot 10^7$ pulses/day, ~12 days

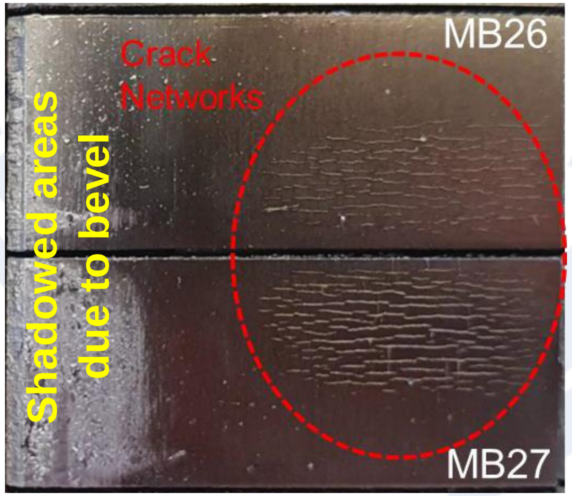
Technically complex: vacuum viewport has to resist hours!

Deliverable: PWIE-SP A.1.T-T003-D003
Status: *ongoing*
Facilities: *OLMAT 5 days*
Linked WP or TSVV: *none*

CEA SPA 4 Next Steps 2025

- Topic A: Assessment of plasma impact on material properties linked to ITER relevant PFUs (CEA) (follow-up)
  - Study the influence of He on the evolution of tungsten properties (comparative study with WEST samples)
  - Perform He implantation study to characterize defects generated and assess the evolution of mechanical props based on multi-scale approach

- Topic B: Top surface cracking investigation
  - Perform an overview highlighting the crack networks distribution at the WEST divertor (Phase II) → follow up (cf leading edge study)
  - Investigate the rational: Are these cracks resulting from manufacturing stress release? Is a common link between leading edge and top surface (impact of the manufacturing route?)
  - Perform post-mortem analysis (microscopy, XRD) on the top surface and the leading edge
  - Consider residual stresses the modelling (if needed)



VR SPA 4 Outlook

RE-induced damage

Modelling development:

- Complete modelling of WEST BN tiles with re-visited loading (Geant4 + COMSOL)
- Fragmentation of brittle materials (C, BN): GEANT4 + LS-DYNA modelling of debris release
- Initial model for thermo-mechanical response of ductile materials (W), including plasticity (Geant4 + COMSOL)

Modelling of experiments

- WPTE 2025 proposal: controlled RE-induced damage of W in WEST
- WPTE 2025 proposal: controlled RE-induced damage of W in AUG
- JET data: explosive damage of W coated CFC tiles in JET (experiment requested by ITER, shots prior to the machine shut-down) → *pending availability of information on anisotropic CFC thermo-physical properties*

Thermal transient load induced damage

- MEMENTO modelling of 2024 AUG experiment on *sustained* melt flow across the gap (exposures are scheduled on Dec 10th 2024 and January 2025)

FZJ SPA 4 Plans for 2025

Based on the first exposure to **94% D + 5% He + 1% Ne** plasma plus laser loading

further experiments with plasma exposure to mixed D+He+Ne plasma with various fractions of Ne (0.1, 1 and 5 % of Ne) to explore its influence on the structure and morphology of W.

The goal of the experiment is to help assess the influence of seeding gases foreseen for ITER with relevant ELM like laser loading in the PSI-2 on the morphology changes of exposed W.

For each exposure samples exposed only to mixed plasma as well as plasma and laser will be investigated. Multi sample holder in PSI-2 allows simultaneous exposure up to 8 samples.

Samples will be characterized by means of electron microscopy techniques – SEM, FIB and TEM

ENEAR_CNR SPA 5 2025 Activity

- To assess the morphology modifications that have occurred in the W surface layers due to plasma, a repeated series of post-exposure characterization tests will be addressed by:
- Scanning Electron Microscopy (SEM)
- and Atomic Force Microscopy (AFM)


FAIRNESS
Transparency
Collaboration
Loyalty
OPENNESS
Open doors
Open hearts
Open minds
Open ears
COMMITMENT
Ownership
Critical thinking
Determination
Respect
DIVERSITY
Cooperation
Equal opportunities
Inclusion