

Meeting PWIE 2025 Prague

PWIE SP A: WPPWIE Meeting Juelich – Report & Overview

Jan W.Coenen & SPA Contributors

Forschungszentrum Jülich GmbH, Institut for Fusion Energy and Nuclear Waste Management IFN-1 52425 Jülich, Germany,



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.



Agenda

- Overview & Report J.W.Coenen
- Highlight Talk SPA 1
- Highlight Talk SPA 2
- Highlight Talk SPA 3/ SPA 4
- Highlight Talk SPA5





SPA– 2025 - 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 circumstances*



SPA– 2026 - 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

- Focus on ITER
- *Finalizing of work until 2027*
- *Deliverables soon to be defined*

WP PWIE SPA 1

Report for 2025 & Overview



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.





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

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
M. Wirtz	FZJ	4	D001 (M. Gago, D. Dorow-Gerspach*)
T. Morgan	DIFFER	4	D002, (T. Morgan)
P. Tabares	CIEMAT	6	D003 (D. Alegre)
H. Greuner	MPG	3	D004 (H. Greuner, H. Maier, J. Riesch)
I. Garkusha	KIPT	15	D005 (I. Garkusha)
Total		32	

Device	Beneficiary	Days	Related Deliverable
PSI-2	FZJ	10	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	5	D002
OLMAT	CIEMAT	10	D003

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) – with focus on Properties under synergistic Loading
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).

- Establish a test matrix for Materials utilized in WEST and ITER with respect to updated load specifications. in the available devices (DIFFER, FZJ, MPG)
- Study the impact of synergistic loads on ITER and DEMO relevant baseline Materials (tungsten, W-FGMs on Steel) and new materials developments with Laser (Laser at PSI-2) and e-beam (JUDITH) as well as steady-state plasma exposure (He, H). A special focus will be the qualification of these materials under high cycle numbers and seed-impurities exposure. (FZJ)
- Post-mortem analysis will characterize the induced surface modifications and damages as well as investigate changes of the materials properties due to e.g. recrystallization behavior and/or surface morphology changes. (FZJ, MPG, DIFFER, KIPT)
- Determine underlying mechanisms of evolution of crack propagation in materials for ITER and current day devices. (FZJ, DIFFER, KIPT, MPG, CIEMAT)
- Qualify W materials for use in W7-X. (MPG, FZJ)
- Synergy effects from sequential stationary (PSI-2 / MAGNUM-PSI, OLMAT) and transient (QSPA) plasma loads. (DIFFER, MPG, FZJ, KIPT, CIEMAT)
- Studies of fatigue cracks formation in deformed/re-crystallized W, fatigue damage of W_f/W wires, latticing W etc. (FZJ)
- Combination of pulsed and steady state loading (e.g. behavior of QSPA pre-damaged targets in PSI-2, JUIDTH compared with reference samples). (FZJ, KIPT)

Study the Behavior of pre-cracked samples under edge loading conditions - links to HHF facilities such as JUDITH and WEST. (DIFFER, FZJ)



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

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



PWIE-SP A.A1.T-T004-D005: Conditions of sequential loads

- Samples

We received 12 conventional tungsten samples from DIFFER.

12x12 mm square samples with a 2 mm thickness were cut from ITER-grade tungsten produced by PLANSEE.

- Samples were exposed in the Upgraded Pilot-PSI (UPP) and Magnum-PSI (Magnum) at DIFFER. In UPP, fluence and temperature scans were performed, exposing samples to temperatures 400-500-600-700 K and fluences of 10^{25} – 10^{26} – 10^{27} m⁻² to successive D - H -D plasma. In Magnum, the same temperature scan was performed at a fluence of 10^{27} m⁻².
- Post-mortem and in-situ ion beam analysis between plasma exposures were performed to analyze retention in the samples.
- **Samples W3;W4; W13; W14; W1, W2, W6, W7** were irradiated with 10 QSPA plasma pulses of 0.9 MJ/m²

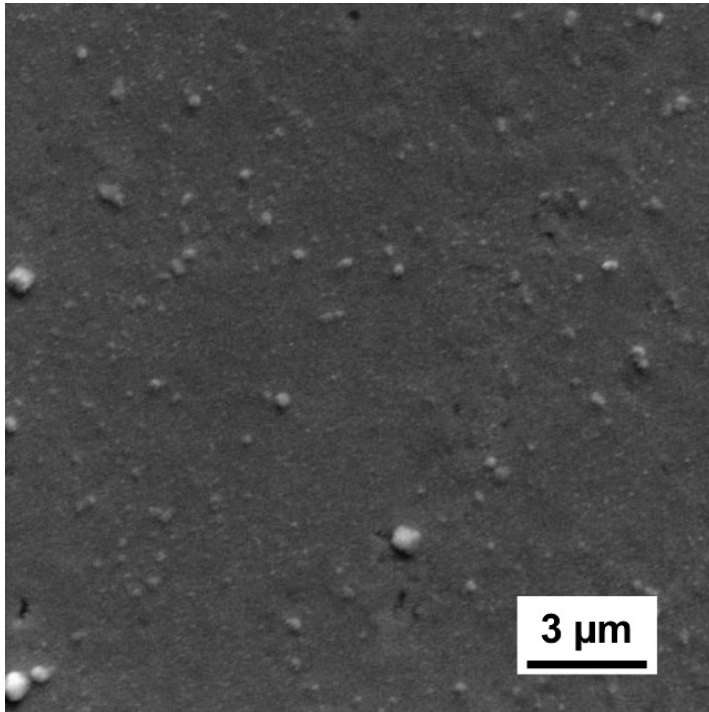


https://pure.tue.nl/ws/portalfiles/portal/319778422/0952393_-_Elenbaas_J.K._-_MSc_thesis_Thesis_-_NF.pdf



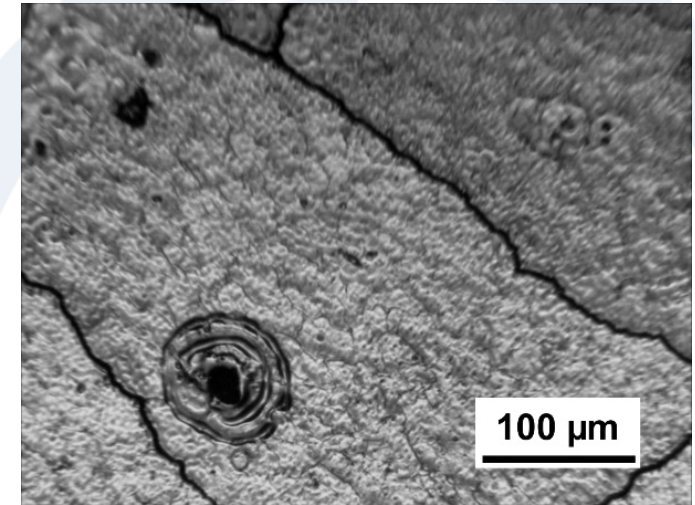
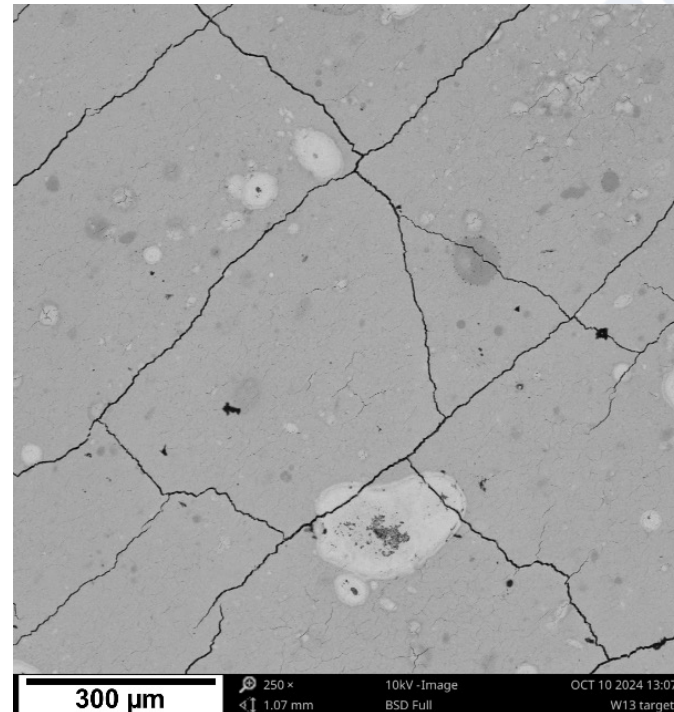
PWIE-SP A.A1.T-T004-D005: Magnum + QSPA

Magnum-PSI



- After Magnum-PSI exposure:
 $T = 600 \text{ C}$, 10^{27} m^{-2}
- Surface relief typical for physical sputtering
- Blisters in the hundred-nanometer range

Magnum-PSI + QSPA

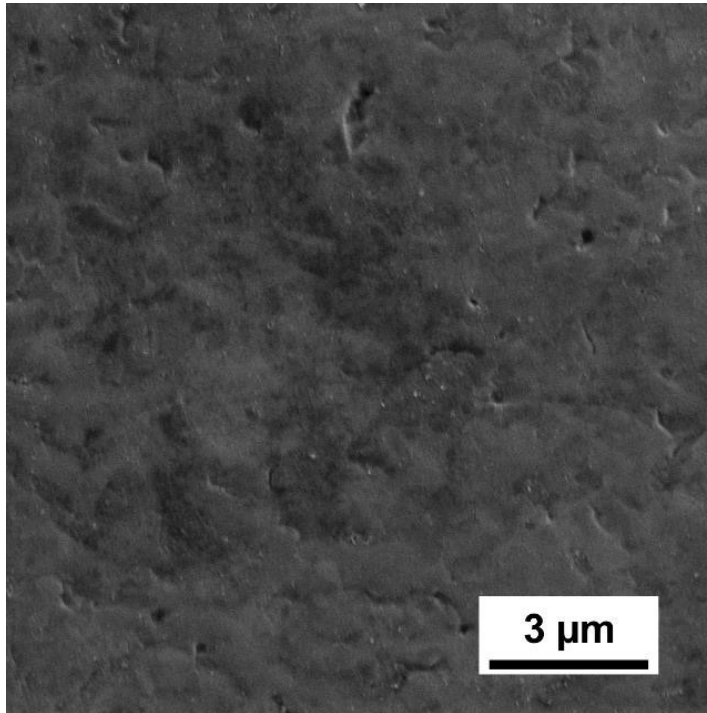


- After QSPA Kh-50 exposure: $T = \text{RT}$, 10 pulses, surface heat load of 0.9 MJ/m^2 and a duration of 0.25 ms.
- Surface melting, re-solidified layer
- Cracking (large (network up to 0.4 mm) and intergranular (network up to $40 \mu\text{m}$) cracks), cracks width up to $1 \mu\text{m}$.
- Pores resulting from blister cap ruptures ???



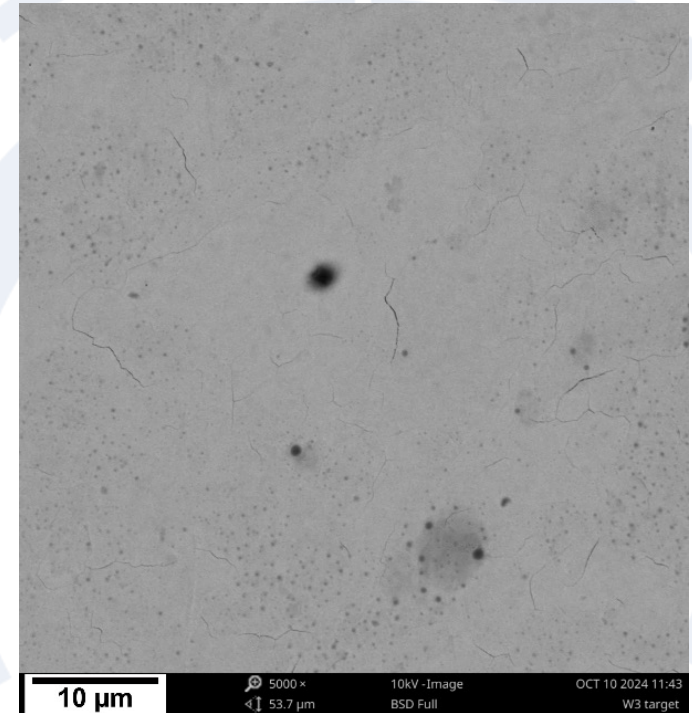
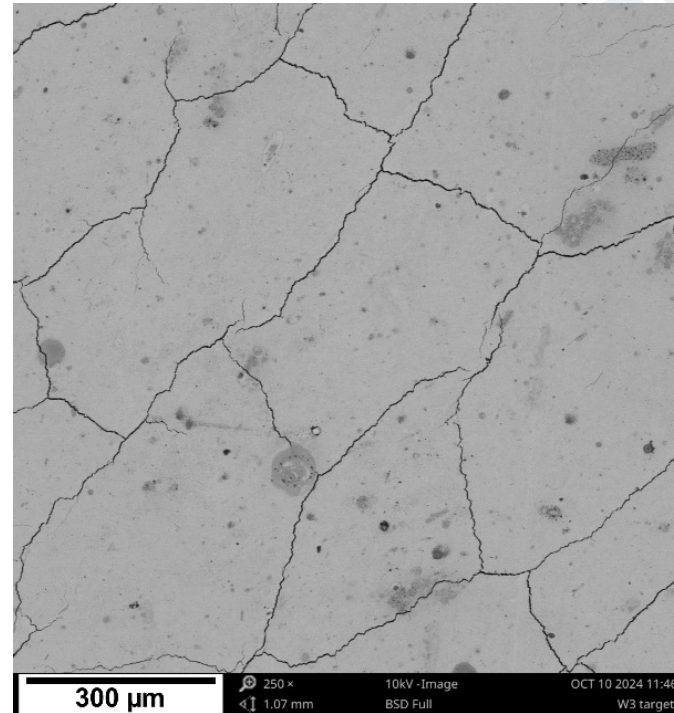
PWIE-SP A.A1.T-T004-D005: UPP + QSPA

Upgraded Pilot-PSI



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

Upgraded Pilot-PSI + QSPA



- After QSPA exposure: $T = \text{RT}$, 10 pulses, surface heat load of $0,9\text{ MJ/m}^2$ and a duration of 0.25 ms.
- Surface melting, re-solidified layer
- Cracking (large (network up to 0.4 mm) and intergranular (network up to 40 μm) cracks), cracks width up to 1 μm.



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

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

Summary 2025

- Samples were initially exposed in the Upgraded Pilot-PSI (UPP) and Magnum-PSI in collaboration with Thomas Morgan
- Additional QSPA exposure (T=RT, 10 pulses, 0.9 MJ/m^2) was performed
- Observed effects include surface melting, cracking (large and intergranular cracks), pore formation
- A paper on the performed work has been submitted as a contribution to the 20th PFMC (19-23 May 2025, Ljubljana, Slovenia)
- Post-mortem analyses using XRD and cross-sectional studies are currently in progress in collaboration with **Wolfgang Pantleon (DTU)**

SPA1 DIFFER task and activities

Deliverable: *“Evaluation of redeposited tungsten microstructure and evolution under transient loading”*

Goal

- Create “realistic” W redeposits with a sputtering & redeposition setup in Magnum-PSI
- Determine how W redeposited layers impact the divertor

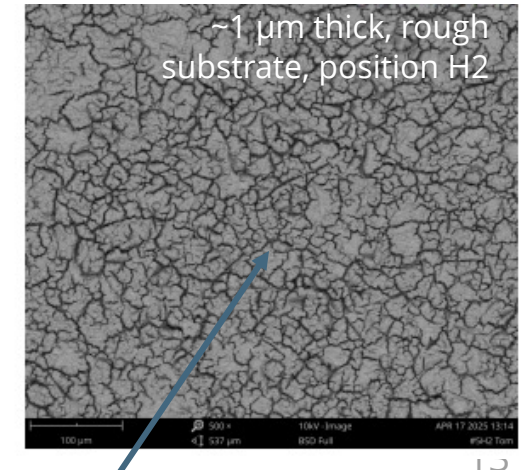
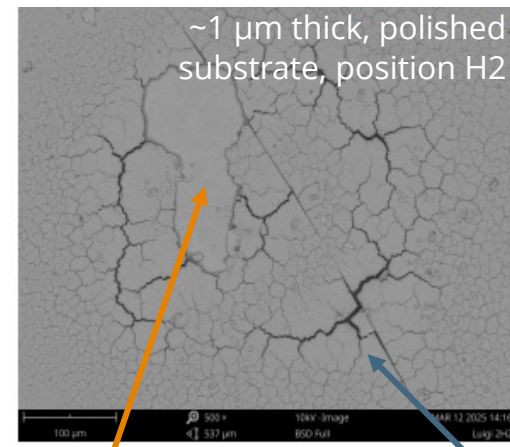
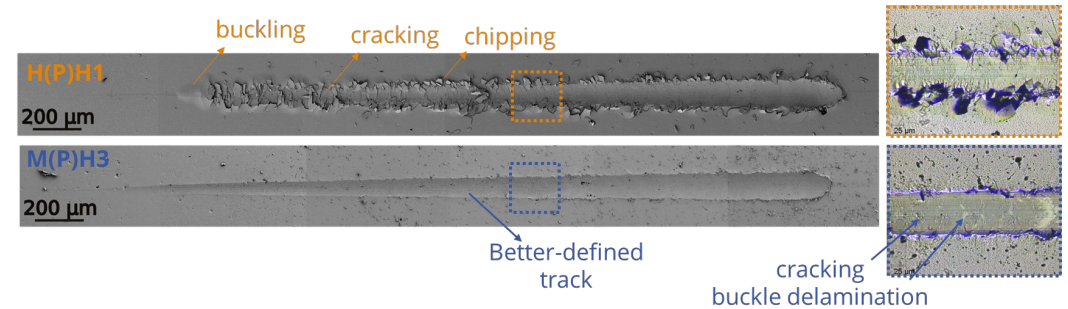
Activities 2025

- Characterize layers grown in 2024
- Exposure 2024 layers to ELM-like (laser) loading combined with H-plasma loading to evaluate layer stability



Overview of activity

- XRD (crystallite size, phase, crystallinity) shows mainly nanocrystalline alpha-phase W
- scratch testing (coating adhesion) shows that plasma interaction regions had better film-substrate adhesion than shadowed regions
- ELM-like loading showed flaking of previously adhered deposits for thicker layers, with melting at edges of delaminated regions.
- Strongly substrate dependent: rough substrates increase adhesion, leading to cracking through to substrate



Publications related to SPA 2020-2025

Publications

J. Hargreaves, H.E. Tipping, S. Moore, D. Kumar, D. J. Harding, H. Dominguez-Andrade, C. Bell, P.D. Hanna, H. Dawson, T. L. Martin , The transient thermal ageing of Eurofer 97 by mitigated plasma disruptions , *Materials and Design* , 244 (2024) 113207

[Y. Li, J. Hou, V. Shah, Y. Huang, J. A. W. van Dommelen, W. J. Lu, Q. Zhu, T. W. Morgan , Amorphous and anisotropic surface relief formation in tungsten under repeated high-flux hydrogen plasma loads , *Nuclear Materials and Energy* , 37 \(2023\) 101544](#)

[Y. Li, T. Vermeij, J.P. M. Hoefnagels, Q. Zhu, T. W. Morgan , Influence of porosity and blistering on the thermal fatigue behavior of tungsten , *Nuclear Fusion* , 62 \(2022\) 076039](#)

[Y. Li, T. W. Morgan, T. Vermeij, J. W. M. Vernimmen, T. Loewenhoff, J.P. M. Hoefnagels, J. A. W. van Dommelen, M. Wirtz, G. De Temmerman, K. Verbeken , et al. , Recrystallization-mediated crack initiation in tungsten under simultaneous high-flux hydrogen plasma loads and high-cycle transient heating , *Nuclear Fusion* , 61 \(2021\) 046018](#)

[T. W. Morgan, Y. Li, M. Balden, S. Brezinsek, G. De Temmerman , Combined high fluence and high cycle number transient loading of ITER-like monoblocks in Magnum-PSI , *Nuclear Fusion* , 61 \(2021\) 116045](#)

[Z. Chen, Y. Li, L. Cheng, Z. Wang, Y. Lian, X. Liu, F. Feng, J. Wang, Y. Tan, T. W. Morgan , et al. , Recent progress of thick tungsten coating prepared by chemical vapor deposition as the plasma-facing material , *Nuclear Fusion* , 61 \(2021\) 126024](#)

[V. Shah, J. T.S. Beune, Y. Li, T. Loewenhoff, M. Wirtz, T. W. Morgan, J. A. W. van Dommelen , Recrystallization behaviour of high-flux hydrogen plasma exposed tungsten , *Journal of Nuclear Materials* , 545 \(2021\) 152748](#)

[Y. Li, T. W. Morgan, J. van den Berg, J.W. Genuit, G. De Temmerman, J.P. M. Hoefnagels, J. A. W. van Dommelen, K. Verbeken, M.G. D. Geers , Power deposition behavior of high-density transient hydrogen plasma on tungsten in Magnum-PSI , *Plasma Physics and Controlled Fusion* , 63 \(2021\) 085016](#)

[Y. Li, T. W. Morgan, J. van den Berg, J.W. Genuit, G. De Temmerman, J.P. M. Hoefnagels, J. A. W. van Dommelen, K. Verbeken, M.G. D. Geers , Power deposition behavior of high-density transient hydrogen plasma on tungsten in Magnum-PSI , *Plasma Physics and Controlled Fusion* , 63 \(2021\) 085016](#)

[A. Litnovsky, J. Schmitz, F. Klein, K. De Lannoye, S. Weckauf, A. Kreter, M. Rasinski, J. W. Coenen, C. Linsmeier, T. W. Morgan , et al. , Smart Tungsten-based Alloys for a First Wall of DEMO , *Fusion Engineering and Design* , 159 \(2020\) 111742](#)

[K. L. Li, Y. Li, W. Q. Chen, C. Zhao, Y. Yuan, L. Cheng, T. W. Morgan, W. Liu, Z. J. Shen , Effect of Ta addition on the fuzz formation of additively manufactured W based materials , *Nuclear Fusion* , 60 \(2020\) 064004](#)

[Y. Li, T. W. Morgan, D. Terentyev, S. Ryelandt, A. Favache, S. Wang, M. Wirtz, J. P. M. Hoefnagels, J. A. W. van Dommelen, G. De Temmerman , et al. , Three mechanisms of hydrogen-induced dislocation pinning in tungsten , *Nuclear Fusion* , 60 \(2020\) 086015](#)

[M. Balden, S. Elgeti, T. W. Morgan, S. Brezinsek, G. De Temmerman , Scanning electron microscopy analyses of an ITER plasma-facing unit mockup exposed to extreme ion fluences in Magnum-PSI , *Physica Scripta* , 95 \(2020\) 014026](#)

[T. W. Morgan, M. Balden, T. Schwartz-Selinger, Y. Li, T. Loewenhoff, M. Wirtz, S. Brezinsek, G. De Temmerman , ITER monoblock performance under lifetime loading conditions in](#)



Overview of main results DIFFER SPA (2020-2025)

SPA1

- Evaluated lifetime of pre-damaged surfaces under fatigue (ELM-like loading)
- Evaluated the mechanical properties and adhesion of re-deposited tungsten under steady and transient loading

SPA2

- Evaluated performance of tungsten (monoblocks) under “slow transient” conditions with and without ELM-like loading and impurity seeding
- Evaluated fatigue behaviour of tungsten under “strikepoint sweeping” conditions

SPA3

- Evaluated performance under high flux (transient) loading of advanced materials
 - CVD-W
 - Smart alloys
 - EUROfer

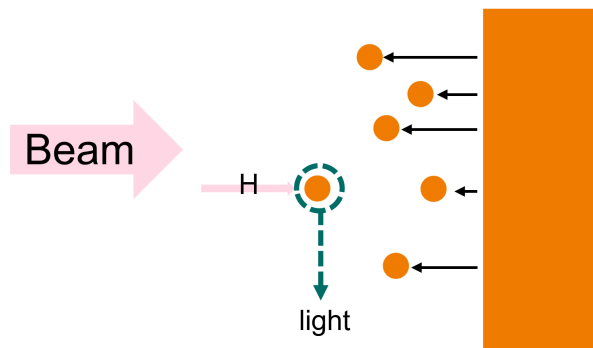
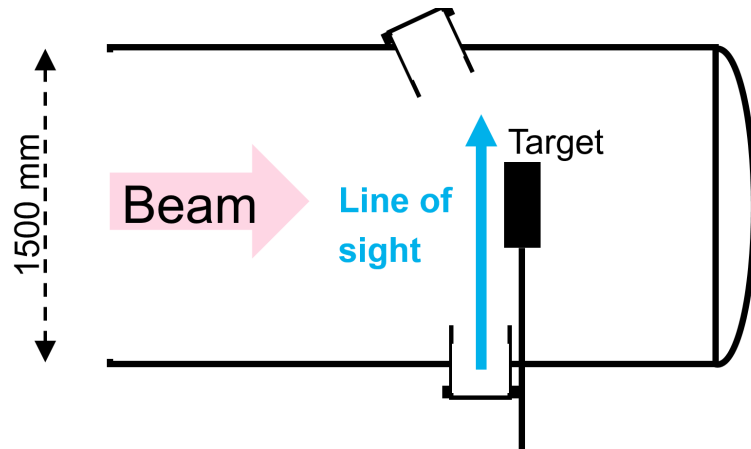
SPA5

- Evaluated performance of different W grades under repeated COMPASS-U divertor loading conditions

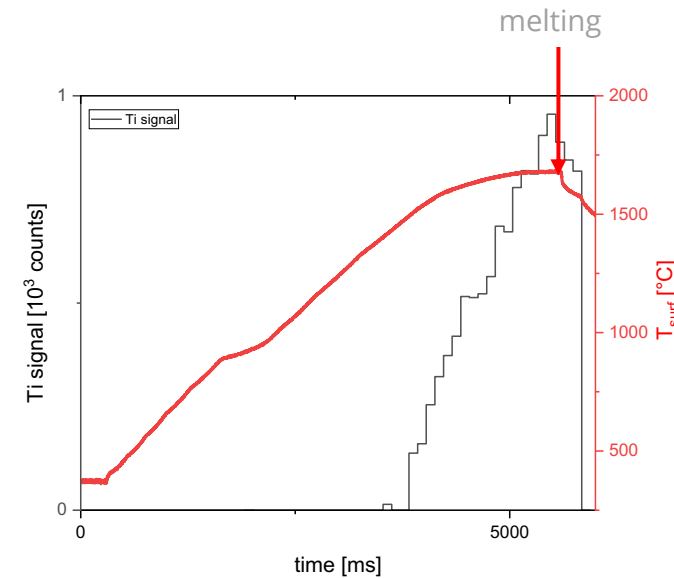


Using Optical Spectroscopy at GLADIS for the investigation of tungsten alloys

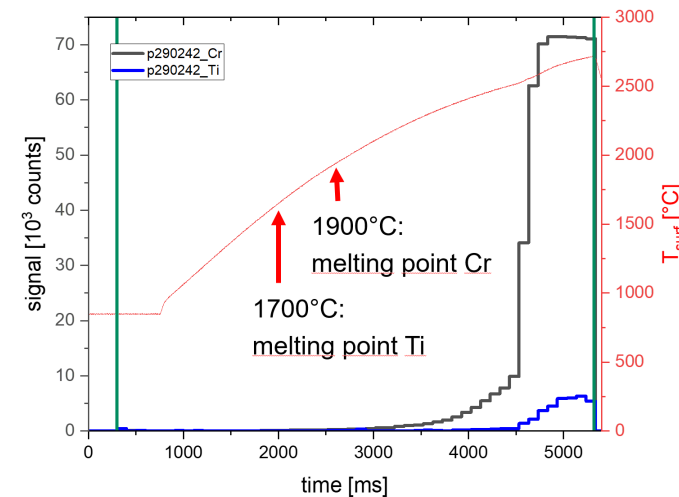
- Collect light only from atoms in front of target
- Avoid thermal radiation from target



Max-Planck-Institut für Plasmaphysik | H. Maier



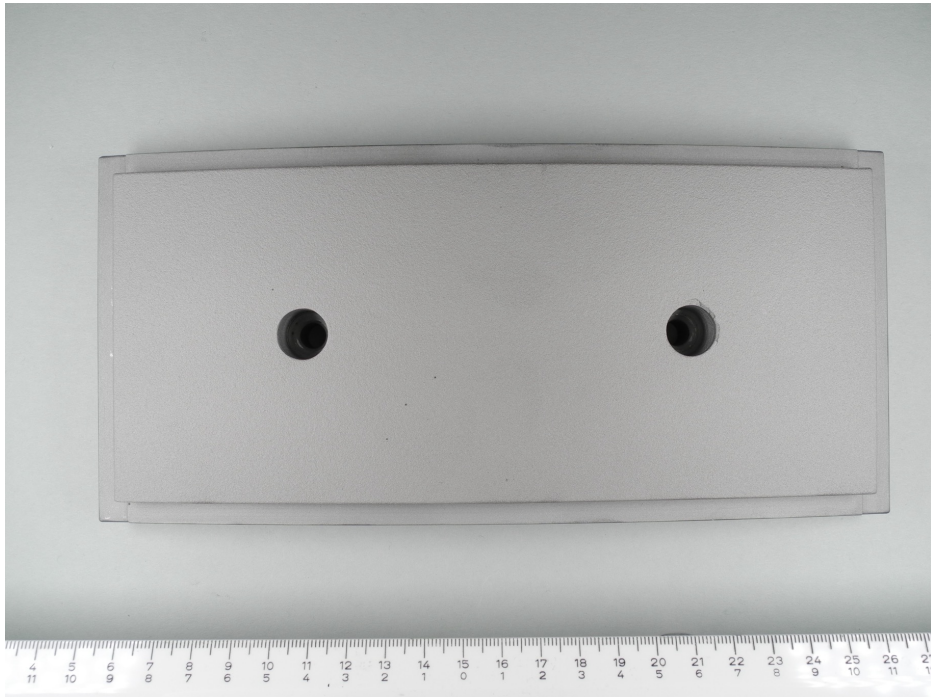
Spectroscopic signal evaluation
pure Ti plate



Cr and Ti signals from an
experimental
tungsten heavy alloy:
W-10Cr-10Ti
laboratory sample,
Stony Brook University
(J. Trelewicz)

Testing of tungsten coatings from new suppliers

- Securing and widening the range of tungsten coating suppliers for the operation of ASDEX Upgrade wrt coating method/thickness/substrate
- High Heat Flux Testing: Cyclic loading at various power densities



VPS coating on steel for central column: 2
MW/m²

Provider KIT, test successful



PVD coating on graphite for upper divertor: 10
MW/m²

Provider IPP CZ, test ongoing





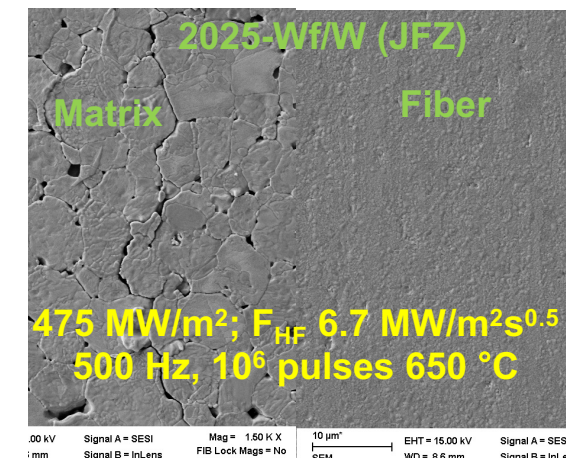
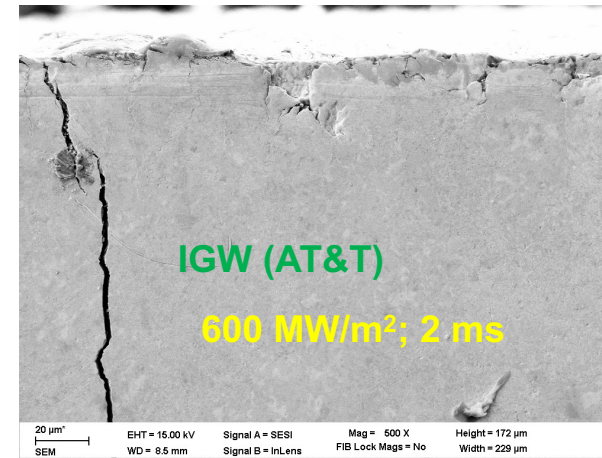
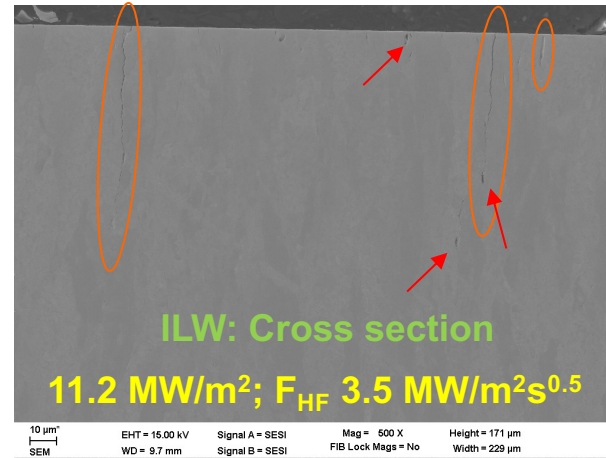
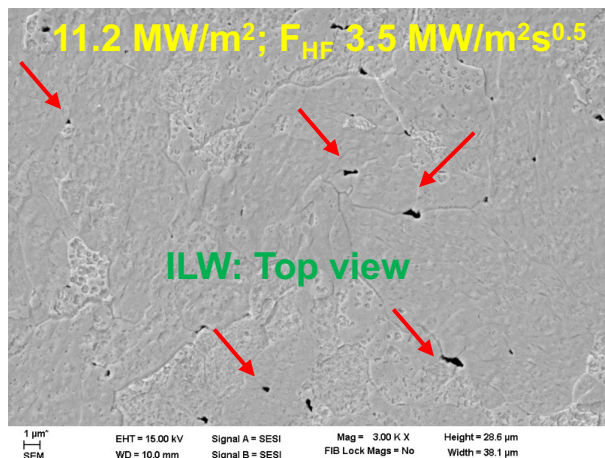
- D003: Exploitation of OLMAT as HHF facility – Testing of baseline and advanced materials – Laser & OLMAT exposures

OLMAT summary

- Successful commissioning of OLMAT device
- Successful upgrades applied:
 1. High-energy laser for disruptions ($0.1\text{-}3\text{ GW/m}^2$) and small-ELMs regimes ($<475\text{ MW/m}^2$, $50\text{-}2000\text{ Hz}$, $10^5\text{-}10^7$ pulses)
 2. Large holder: up to 75 samples exposed at a Gaussian power density distribution $1\text{-}40\text{ MW/m}^2$
- Results summary:

NBI

Laser



Multiple **voids** appear at grain borders (and a few **cracks**) when close to damage threshold (cracks found above it).

Both in ITER-like W and PoMA Wf/W

Different spot sizes (0.6-6 mm) while maintaining flat top profile of laser beam: converging lens and fiber size

Analyzing cracking threshold in disruptions and small-ELMs



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**

Publications 2020-2025 for SPA

➤ Articles:

- D. Alegre, E. Oyarzabal, D. Tafalla, M. Liniers, A. Soletto, F. L. Tabares, “Design and Testing of Advanced Liquid Metal Targets for DEMO Divertor: The OLMAT Project”, *J. Fusion Energy*, **6**, 411, (2020), DOI: 10.1007/s10894-020-00254-5.
- F L Tabarés, K.J. McCarthy, D Tafalla, [...], D. Alegre et al., “Spectroscopic Characterization of Ablation Plasmas in the OLMAT HHF Facility”, Conference paper in *49th IEEE International Conference on Plasma Science (ICOPS)*, DOI: 10.1109/ICOPS45751.2022.9813313
- F. L. Tabarés, E. Oyarzabal, D. Alegre, D. Tafalla et al, “Commissioning and First Results of the OLMAT facility”, *Fusion Engineering and Design*, **187** (2023) 113373. DOI: 10.1016/j.fusengdes.2022.113373.
- E. Oyarzábal, A. De Castro, D. Alegre, D. Tafalla, et al. "Overview of the OLMAT high heat flux facility activities testing liquid and solid metal targets for their use as divertor materials", Conference paper in 29th FEC, IAEA-CN-316/2012
- D. Alegre, D. Tafalla, A. De Castro, M. González et al., “First thermal fatigue studies of tungsten armor for DEMO and ITER at the OLMAT High Heat Flux facility”, *Nuclear Materials and Energy* **38** (2024) 101615. <https://doi.org/10.1016/j.nme.2024.101615>.
- J. Gómez Manchón, P. Fernández-Mayo, A. De Castro, D. Alegre, F. Martín, D. Tafalla, E. Oyarzábal, Beam power density and spatial distribution characterization using calorimetry and IR thermography at OLMAT, *Fusion Engineering and Design* **222** (2026) 115499. <https://doi.org/10.1016/j.fusengdes.2025.115499>

➤ Conferences:

- Talk: P. Fernandez-Mayo, D. Alegre, A. de Castro, I Rivera, D. Tafalla, E. Oyarzabal et al. “OLMAT: a HHF facility for testing liquid metal and solid PFCs under extreme thermal loads” , 2nd AM2F in Cambridge, USA. 2025
- Poster: F. L. Tabarés, E. Oyarzabal, M. Liniers, D. Alegre et al. “OLMAT. A new Facility for testing materials under DEMO-relevant Heat Loads”, 38th *Reunión Bienal de la Real Sociedad Española de Física* in Murcia (Spain). 2022
- Poster: F L Tabarés, K.J. McCarthy, D Tafalla, [...], D. Alegre et al., “Spectroscopic Characterization of Ablation Plasmas in the OLMAT HHF Facility”, *49th ICOPS*, in Seattle (USA) 2022
- Poster: F. L. Tabarés, E. Oyarzabal, M. Liniers, D. Alegre et al., “The OLMAT Facility: Commissioning and First Results”, *25th PSI*, online. 2022
- Poster: E. Oyarzábal, A. De Castro, D. Alegre, D. Tafalla, et al. "Overview of the OLMAT high heat flux facility activities testing liquid and solid metal targets for their use as divertor materials", *29th IAEA fusion conference (FEC-2023)* in London (UK) 2023
- Poster: D. Alegre, E. Oyarzábal, A. De Castro, D. Tafalla et al. “Disruption simulation at leading edges of ITER-relevant materials with the high-energy CW laser at the OLMAT High Heat Flux facility” *19th PFMC in Bonn* (Germany). 2023
- Poster: D. Alegre, D. Tafalla, A. De Castro, P. Fernández Mayo, et al. "Testing of advanced materials, solid W and liquid metals, for future nuclear reactors at OLMAT High Heat Flux facility" *33rd SOFT-2024*, Dublin, Ireland 2024
- Poster: D. Alegre, P. Fernández-Mayo, D. Tafalla, A. De Castro, et al. "Thermal fatigue study of different advanced tungsten materials at a wide Gaussian power density distribution at the OLMAT high heat flux facility", *20th PFMC in Ljubjana* (Slovenia) 2025

WP PWIE SPA 2

Report for 2025 & Overview



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	5	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)

- Recrystallization behavior of DEMO tungsten grades under high flux/fluence plasma loading with impurity seeded deuterium plasmas (DIFFER)
- Pre- and post-analysis of materials and components (MPG)

Further analysis linked to facilities and staffing in SP B

SPA2 DIFFER task and activities

Deliverable: *“Fatigue cracking and creep evolution of W samples and W-monoblocks exposed to strike point sweeping”*

Goal

- Generate data on fatigue behaviour of tungsten (monoblocks), particularly at high temperatures – understand impact of “strike point sweeping” approach for DEMO
- Evaluate influence of H and He plasma on fatigue behaviour

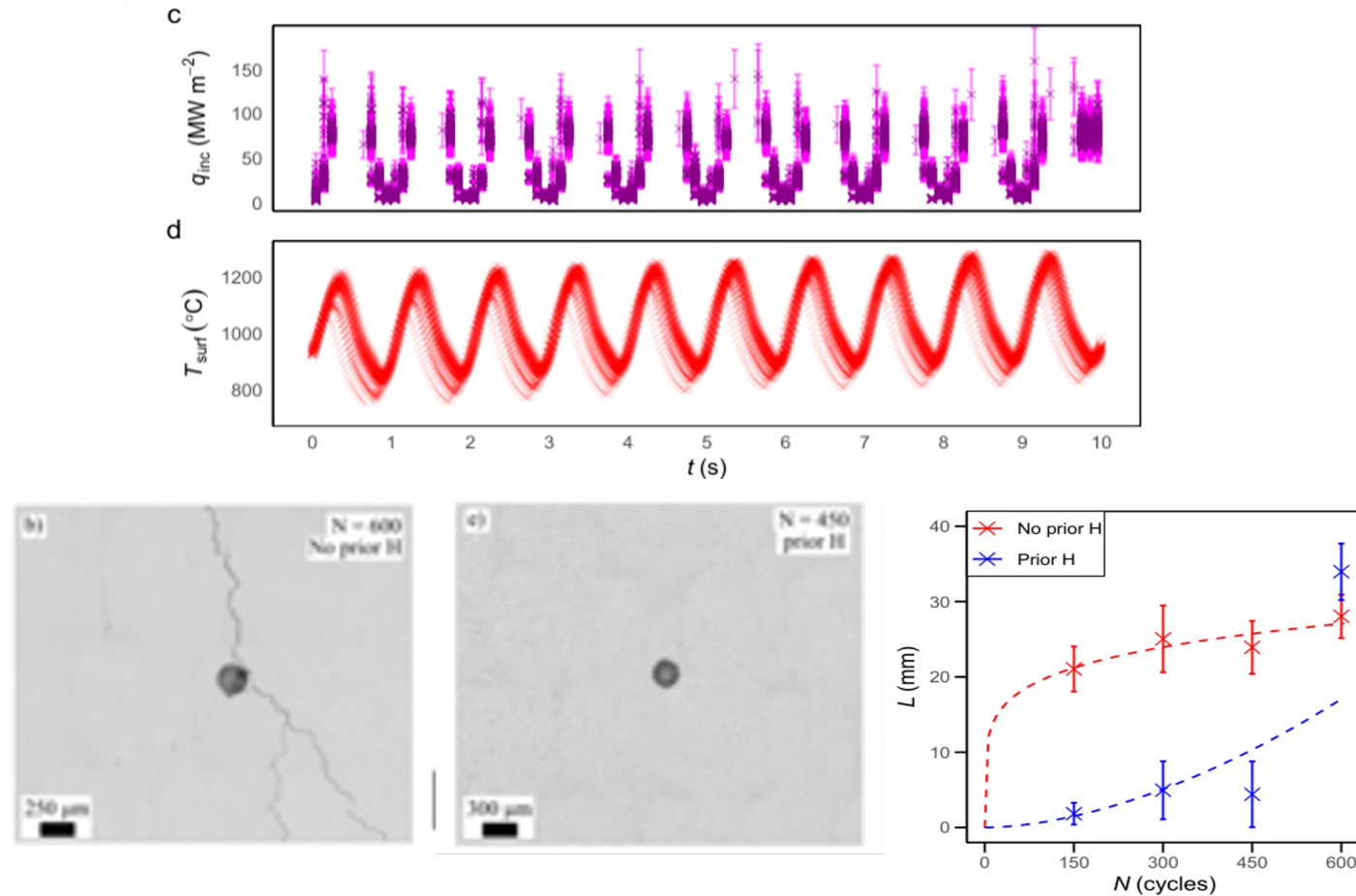
Activities 2025

- Advance fatigue testing method in Magnum-PSI
- Evaluate effect of prior H implantation on fatigue lifetime.



Overview of activity

- Fatigue testing approach by time-varying plasma loading in Magnum-PSI demonstrated
- Prior implantation of H ($2.2 \times 10^{26} \text{ m}^{-2}$ at 573K) lead to delay in intergranular cracking
- H implantation forms blisters, increasing dislocation density in near-surface region- delay in persistent slip band formation and in crack initiation





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

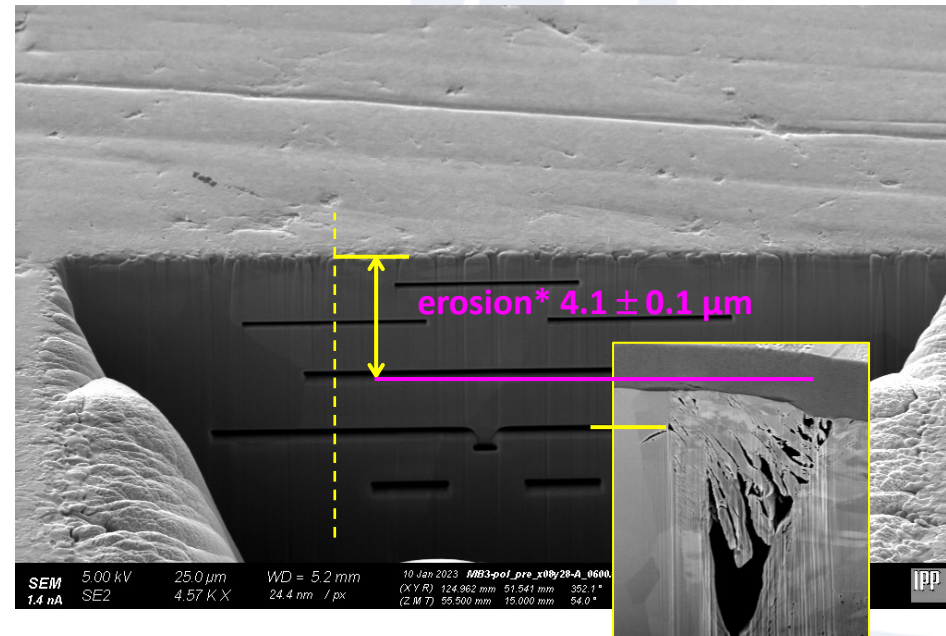
Work done in 2020 - 2025:

- ❖ Pre- and post-analysis of three W monoblock mockups
- ❖ Aim 1: Effect of high-flux high-fluence high cycle number transient loading
- ❖ Aim 2: Determination of erosion by noble gas seeding → validation of assumption for calculation of impurity impact energy for high flux/fluence
- ❖ Aim 3: Progression of study of synergy of ELM-like events to plasma exposure

Highlight: Determine erosion by μm -ruler cutting and analyzing by FIB

Paper in 2020 - 2025:

- ❖ None



WP PWIE SPA 3

Report for 2025 & Overview



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.





Advanced Materials under thermo-mechanical and plasma loads

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
J.W. Coenen	FZJ	5	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 (S. Elgeti)
Total		29	

Device	Beneficiary	Days	Related Deliverable
PSI-2	FZJ	8	D001
JUDITH	FZJ	10	D001
GLADIS	MPG	5	D002, D003, D006
Accelerator	MPG	12	D002, D003, D006
QSPA	KIPT	10	D004
MAGNUM-PSI	DIFFER	5	D005
UPP	DIFFER	5	D005

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)

- Plasma qualification of new materials (WPMAT) and components (WPDIV) for DEMO: Thermal shock and plasma synergistic loading of advanced material including exposures in Magnum-PSI (KIPT, DIFFER, FZJ)
- Exposure of advanced materials e.g. W_f/W (WPPRD), SMART alloys (WPMAT), additively manufactured components (WPDIV) and others to heat loads and/or plasma loads for assessment of their PWI properties and exploration of limits of their application (FZJ, MPG)
- Study of basic thermo-mechanical properties for advanced materials for divertor applications including reference material properties for comparison with neutron-irradiated sample in future (LPP-ERM/KMS, MPG)
 - Establish experimental techniques
 - Mechanical testing of W-yarns up to very high temperatures, subsequent microstructural characterization (link to neutron irradiation of W yarns & subsequent mechanical testing) (SCK-CEN as part of RU LPP-ERM/KMS)
 - Establish experimental basis by e.g. self or proton damage (MPG, FZJ)
 - Effect of fusion environment on the mechanical properties of W wire (MPG/SCKCEN)
- Exposure in plasma devices to study the interplay of recovery, recrystallization, plasma and ELM-like loading on surface cracking and fatigue lifetime (FZJ, KIPT, DIFFER)

Post-mortem analysis to characterize the induced surface and microstructure modifications as well as changes of the materials properties due to e.g. recrystallization behavior and/or surface morphology changes (FZJ, MPG)



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

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



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

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

Summary 2025

- Analysis of surface modification of fusion-relevant materials caused by repetitive transient plasma pulses has been performed for samples exposed to QSPA loads near the W cracking threshold.
- Exposition of LPPS-W samples did not cause any coating delamination. After QSPA loads near the W evaporation threshold, networks of large and intergranular cracks were observed, with characteristic cell sizes of approx. 0.5 mm and 0.05 mm, and crack widths of up to 5 μm . The destroyed crack edges could be a potential source of ejected particles. The damage observed in the LPPS-W coatings is similar to that in bulk W material.
- Irradiation of EBM-W samples was also performed. Network of large cracks was observed, with a cell size of about 0.4 mm and crack widths of up to 1 μm . The damage of EBM sample is similar to that in bulk W material.
- *Next steps: FIB cuts and metallographic cross-sections of samples irradiated in 2024 are currently in progress in collaboration with **M. Wirtz (FZJ)***

SPA3 DIFFER task and activities

Deliverable: *“Effect of ELM loading on microstructure evolution of W coated RAFM steels”*

Goal

- Goal to evaluate changes to microstructure and properties of EUROfer under disruption loading to find out if disruptions will affect first wall structural materials

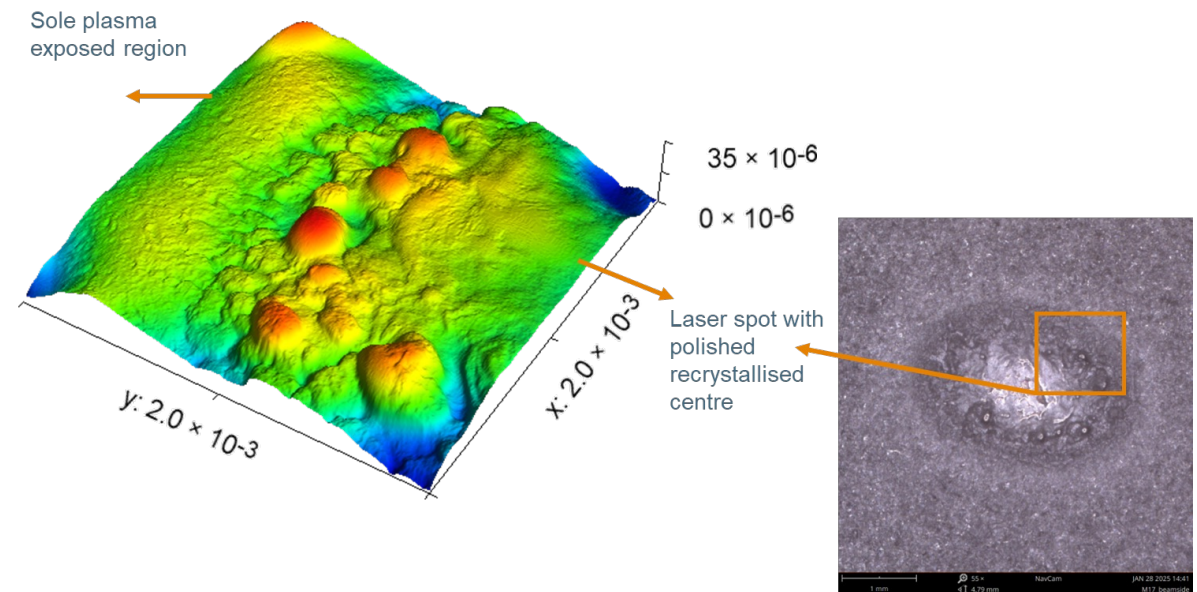
Activities 2025

- Use transient loading by laser plus heating with plasma to simulate a disruption load on EUROfer coated with W



Overview of activity

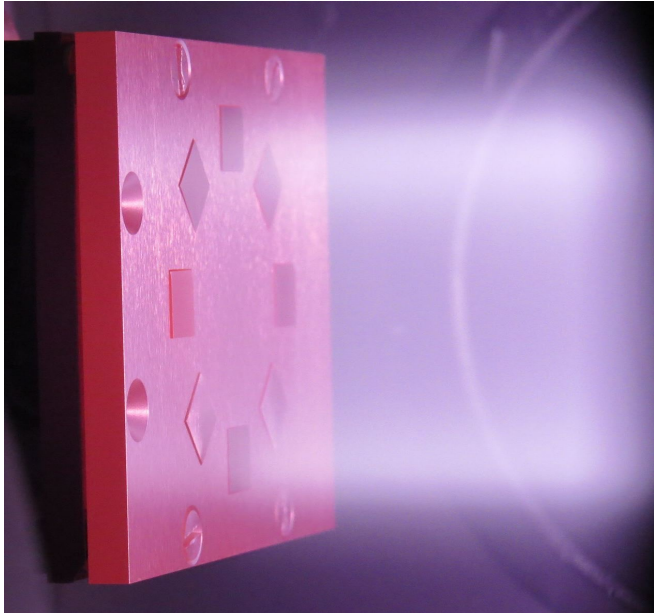
- EUROfer samples coated with 0.5-1 mm W
- Base temperature of 500 °C generated by H plasma
- $\Delta T = 1100\text{--}2500$ °C from 3-4 ms laser pulse, leading to max 950 °C at EUROfer surface
- Laser spot shows strong recrystallization and morphology changes
- Analysis of cross sections ongoing



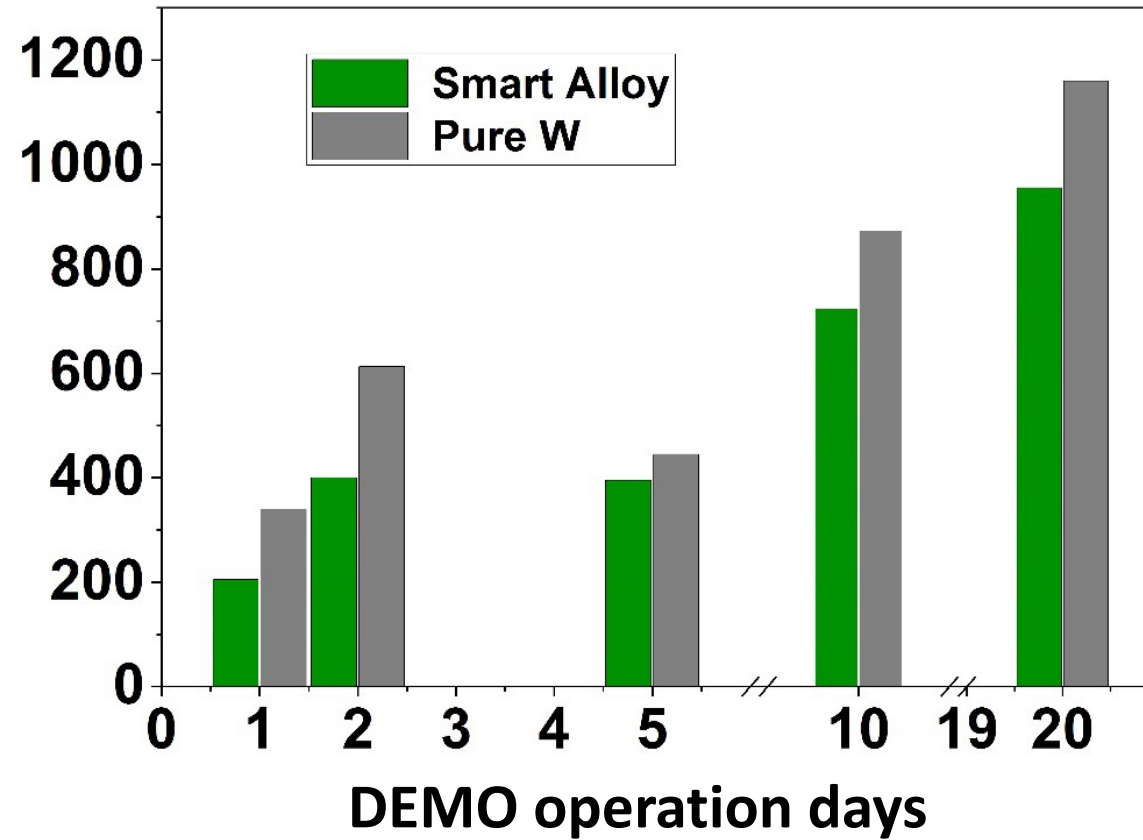


Highlight result Plasma performance: sputtering resistance^{1,2}

Steady-state
deuterium plasma



Mass loss, microgram



Surface recession
W vs. SMART
210 nm : 220 nm
260 nm : 260 nm

Higher mass loss for pure W

Identical sputtering of W and SMART

¹J. Schmitz Ph.D. Thesis, FZJ, Univ. of Bochum and Univ. of Gent, 2020

²A. Litnovsky et al., Metals 11 (2021) 1255



Top 5

1. Litnovsky, A., Duran, I., Coenen, J. W., Gasparyan, Y., Gilbert, M. R., Hollmann, E., Linsmeier, C., Nogami, S., Skinner, C. H., & Zinkle, S. (2021). Fusion—Reactor Materials. In E. Greenspan (Ed.), *Encyclopedia of Nuclear Energy* (Vol. 3, pp. 594–619). Elsevier Inc. <https://doi.org/10.1016/b978-0-12-819725-7.00146-x>
2. Litnovsky, A., Klein, F., Tan, X., Ertmer, J., Coenen, J. W., Linsmeier, C., Gonzalez-julian, J., Bram, M., Povstugar, I., Morgan, T., Gasparyan, Y. M., Suchkov, A., Bachurina, D., Nguyen-manh, D., Gilbert, M., Sobieraj, D., Wr, J. S., Tejado, E., Matejicek, J., ... Reuban, A. (2021). Advanced Self-Passivating Alloys for an Application under Extreme Conditions. *Metals*, 11, 1255. <https://doi.org/10.3390/met11081255>
3. Schmitz, J., Litnovsky, A., Klein, F., Lannoye, K. De, Kreter, A., Rasinski, M., Breuer, U., Gonzalez-Julian, J., Bram, M., Coenen, J. W., & Linsmeier, C. (2020). On the plasma suitability of WCrY smart alloys-the effect of mixed D+Ar/He plasmas. *Physica Scripta*, T171, 014002. <https://doi.org/10.1088/1402-4896/ab367c>
4. Litnovsky, A., Schmitz, J., Klein, F., Lannoye, K. De, Weckauf, S., Kreter, A., Rasinski, M., Coenen, J. W., Linsmeier, C., Gonzalez-julian, J., Bram, M., Povstugar, I., Morgan, T., Nguyen-manh, D., Gilbert, M., Sobieraj, D., & Wróbel, J. S. (2020). Smart Tungsten-based Alloys for a First Wall of DEMO. *Fusion Engineering and Design*, 159, 111742. <https://doi.org/10.1016/j.fusengdes.2020.111742>
5. Chen, J., Tejado, E., Rasiński, M., Litnovsky, A., Nguyen-Manh, D., Prestat, E., Whitfield, T., Pastor, J. Y., Bram, M., Coenen, J. W., Linsmeier, C., & Gonzalez-Julian, J. (2024). Effect of Yttrium and Ytria Addition in Self-Passivating WCr SMART Material for First-Wall Application in a Fusion Power Plant. *Metals*, 14(9). <https://doi.org/10.3390/met14091092>



Overall list (continuation)

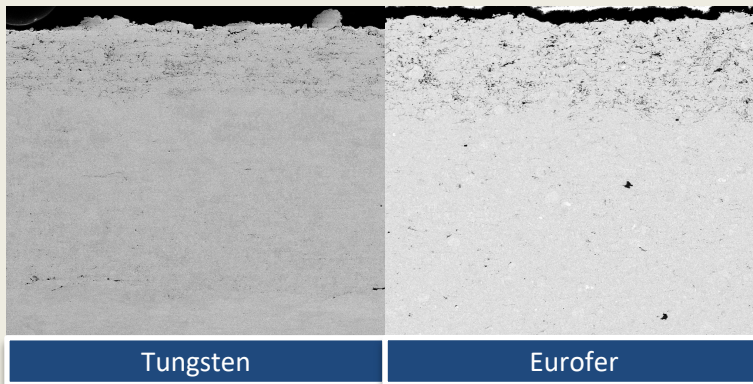
6. Bachurina, D., Tan, X., Klein, F., Suchkov, A. N., Litnovsky, A., Schmitz, J., Gonzalez-Julian, J., Coenen, J. W. J. W., Wu, Y. C. Y.-C., Linsmeier, C., Bram, M., Coenen, J. W. J. W., Wu, Y. C. Y.-C., & Linsmeier, C. (2021). Self-passivating smart tungsten alloys for DEMO: a progress in joining and upscale for a first wall mockup. *Tungsten*. <https://doi.org/10.1007/s42864-021-00079-5>
7. Bram, M., Laptev, A. M., Mishra, T. P., Nur, K., Kindelmann, M., Ihrig, M., Pereira da Silva, J. G., Steinert, R., Buchkremer, H. P., Litnovsky, A., Klein, F., Gonzalez-Julian, J., & Guillon, O. (2020). Application of Electric Current-Assisted Sintering Techniques for the Processing of Advanced Materials. *Advanced Engineering Materials*, 22, 2000051. <https://doi.org/10.1002/adem.202000051>
8. Chen, J., Litnovsky, A., Tan, X., & Linsmeier, C. (2022). Studies of self-passivating SMART alloys with reduced brittleness. *Proceedings of the 32nd Symposium of Fusion Technology (SOFT 2022)*.
9. Chen, J., Tejado, E., Litnovsky, A., Nguyen-Manh, D., Prestat, E., Whitfield, T., Ygnacio Pastor, J., Bram, M., Willem Coenen, J., Linsmeier, C., & Gonzalez-Julian, J. (2024). Influence of phase decomposition on mechanical properties and oxidation resistance of WCrY SMART material. *Nuclear Materials and Energy*, 41. <https://doi.org/10.1016/j.nme.2024.101762>
10. Gilbert, M. R., Arakawa, K., Bergstrom, Z., Caturla, M. J., Dudarev, S. L., Gao, F., Goryaeva, A. M., Hu, S. Y., Hu, X., Kurtz, R. J., Litnovsky, A., Marian, J., Marinica, M.-C., Martinez, E., Marquis, E. A., Mason, D. R., Nguyen, B. N., Olsson, P., Osetskiy, Y., ... Zinkle, S. J. (2021). Perspectives on multiscale modelling and experiments to accelerate materials development for fusion. *Journal of Nuclear Materials*, 554, 153113. <https://doi.org/10.1016/j.jnucmat.2021.153113>
11. Klein, F., Gilbert, M. R., Litnovsky, A., Gonzalez-Julian, J., Weckauf, S., Wegener, T., Schmitz, J., Linsmeier, C., Bram, M., & Coenen, J. W. (2020). Tungsten–chromium–yttrium alloys as first wall armor material: Yttrium concentration, oxygen content and transmutation elements. *Fusion Engineering and Design*, 158, 111667. <https://doi.org/10.1016/j.fusengdes.2020.111667>
12. Klein, F., Litnovsky, A., Tan, X., Gonzalez-Julian, J., Rasinski, M., Linsmeier, C., Bram, M., & Coenen, J. W. (2021). Smart alloys as armor material for DEMO: Overview of properties and joining to structural materials. *Fusion Engineering and Design*, 166, 112272. <https://doi.org/10.1016/j.fusengdes.2021.112272>
13. Litnovsky, A., Chen, J., Bram, M., Gonzalez-Julian, J., Zoz, H., Benz, H. U., Huber, J., Pintsuk, G., Coenen, J. W., & Linsmeier, C. (2024). SMART materials for DEMO: towards industrial production. *Accepted for Publication in Fusion Engineering and Design*.
14. Sobieraj, D., Wróbel, J. S., Gilbert, M. R., Litnovsky, A., Klein, F., Kurzydłowski, K. J., & Nguyen-Manh, D. (2021). Composition Stability and Cr-Rich Phase Formation in W-Cr-Y and W-Cr-Ti Smart Alloys. *Metals*, 11, 743. <https://doi.org/10.3390/met11050743>
15. Wang, W. J. J., Tan, X. Y., Liu, J. Q. Q., Chen, X., Wu, M., Luo, L. M. M., Zhu, X. Y. Y., Chen, H. Y. Y., Mao, Y. R. R., Litnovsky, A., Coenen, J. W. W., Linsmeier, Ch., & Wu, Y. C. C. (2020). The influence of heating rate on W-Cr-Zr alloy densification process and microstructure evolution during spark plasma sintering. *Powder Technology*, 370, 9–18. <https://doi.org/10.1016/j.powtec.2020.05.020>
16. Wang, W. J., Tan, X. Y., Yang, S. P., Luo, L. M., Zhu, X. Y., Mao, Y. R., Litnovsky, A., Coenen, J. W., Linsmeier, Ch., & Wu, Y. C. (2021). On grain growth and phase precipitation behaviors during W-Cr-Zr alloy densification using field-assisted sintering technology. *International Journal of Refractory Metals and Hard Materials*, 98, 105552. <https://doi.org/10.1016/j.ijrmhm.2021.105552>
17. Wang, W. J., Tan, X. Y., Yang, S. P., Mao, Y. R., Luo, L. M., Zhu, X. Y., Litnovsky, A., Coenen, J. W., Linsmeier, Ch., & Wu, Y. C. (2022). The influence of powder characteristics on densification behavior and microstructure evolution of W-Cr-Zr alloy consolidated by field-assisted sintering technology. *International Journal of Refractory Metals and Hard Materials*, 108(March), 105939. <https://doi.org/10.1016/j.ijrmhm.2022.105939>
18. Yang, S. P., Wang, W. J., Tan, X. Y., Zhu, H. J., Litnovsky, A., Klein, F., Mao, Y. R., Coenen, W., Linsmeier, C., Luo, L. M., Li, P., & Wu, Y. C. (2021). Influence of the applied pressure on the microstructure evolution of W-Cr-Y-Zr alloys during the FAST process. *Fusion Engineering and Design*, 169(March 2021), 112474. <https://doi.org/10.1016/j.fusengdes.2021.112474>

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

EUROFusion Engineering Grant 2023

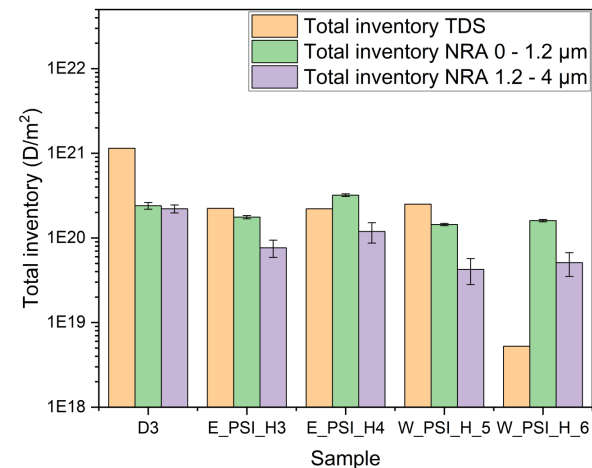
Coating campaign

- The coating campaign has been finalized.
- High-quality coatings were produced on tungsten substrate and Eurofer97:
 - $\geq 500 \mu\text{m}$ thickness
 - Porosity $\leq 3\%$



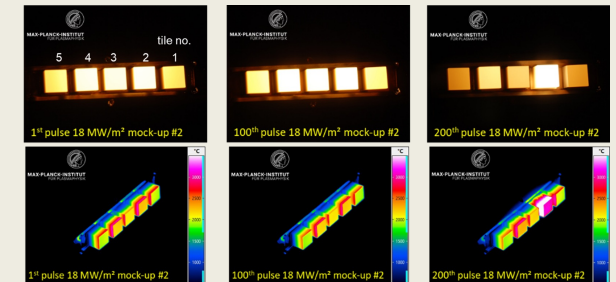
Testing for fusion application

- Plasma exposure experiments in PSI-2
 - Decreased deuterium retention compared to reference bulk tungsten
 - Slightly increased sputtering yield



Ongoing analysis

- Plasma exposure experiments in Magnum-PSI
 - Higher total ion fluences
 - High heat flux tests in GLADIS
 - 200 Pulses
 - Up to 18 MW/m^2
 - $T_{\text{Surface}} > 2250 \text{ }^\circ\text{C}$ (W-W)
 - $T_{\text{Surface}} > 550 \text{ }^\circ\text{C}$ (W-Eurofer)
- No delamination
→ No cracking





Publications

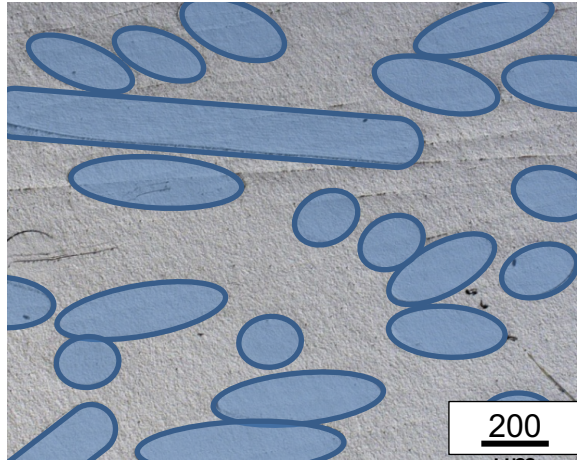
- Schmidtman, G., Sohn, Y.J., Litnovsky, A., Rasinski, M., Vaßen, R., Coenen, J.W., Brezinsek, S., Linsmeier, Ch., Guillon, O., Mauer, G. - Optimizing Plasma Spraying Process Parameters for Tungsten Coatings Used in Fusion Reactors. *J Therm Spray Tech* **34**, 2129–2144 (2025). <https://doi.org/10.1007/s11666-025-02034-z>
- G. Schmidtman, A. Litnovsky, A. Kreter, M. Rasinski, S. Möller, A. Houben, J. W., Coenen, R. Vaßen, S. Brezinsek, Ch. Linsmeier, O. Guillon, and G. Mauer. Deuterium retention and erosion resistance of low-pressure plasma sprayed tungsten coatings. *J Nucl. Mater.* **691**, 619:156267, (2026).



Tungsten Fibre Reinforced Tungsten

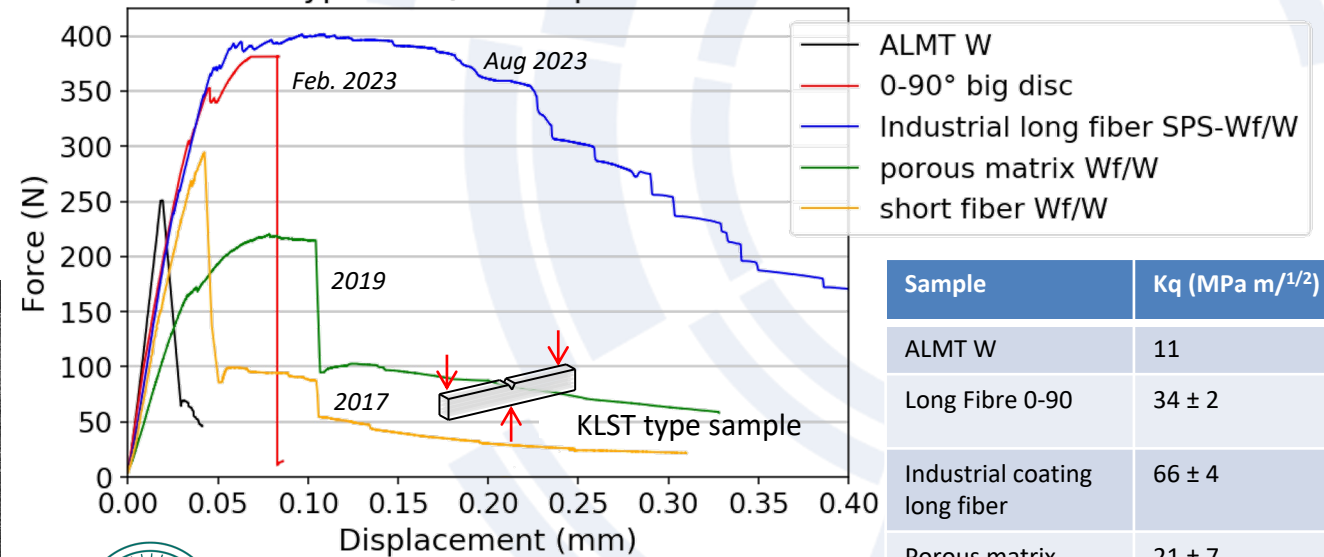
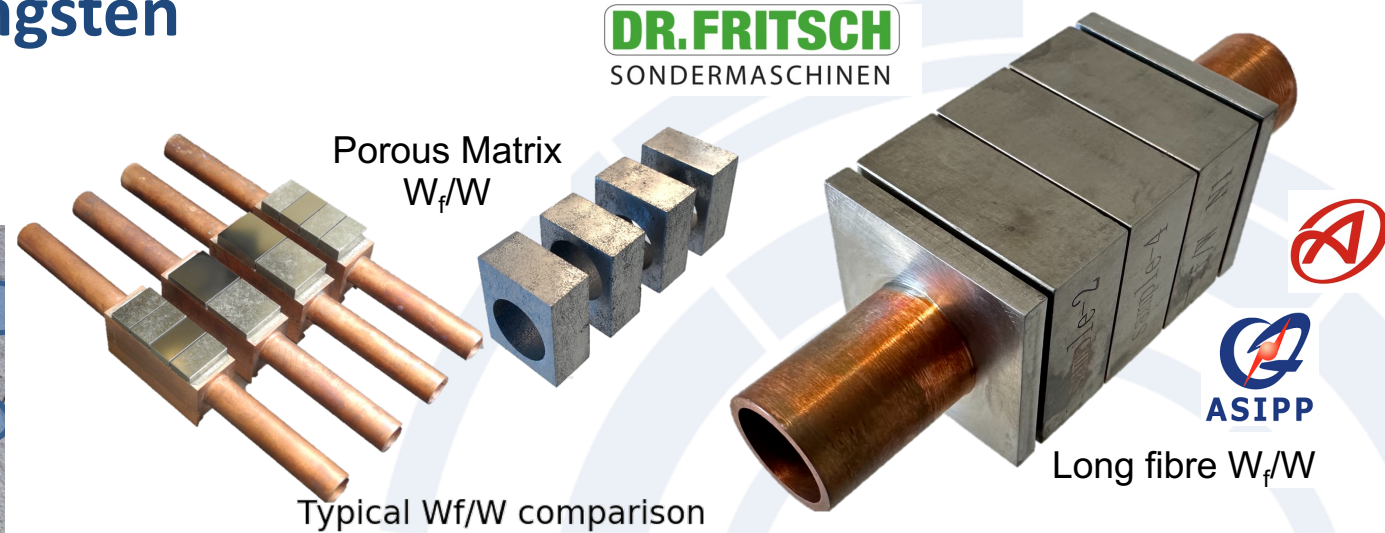
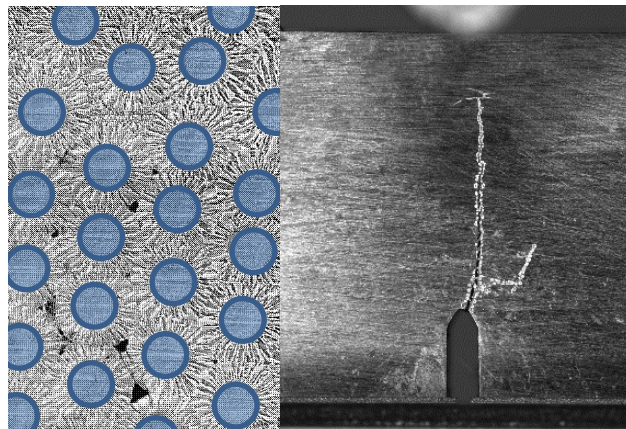
PM-W_f/W

Short fibres, isotropic orientation, produced by powder metallurgy



CVD-W_f/W

Long fibre reinforced, continuous & directional, produced by chemical vapour deposition

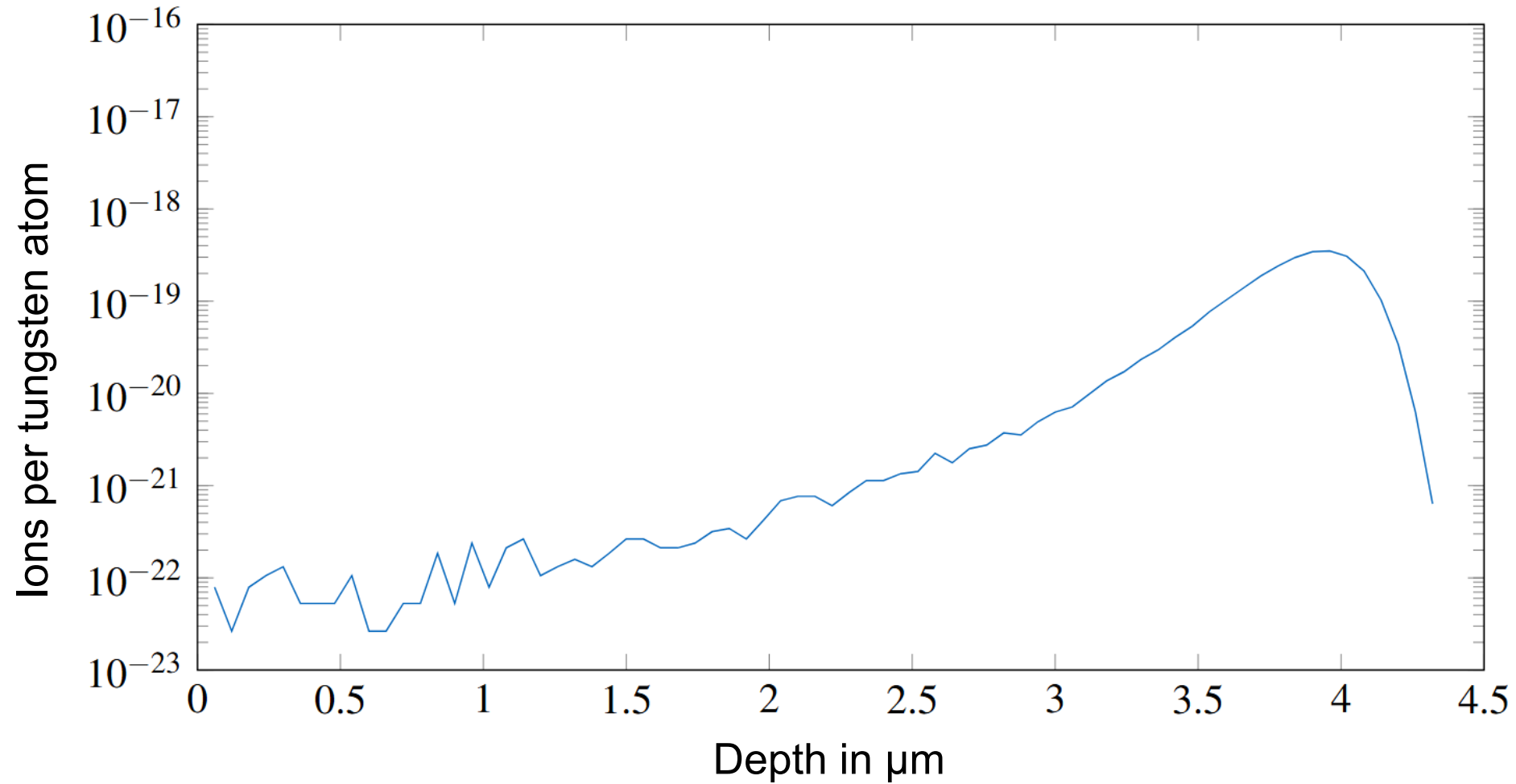


Test up to 20MW/m²

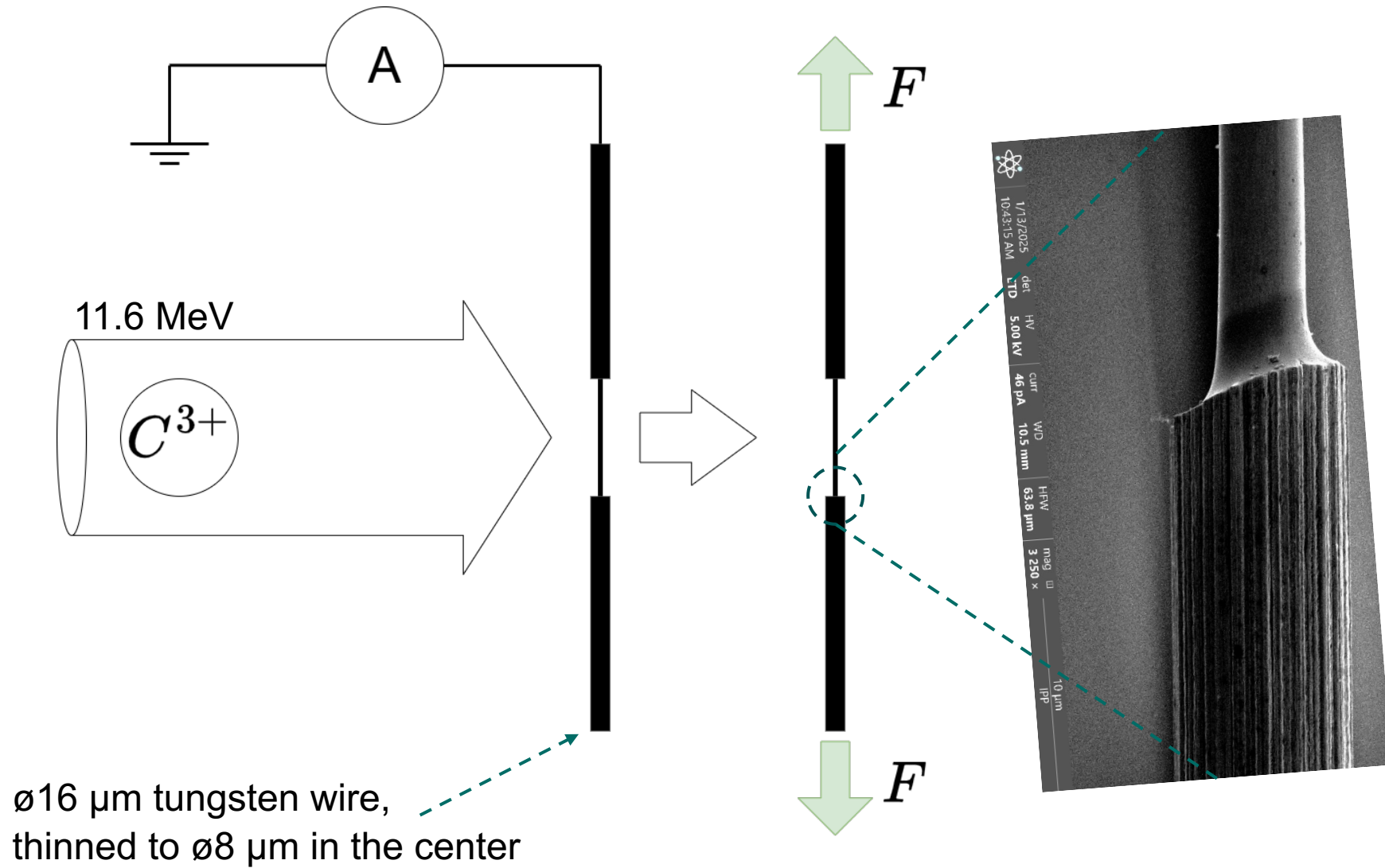


- Chen, C., Chen, Y., Han, X., Li, K., Wang, S., Zhang, Y., Mao, Y., Coenen, J.W., Wang, J., Luo, L., 2024. Microstructure and failure mechanism of Y2O3 coating on the W fiber in Wf/W composites during field assisted sintering. *Journal of Materials Research and Technology* 30, 8661–8670. <https://doi.org/10.1016/j.jmrt.2024.05.237>
- Chen, C., Chen, Y., Li, K., Wang, S., Zhang, Y., Mao, Y., Coenen, J.W., Wang, J., Luo, L., Wu, Y., 2024. Interfacial microstructure and mechanical property of the discontinuous short tungsten fiber-reinforced tungsten matrix composites. *Materials Characterization* 215. <https://doi.org/10.1016/j.matchar.2024.114214>
- Chen, Y., Chen, C., Wang, J., Wang, S., Gong, H., Mao, Y., Coenen, J.W., Luo, L., Wu, Y., 2025. The effect of Re on the microstructure and mechanical properties of tungsten fiber-reinforced tungsten composites. *Journal of Alloys and Compounds* 1042. <https://doi.org/10.1016/j.jallcom.2025.184139>
- Coenen, J.W., 2020. Fusion Materials Development at Forschungszentrum Jülich. *Advanced Engineering Materials* 22. <https://doi.org/10.1002/adem.201901376>
- Coenen, J.W., Huber, P., Lau, A., Raumann, L., Schwalenberg, D., Mao, Y., Riesch, J., Terra, A., Linsmeier, C., Neu, R., 2021. Tungsten fiber reinforced tungsten (Wf/W) using yarn based textile preforms. *Physica Scripta* 96. <https://doi.org/10.1088/1402-4896/ac37cf>
- Coenen, J.W., Lee, V.Y.S., Mao, Y., Morrison, A.P.C., Dorow-Gerspach, D., Tan, X., Terra, A., Wu, Y., Linsmeier, C., 2023. Evolution of Tungsten Fiber-Reinforced Tungsten-Remarks on Production and Joining. *Advanced Engineering Materials* 25. <https://doi.org/10.1002/adem.202300569>
- Crea, F., Cacciotti, E., de Luca, R., Lorusso, P., Roccella, S., Satriano, A., Verdini, L., Coenen, J.W., Mao, Y., Riesch, J., Wirtz, M., 2025. Fabrication of DEMO divertor target mock-up by HRP technology with tungsten fiber reinforced tungsten as armour material. *Fusion Engineering and Design* 215. <https://doi.org/10.1016/j.fusengdes.2025.115025>
- Gietl, H.A., Olbrich, S., Riesch, J., Holzner, G., Höschen, T., Coenen, J.W., Neu, R., 2020. Estimation of the fracture toughness of tungsten fibre-reinforced tungsten composites. *Engineering Fracture Mechanics* 232. <https://doi.org/10.1016/j.engfracmech.2020.107011>
- Gietl, H.A., Riesch, J., Coenen, J.W., Höschen, T., Neu, R., 2019. Production of tungsten-fibre reinforced tungsten composites by a novel continuous chemical vapour deposition process. *Fusion Engineering and Design* 146, 1426–1430. <https://doi.org/10.1016/j.fusengdes.2019.02.097>
- Gietl, H.A., Riesch, J., Höschen, T., Rieth, M., Coenen, J.W., Neu, R., 2022. Charpy impact tests of tungsten fiber-reinforced composite from –150 °C to 1000 °C. *Materials Letters* 311. <https://doi.org/10.1016/j.matlet.2021.131526>
- Gietl, H.A., Riesch, J., Zielinski, M., Höschen, T., Coenen, J.W., Schönen, S., Neu, R., 2021. Interlayer properties of tungsten fibre-reinforced composites and their determination by different methods. *Nuclear Materials and Energy* 28. <https://doi.org/10.1016/j.nme.2021.101060>
- Kärcher, A., Riesch, J., Almanstötter, P., Manhard, A., Balden, M., Coenen, J.W., Hunger, K., Maier, H., Raumann, L., Schwalenberg, D., Neu, R., 2021. Deuterium retention in tungsten fiber-reinforced tungsten composites. *Nuclear Materials and Energy* 27. <https://doi.org/10.1016/j.nme.2021.100972>
- Lau, A., Coenen, J.W., Schwalenberg, D., Mao, Y., Höschen, T., Riesch, J., Raumann, L., Treitz, M., Gietl, H.A., Terra, A., Göhls, B., Linsmeier, C., Theis-Bröhl, K., Gonzalez-Julian, J.J., 2023. Bulk Tungsten Fiber-Reinforced Tungsten (Wf/W) Composites Using Yarn-Based Textile Preforms. *Journal of Nuclear Engineering* 4, 375–390. <https://doi.org/10.3390/jne4020027>
- Lau, A., Mao, Y., Shu, R., Coenen, J.W., Poll, M., Linsmeier, C., Gonzalez-Julian, J.J., 2024. Combining Chemical Vapor Deposition and Spark Plasma Sintering for the Production of Tungsten Fiber-Reinforced Tungsten (Hybrid – Wf/W). *Advanced Engineering Materials* 26. <https://doi.org/10.1002/adem.202301929>
- Mao, Y., Coenen, J.W., Liu, C., Terra, A., Tan, X., Riesch, J., Höschen, T., Wu, Y., Broeckmann, C., Linsmeier, C., 2022. Powder Metallurgy Produced Aligned Long Tungsten Fiber Reinforced Tungsten Composites. *Journal of Nuclear Engineering* 3, 446–452. <https://doi.org/10.3390/jne3040030>
- Mao, Y., Coenen, J.W., Riesch, J., Sistla, S.K., Almanstötter, 2020. Fiber Volume Fraction Influence on Randomly Distributed Short Fiber Tungsten Fiber-Reinforced Tungsten Composites. *Advanced Engineering Materials* 22. <https://doi.org/10.1002/adem.201901242>
- Mao, Y., Coenen, J.W., Terra, A., Gao, L., Kreter, A., Wirtz, M., Liu, C., Chen, C., Riesch, J., Wu, Y., Broeckmann, C., Linsmeier, C., 2022. Demonstrating tungsten fiber-reinforced porous-matrix tungsten composites for future fusion application. *Nuclear Fusion* 62. <https://doi.org/10.1088/1741-4326/ac8c55>
- Mao, Y., Duggal, A., Dittes, A., Lampke, T., Coenen, J.W., Linsmeier, C., 2023. Electrophoretic deposition prepared yttria as interface of tungsten fiber reinforced tungsten composites. *Nuclear Materials and Energy* 36. <https://doi.org/10.1016/j.nme.2023.101487>
- Palaniyappan, S., Trautmann, M., Mao, Y., Riesch, J., Gowda, P., Rudolph, N., Coenen, J.W., Neu, R., Wagner, G., 2021. Yttria-coated tungsten fibers for use in tungsten fiber-reinforced composites: A comparative study on pvd vs. cvd routes. *Coatings* 11. <https://doi.org/10.3390/coatings11091128>
- Raumann, L., Coenen, J.W., Riesch, J., Mao, Y., Gietl, H.A., Höschen, T., Linsmeier, C., Guillon, O., 2020. Modeling and validation of chemical vapor deposition of tungsten for tungsten fiber reinforced tungsten composites. *Surface and Coatings Technology* 381. <https://doi.org/10.1016/j.surfcoat.2019.06.065>
- Raumann, L., Coenen, J.W., Riesch, J., Mao, Y., Schwalenberg, D., Wegener, T., Gietl, H.A., Höschen, T., Linsmeier, C., Guillon, O., 2021. Modeling and experimental validation of a Wf/W-fabrication by chemical vapor deposition and infiltration. *Nuclear Materials and Energy* 28. <https://doi.org/10.1016/j.nme.2021.101048>
- Riesch, J., v. Müller, A.V., Mao, Y., Coenen, J.W., Böswirth, B., Elgeti, S., Fuhr, M., Greuner, H., Höschen, T., Hunger, K., Junghanns, P., Lau, A., Roccella, S., Vanlitsenburgh, L., You, J.-h., Linsmeier, C., Neu, R., 2024. Progress in the development of industrial scale tungsten fibre-reinforced composite materials. *Nuclear Materials and Energy* 38. <https://doi.org/10.1016/j.nme.2024.101591>
- Schwalenberg, D., Coenen, J.W., Riesch, J., Hoeschen, T., Mao, Y., Lau, A., Gietl, H.A., Raumann, L., Huber, P., Linsmeier, C., Neu, R., 2022. Large-Scale Tungsten Fibre-Reinforced Tungsten and Its Mechanical Properties. *Journal of Nuclear Engineering* 3, 306–320. <https://doi.org/10.3390/jne3040018>
- Shu, R., Mao, Y., Coenen, J.W., Terra, A., Liu, C., Schönen, S., Höschen, T., Riesch, J., Linsmeier, C., Broeckmann, C., 2023. Microstructure and mechanical properties of Wf/W composites influenced by Y2O3 coating. *International Journal of Refractory Metals and Hard Materials* 115. <https://doi.org/10.1016/j.ijrmhm.2023.106322>
- Shu, R., Mao, Y., Coenen, J.W., Terra, A., Liu, C., Schönen, S., Riesch, J., Linsmeier, C., Broeckmann, C., 2022. Interface and mechanical properties of the single-layer long fiber reinforced Wf/W composites fabricated via field assisted sintering technology. *Materials Science and Engineering: A* 857. <https://doi.org/10.1016/j.msea.2022.144098>
- Shu, R., Mao, Y., Coenen, J.W., Terra, A., Schönen, S., Riesch, J., Linsmeier, C., Broeckmann, C., 2025. Fabrication and fracture behaviors of the continuous brittle fiber reinforced tungsten composites fabricated via field-assisted sintering technology. *Tungsten* 7, 172–182. <https://doi.org/10.1007/s42864-024-00291-z>
- Shu, R., Mao, Y., Martinez-Pechero, A., Coenen, J.W., Terra, A., Schönen, S., Riesch, J., Linsmeier, C., Broeckmann, C., 2024. Study on the fracture behavior and toughening mechanisms of continuous fiber reinforced Wf/Y2O3/W composites fabricated via powder metallurgy. *Composites Part B: Engineering* 287. <https://doi.org/10.1016/j.compositesb.2024.111845>

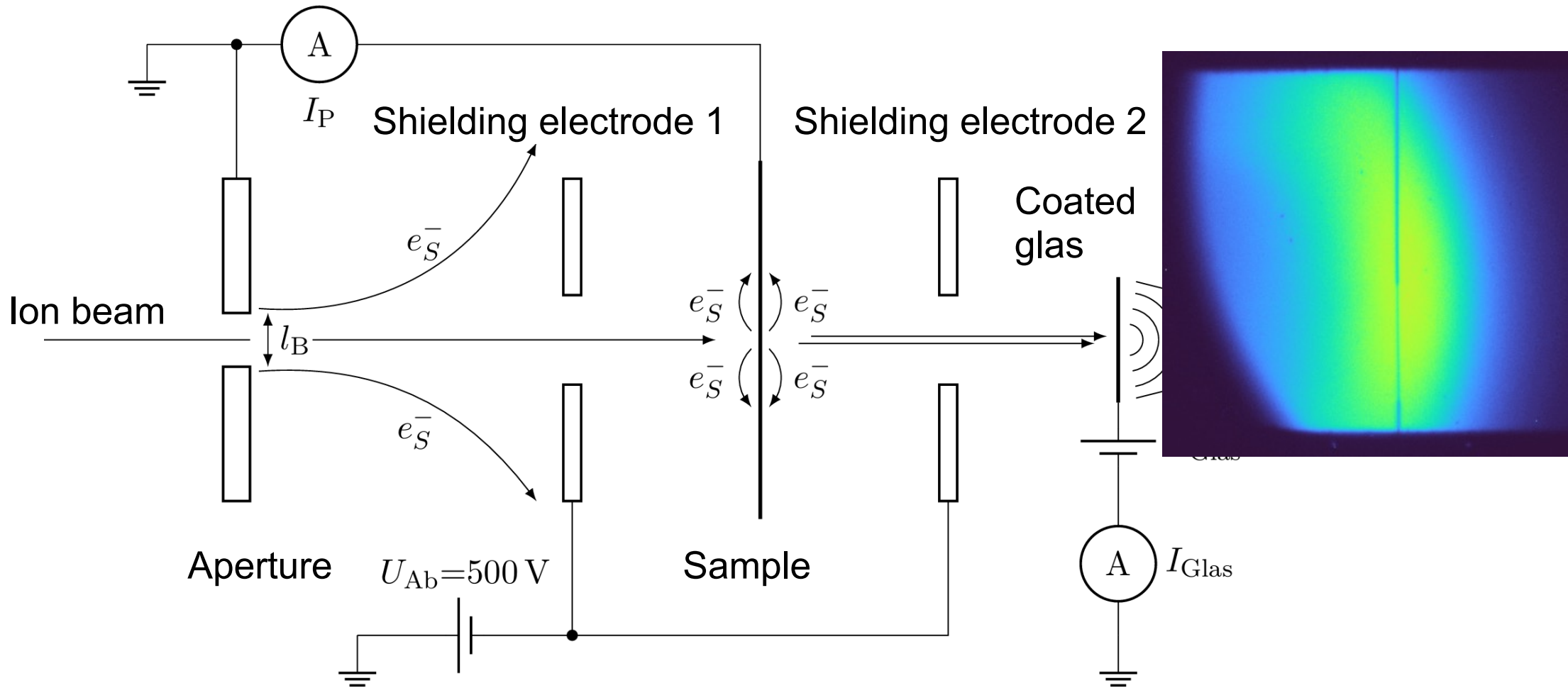
Implantation of carbon (11.6 MeV)



Experimental setup



Implantation setup



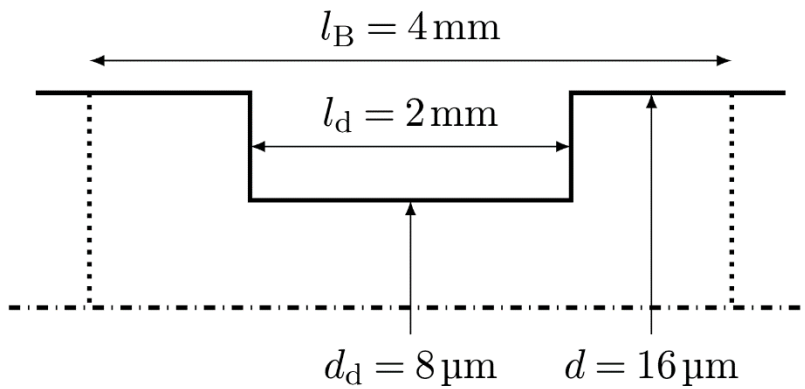
Dependency Ion beam current – Sample temperature

$$T(x) = -\frac{\dot{\omega}}{2 \cdot \lambda} \cdot x^2 + C_1 \cdot x + C_2 \quad \text{Measured ion current (prev. slide)} \quad (1)$$

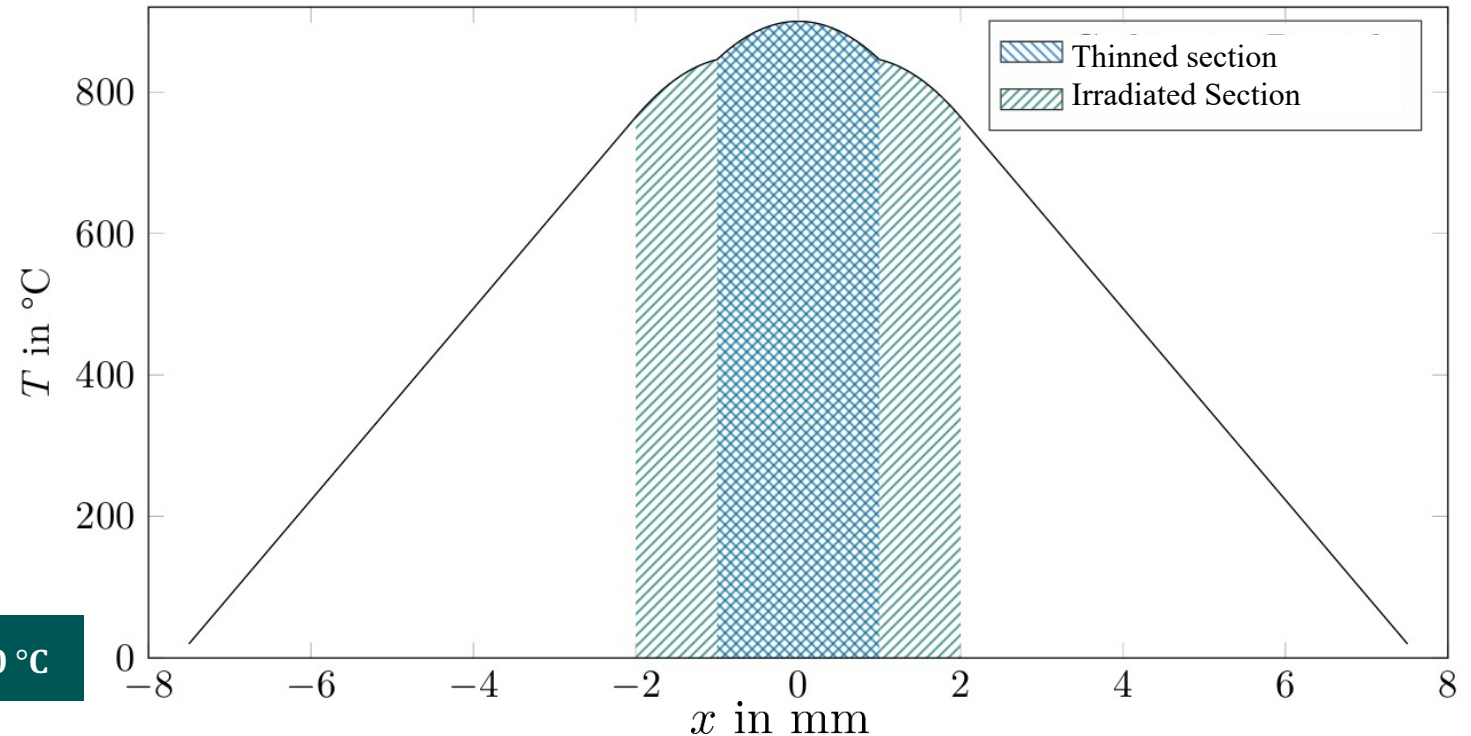
$$\dot{\omega} = \frac{\dot{n} \cdot E_{\text{Ion}}}{V_B} = \frac{4 \cdot I_P \cdot E_{\text{Ion}}}{e \cdot z_{\text{Ion}} \cdot \pi \cdot (d_d^2 \cdot l_d + d^2 \cdot l_B - d^2 \cdot l_d)} \quad \text{Ion energy} \quad (2)$$

Deposited power

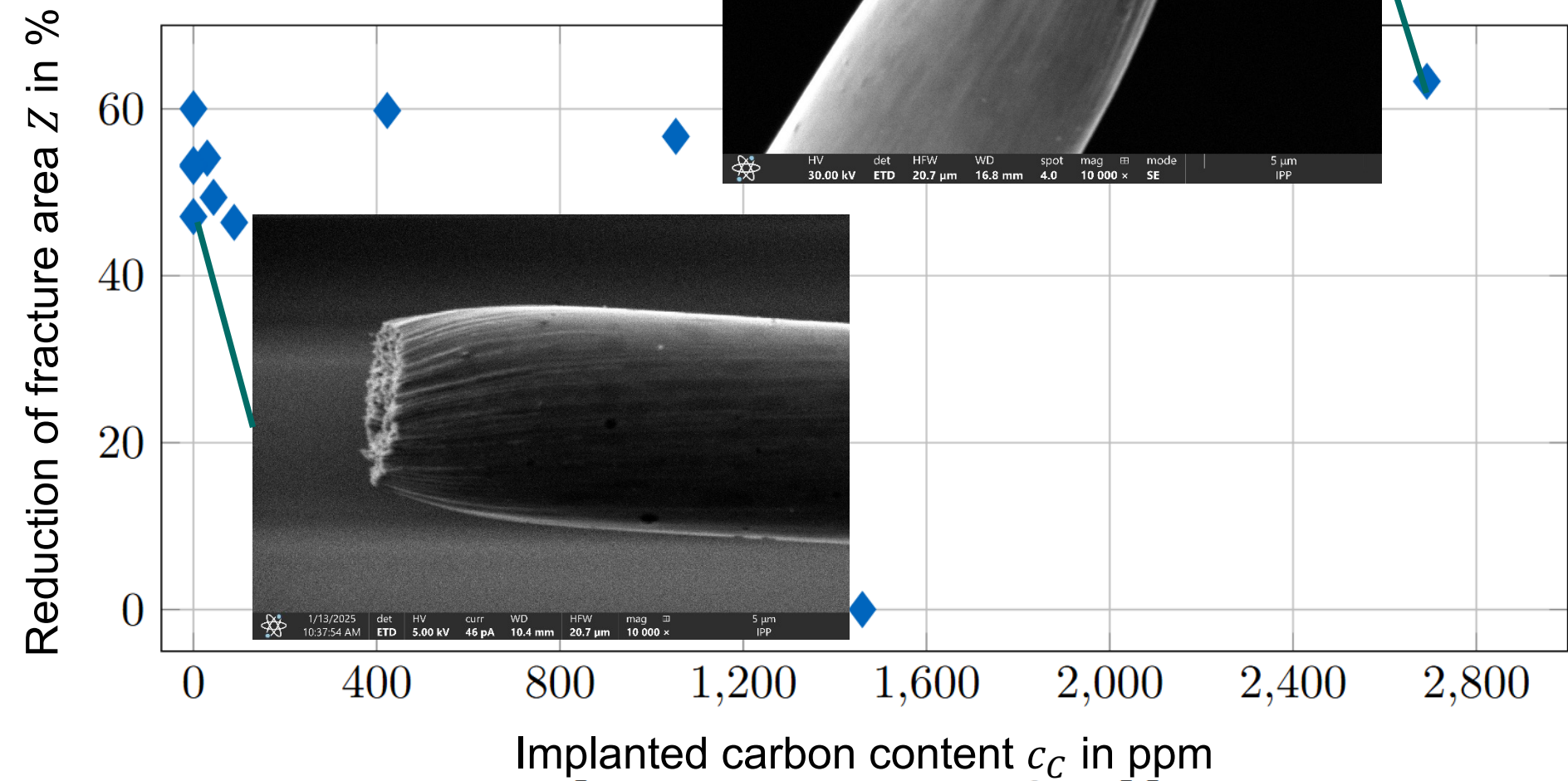
Charge number



$$I_P < 1.74 \text{ nA} \Rightarrow T_{\text{max}} < 900 \text{ } ^\circ\text{C}$$



Carbon dependent ductility of tungsten



WP PWIE SPA 4

Report for 2025 & Overview



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.





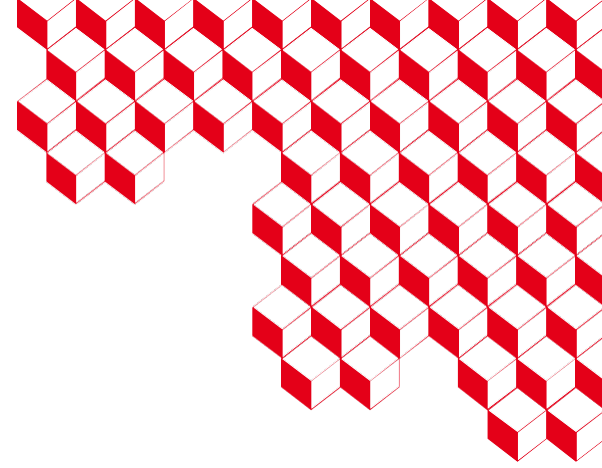
High Temperature performance of Armour Materials: Recrystallization and Melting

Deliverable Owner	Beneficiary	PM	Deliverable (Team)
M. Richou	CEA	9	D001
W. Pantleon	DTU	9	D002
S. Ratynskaia	VR	12	D003 (S.Ratynskaia, P.Tolias, K. Paschalidis, T. Rizzi, A. Kulachenko)
I. Garkusha	KIPT	30	D004
M. Rasinski	FZJ	4	D005 (M. Rasinski, A. Kreter, M. Vogel)
Prof. Hidding	HHU	6	D006
Total		70	

Device	Beneficiary	Days	Related Deliverable
PSI-2	FZJ	3	D005
QSPA	KIPT	10	D004
Accelerator	VR	5	

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	Simulation of Runaway Impact by Electron Beam at 10-100MeV

- Characterization of microstructural changes caused by plasma exposure. Tungsten-based material exposed to different plasma conditions will be investigated in terms of mechanical and microstructural depth profiles. Heterogeneities will be traced in hardness and orientation maps and the locally dominating restoration mechanism identified. (DTU)
 - Tungsten material exposures in the QSPA under giant ELMs or disruptions with pronounced surface melting (KIPT). Characterization of dust in QSPA experiments: size analysis, influence of B field on trajectories. Stick effects at the surface.
 - Plasma heat loads which causes surface recrystallization and changes in Microstructure and melt threshold (QSPA/PSI-2/GLADIS) (KIPT, CEA, VR)
 - Assessment of effect of H and He on W recrystallization with links to WP TE (FZJ, DTU, CEA)
 - Joint activities with WP TE on damaged components (e.g. melting) (VR)
 - Experiments on Recrystallization in PSI-2 linked with SP A1 (FZJ, DTU)
 - Further application of MEMENTO modelling to melt flows across castellated PFCs (link with WPTE experiments).
 - Further development of the MEMENTO + Geant4 code chain for RE-induced bulk melting assessments.
 - Further development of thermomechanical modelling of RE-induced PFC brittle failure (Geant4 + COMSOL).
- Initial development of full thermomechanical modelling of RE-induced explosions of brittle PFCs including fragmentation (Geant4 + LS-DYNA)"



PWIE-SP A.4.T-T004-D001

Assessment of plasma impact on material properties linked to ITER relevant PFUs (CEA)

A. Durif¹, A. Flament¹, M-F. Barthe², S. Kalacska³, N. Peillon³, M. Lenci³, M. Mondon³, M. Diez¹, G. Kermouche³, Y. Corre¹, M. Richou¹, and the WEST team

¹CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France

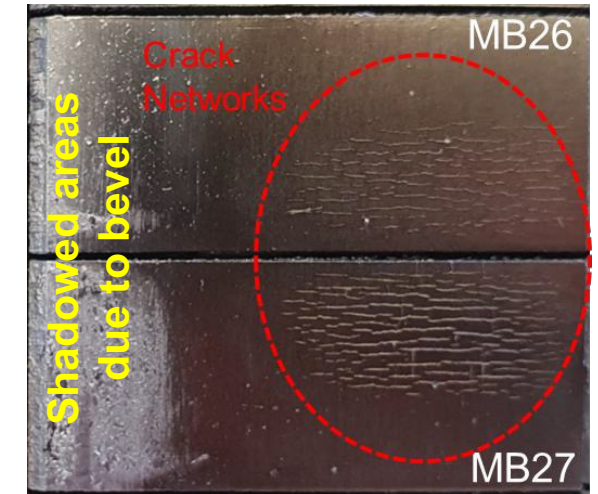
²CEMHTI/CNRS, Université d'Orléans, 3A rue de La Férollerie, 45071 Orléans CEDEX 2, France,

³Mines Saint-Etienne, CNRS, UMR 5307 LGF, Centre SMS, Saint-Etienne F - 42023, France

Investigations on-going - 2 topics (9pm as 2024)

■ Topic A: 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 or PWI? Is a common link between leading edge and top surface (impact of the manufacturing route?)
- Perform post-mortem analysis (microscopy, SEM, XRD) on the tungsten top surface



■ Topic B: Assessment of plasma impact on material properties linked to ITER relevant PFUs

- Perform He implantation study to characterize defects generated and assess the evolution of mechanical props based on multi-scale approach (+ comparative study with WEST samples)

Conclusions & prospects for 2025



■ Topic A: WEST crack network investigations

- Prospect for 2025:
 - Rational related to the crack network opening is still under investigation
 - Tests under thermal loads in HADES under progress
 - Brittle cracking suspected (discrimination of plasticity) → focus on tungsten toughness
 - Focus on crack characterization (depth...)
 - Perform SEM and XRD on WEST samples with crack network (comparative analysis before and after WEST plasma)

■ Topic B: Assessment of plasma impact on material properties

- Samples prepared and characterized + ^3He implantation done + First post-implantation analyses started (PAS, micropillar) to characterize defects generated & assess the evolution of thermomechanical properties of tungsten
- Prospect for 2025:
 - Pursue the post-implantation analysis and perform comparative study (before and after ^3He implantation) in terms of thermochemical properties

Prospects for 2026-27



- Follow-up (topic A & B) strengthening the current investigations :
 - Finalize crack understanding for actively cooled W divertor (HADES testing ?)
 - Perform a second 3He campaign with various conditions (material, implantation temperature, self-irradiation) and related characterizations
 - Perform FEM modeling considering the impact of the evolution of the tungsten thermo-mechanical properties due to presence of light impurities (H, He) (FEM + T-REX modelling?)
- **Additional topic** : W limiters - Provide a preliminary feedback regarding WEST operation

EUROfusion support expected (9 pm in 2025): **12pm/year in 2026-27 + 1 Week/year of HADES HHF tests):**



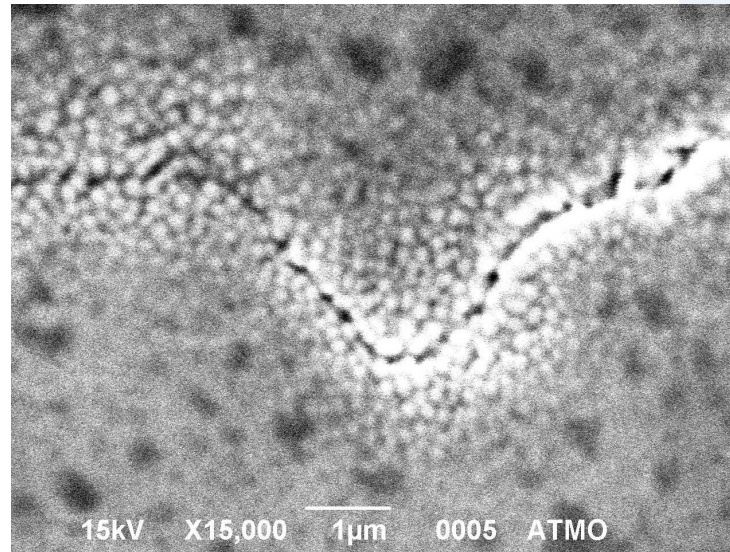
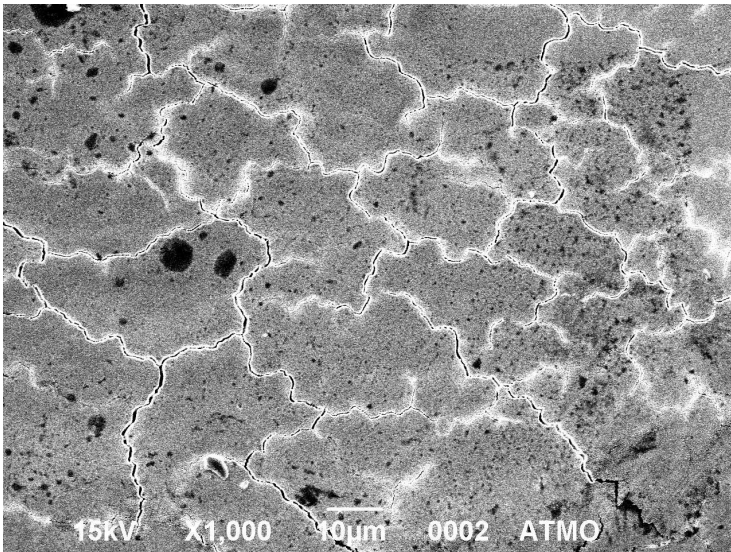
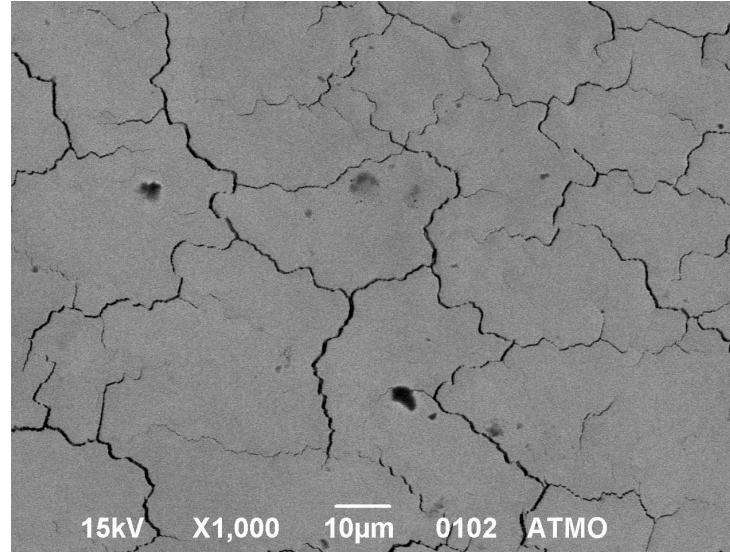
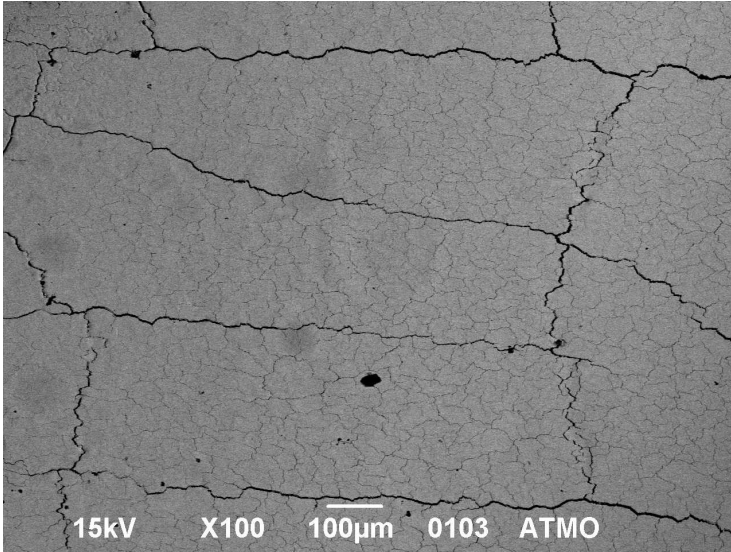
PWIE-SP A.A4.T-T004-D004

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



PWIE-SP A.A4.T-T004-D004: Analysis of re-melted W layers

ATM W under QSPA load above the W melting threshold

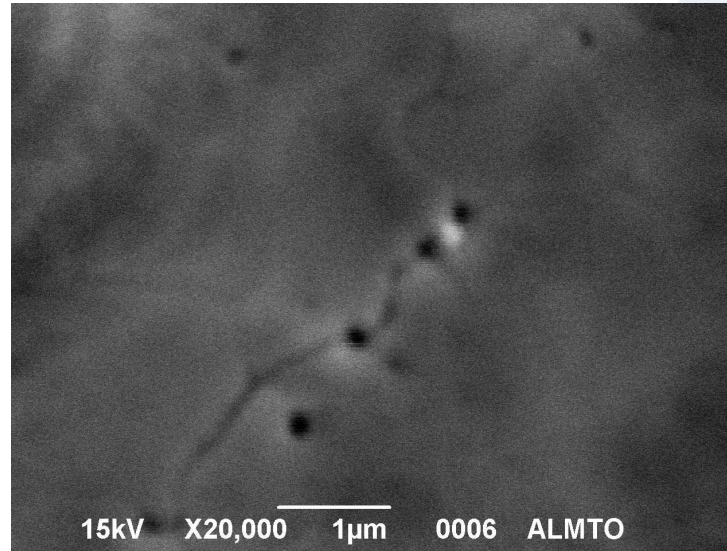
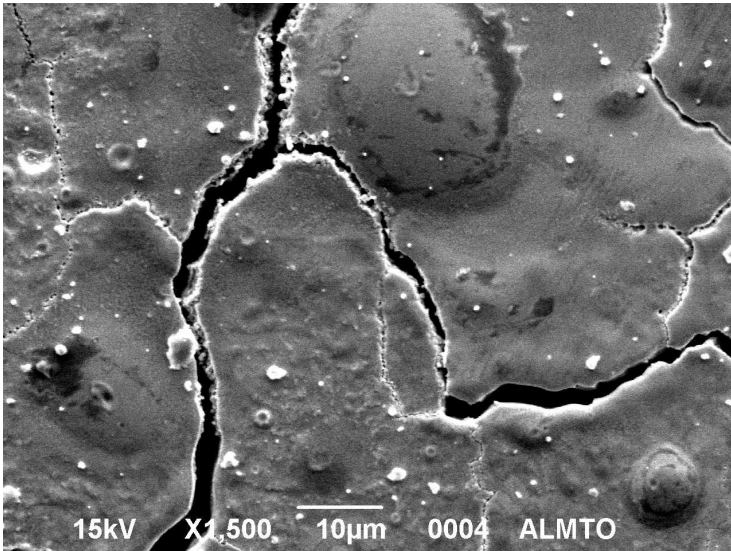
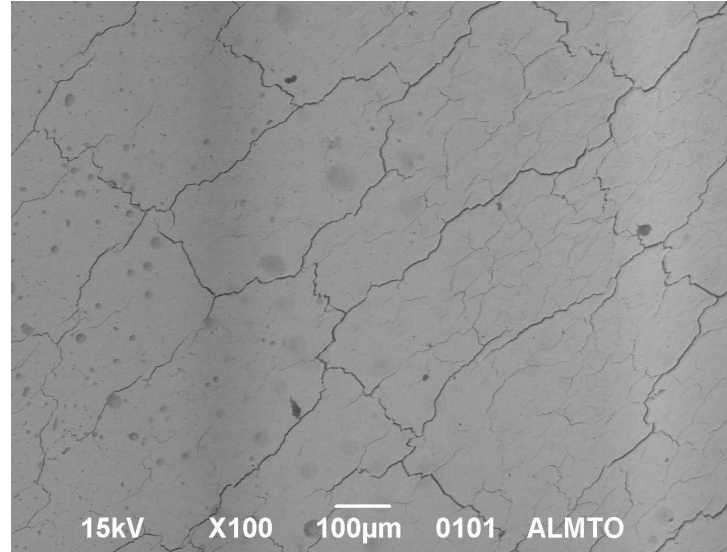
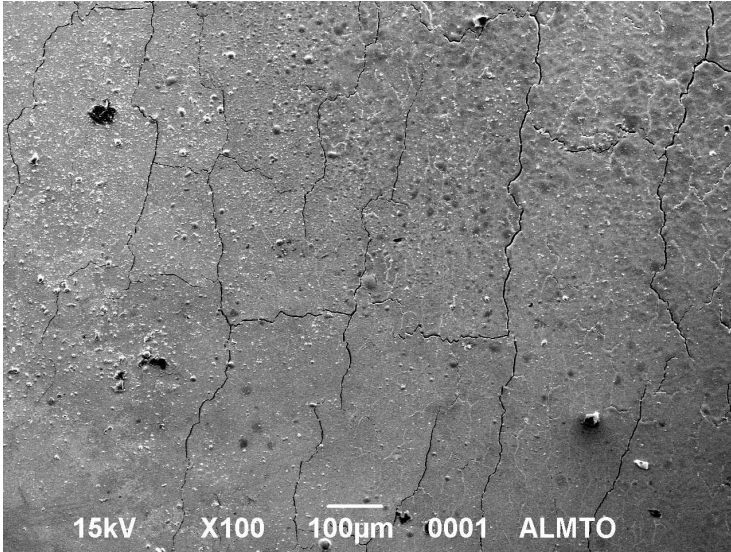


- After QSPA exposure: T=RT, 10 pulses, surface heat load of 0.9 MJ/m^2 and a duration of 0.25 ms.
- Re-solidified layer are observed on affected surface
- Network of large cracks (cell sizes up to 0.5 mm)
- Intergranular network of cracks with cell size up to 0.05 mm
- Cracks width up to $1 \mu\text{m}$.
- Fine cellular structure in re-solidified layer along the crack edges?



PWIE-SP A.A4.T-T004-D004: Analysis of re-melted W layers

ALMT W under QSPA load above the W melting threshold

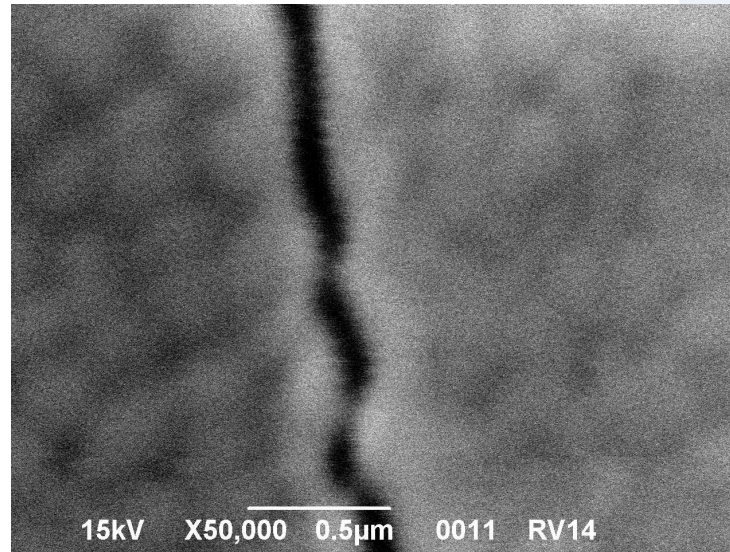
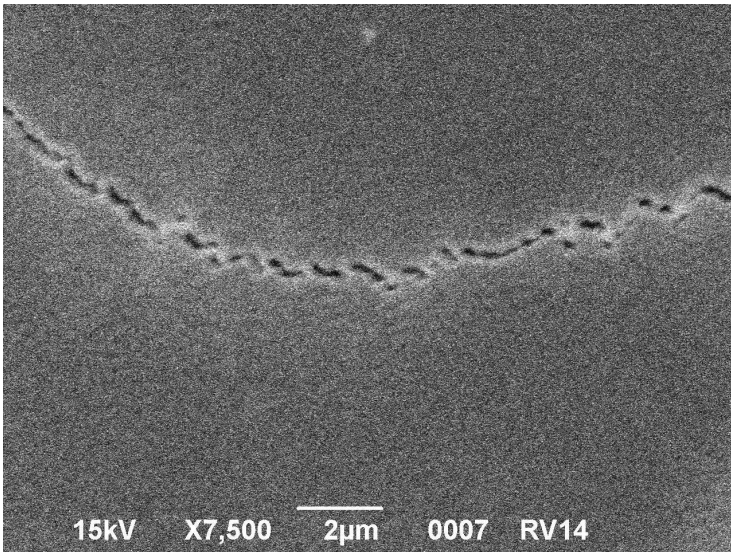
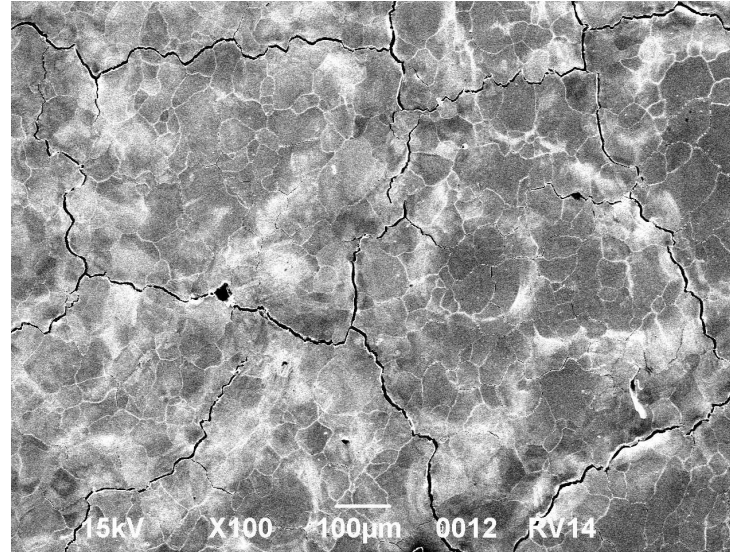
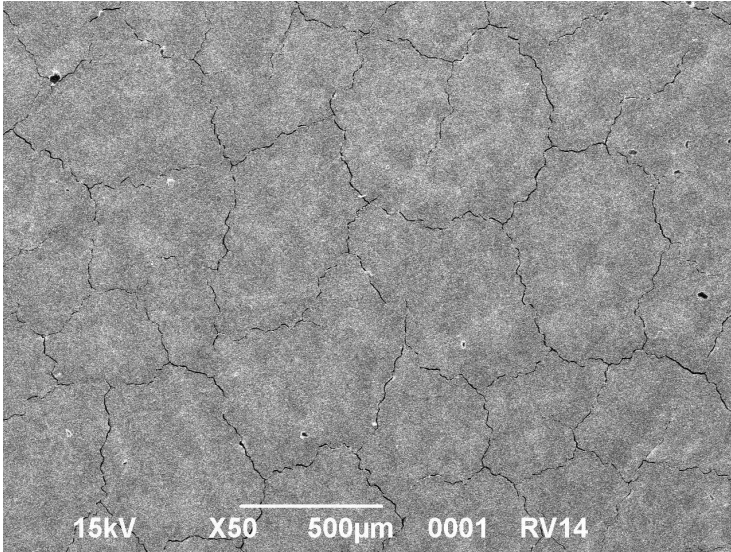


- After QSPA exposure: T=RT, 10 pulses, surface heat load of 0.9 MJ/m^2 and a duration of 0.25 ms.
- Re-solidified layer are observed on affected surface
- Network of large cracks (cell sizes up to 0.4 mm)
- Intergranular network of cracks with cell size up to 0.04 mm
- Cracks width up to $3 \mu\text{m}$.
- Pores?



PWIE-SP A.A4.T-T004-D004: Analysis of re-melted W layers

IGP tungsten with re-crystalized grain under QSPA load above the W melting threshold



- After QSPA exposure: T=RT, 10 pulses, surface heat load of 0.9 MJ/m^2 and a duration of 0.25 ms.
- Re-solidified layer are observed on affected surface
- Network of large cracks (cell sizes up to 0.5 mm)
- Intergranular network of cracks with cell size up to 0.05 mm
- Cracks width up to $1 \mu\text{m}$.
- Fine cellular structure with typical cell size of 150...250 nm in re-solidified layer



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

Influence of plasma pre-irradiation with heat loads above the melting threshold on surface damaging with heat loads near surface recrystallization (KIPT) (the title some modified in compare with 2024)

Summary of 2025:

- SEM studies of various exposed tungsten samples revealed crack formation contributing to surface profile evolution.
- A network of large cracks was observed, with cell sizes up to 1 mm and crack widths of up to 5 μm
- Intergranular network of cracks with cell sizes up to 100 μm was detected.
- Surface modification resulted in the formation of a fine cellular structure within the re-solidified layer, with a typical cell size of 150...250 nm, as well as pores along the cracks.
Gradient T and σ led to the formation of a pronounced pattern along the crack edges during the solidification of the molten layer
- FIB cuts and metallographic cross-sections of samples irradiated in 2024 are currently in progress in collaboration with FZJ



Publication KIPT 2020-2025 within SPA

- 1. V A Makhlai, S S Herashchenko, I E Garkusha, et. al. Damaging of inclined/misaligned castellated tungsten surfaces exposed to a large number of repetitive QSPA plasma loads Phys. Scr. T171 (2020) 014047
- 2. S.S. Herashchenko, O.V. Byrka, V.A. Makhlej, et. al. Damaging of pure tungsten with different microstructure under sequential QSPA and LHD plasma loads problems of atomic science and technology. 2020, № 6. (130), p. 78-82.
- 3. V A Makhlai, I E Garkusha, S S Herashchenko, et. al. Contribution of leading edge shape to a damaging of castellated tungsten targets exposed to repetitive QSPA plasma loads Phys. Scr. 96 (2021) 124043
- 4. N. Mantel, I.E. Garkusha,... V.A. Makhlai,et. al. Development and testing of an additively manufactured lattice for DEMO limiters Nucl. Fusion 62 (2022) 036017 (7pp)
- 5. J.H. You, ..., I.E. Garkusha, S. Gerashchenko, V.A. Makhlai et. al. Limiters for DEMO wall protection: Initial design concepts & technology options Fusion Engineering and Design 174 (2022) 112988
- 6. V.A. Makhlai, S.S. Herashchenko, Yu.V. Petrov, et. al. The effect of a small helium addition on the plasma-surface interaction in QSPA Problems of Atomic Science and Technology. 2023. №1(143). p. 63-66
- 7. V.A. Makhlai, I.E. Garkusha, S.S. Herashchenko, et. al. Effect of transient layers on plasma energy transfer to different surfaces under QSPA exposures Problems of Atomic Science and Technology. 2023. № 6(148), p. 101-105
- 8. I.E. Garkusha, V.A. Makhlai, S.S. Herashchenko, et. al. Influence of Ar injection on shielding layer properties and surface protection from transient high heat loads under the QSPA plasma exposures Nucl. Fusion 64 (2024) 056010
- 9. V. A. Makhlai, I. E. Garkusha, S. S. Herashchenko, et. al. Erosion and modification of tungsten surfaces under sequential steady-state and high heat fluxes transient plasma impacts Proc. 20th International Conference on Plasma-Facing Materials and Components for Fusion Applications.19-23 May 2025, Book of abstract p. 101, poster № POA-28

Analysis of PSI-2 exposed materials, focusing on funding the relevant regime for erosion in AUG Ne seeded campaign

M. Rasiński, S. Brezinsek, A. Kreter, M. Gago, M. Wirtz

Forschungszentrum Jülich, IFN-1



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.



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 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



Experiment

2 samples for each PSI-2 exposure

PSI-2 exposure

Base temperature $\sim 900\text{ }^{\circ}\text{C}$

Ion Flux $\sim 2 - 2.5 \times 10^{21}\text{ m}^{-2}\text{s}^{-1}$

Fluence $\sim 1.0 \times 10^{25}\text{ m}^{-2}$

Energy $\sim 60\text{ eV}$ and 175 eV

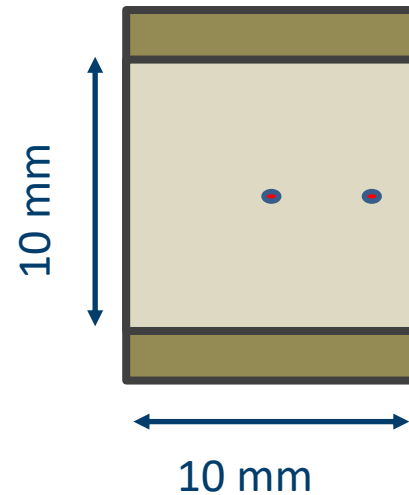
Plasma composition:

D 5% He 0% Ne	}	175 eV
D 5% He 1% Ne		
D 5% He 5% Ne		

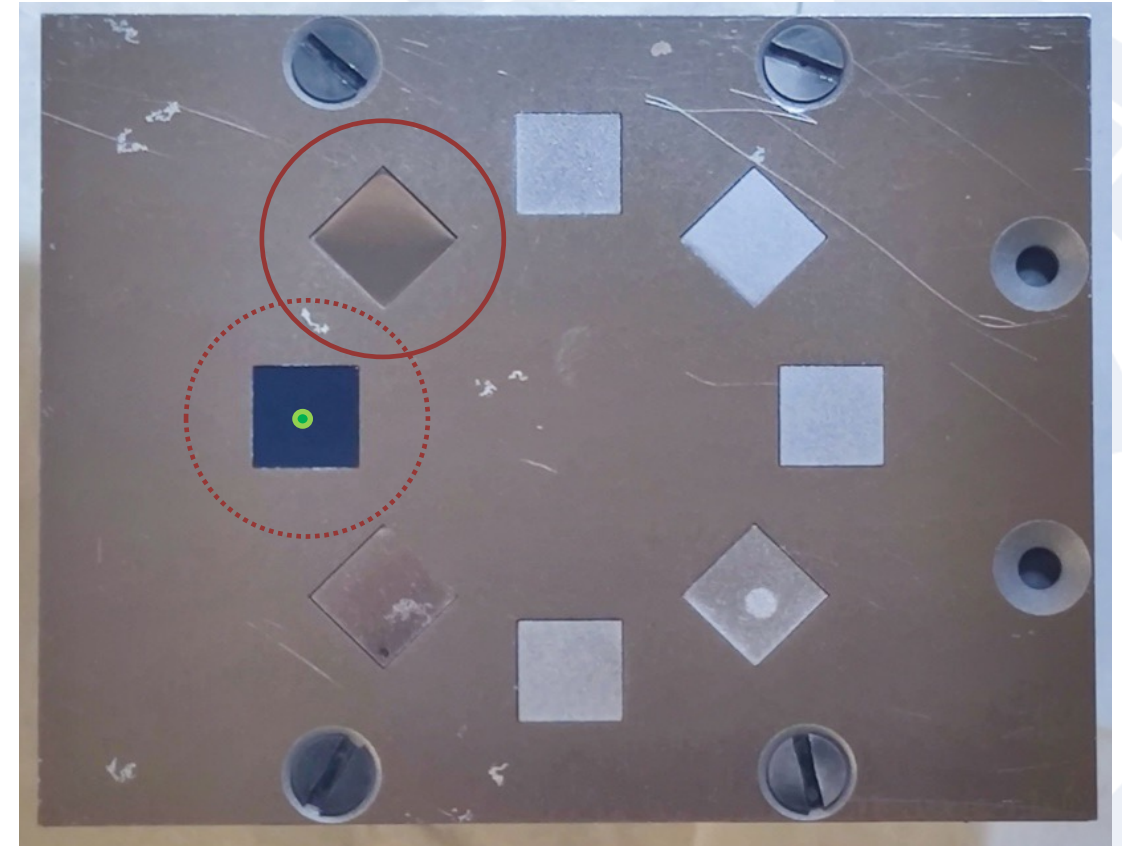
D 5% He 1% Ne	60 eV
----------------------	--------------

Laser

100 MW/m^2 , $0,5\text{ ms}$, 200 Hz



Sample geometry

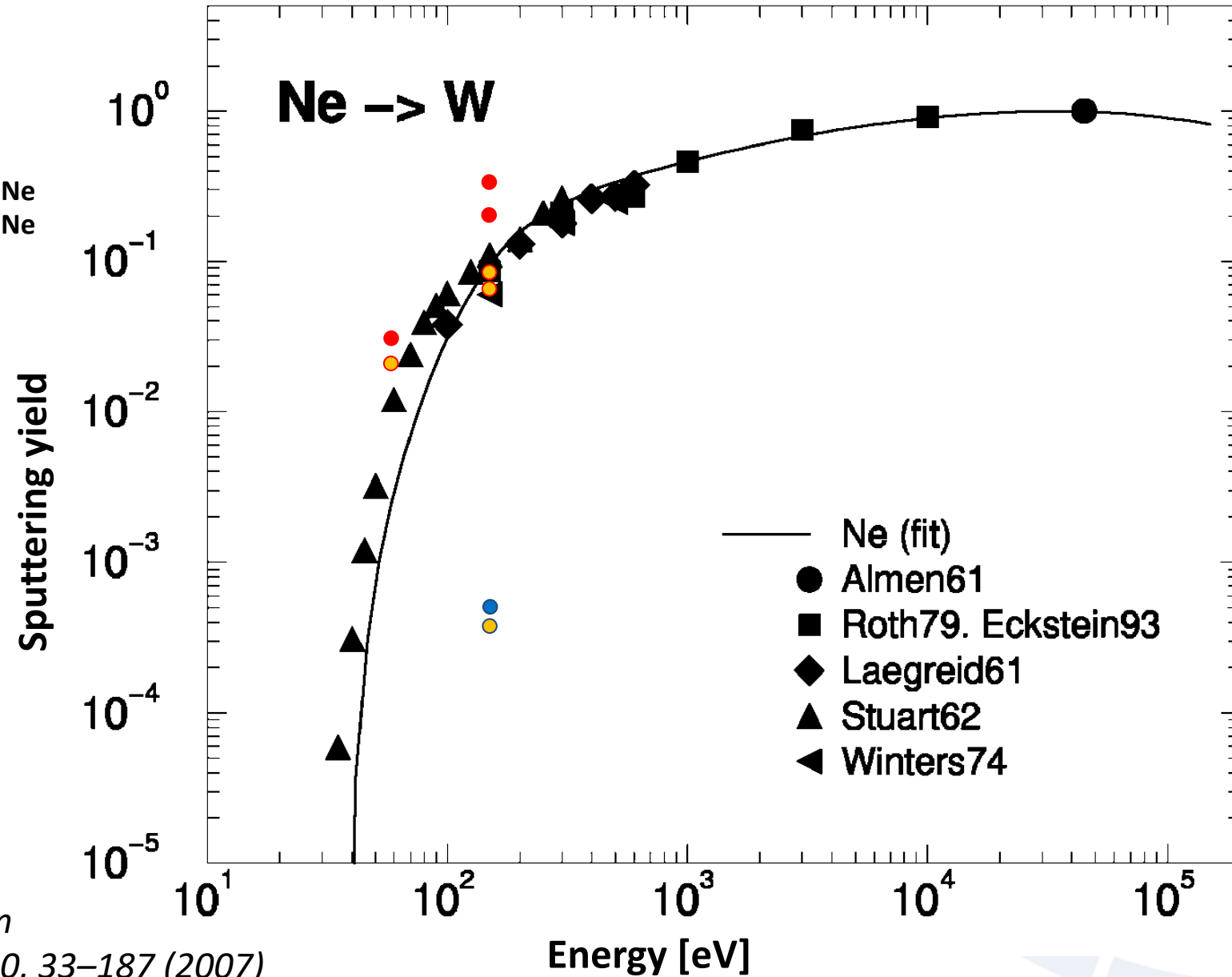


PSI-2 sample holder with samples mounted before plasma exposure



Results

Erosion normalized to Ne flux



R. Behrisch, W. Eckstein
Topics Appl. Physics 110, 33–187 (2007)



Conclusions

- W samples exposed to mixed plasma containing **0, 1 and 5 % of Ne** at 60 and 175 eV in PSI-2 (D + 5%He + Ne)
- Erosion rates estimated based on the FIB prepared cross-sections
- Erosion strongly dependent on Ne content - following the sputtering data of W by Ne
- For two exposures -low energy exposures (60eV) as well as for 0 % Ne early stage of fuzz formation is observed
- Nano-bubble formation on and under the surface for samples exposed to simultaneous plasma and laser loading
- Sample exposed to simultaneous plasma and laser loading exhibit visible larger erosion rate compared to sample without laser



Overview of 2020-2025 Work

2020 – 2021 Analysis for PSI-2 exposed materials, focusing on recrystallization

Samples with transversal grain oriented exposed to D plasma at elevated temperature 1310 – 1390 °C for 1, 2 and 5h.

- Major factor responsible for recovery and recrystallization is temperature.
- Influence of D loading at elevated temperature on W recrystallization is negligible
- Calculated activation energy is with good agreement with literature studies and confirms grain boundary diffusion mechanism.

2022 – 2024 Analysis for PSI-2 exposed materials, focusing on funding the relevant regime for fuzz formation in AUG He campaign

- 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

2024 – 2025 Analysis of PSI-2 exposed materials, focusing on funding the relevant regime for erosion in AUG Ne seeded campaign

- W samples exposed to mixed plasma containing 0, 1 and 5 % of Ne at 60 and 175 eV in PSI-2 (D + 5%He + Ne)
- Erosion strongly dependent on Ne content - following the sputtering data of W by Ne
- For two exposures -low energy exposures (60eV) as well as for 0 % Ne early stage of fuzz formation is observed
- Nano-bubble formation on and under the surface for samples exposed to simultaneous plasma and laser loading
- Sample exposed to simultaneous plasma and laser loading exhibit visible larger erosion rate compared to sample without laser



Publications related to SPA

Rasiński, M., Brezinsek, S., Kreter, A., Dittmar, T., Krieger, K., Balden, M., de Marne, P., Dux, R., Faitsch, M., Hakola, A., Likonen, J., Tsitrone, E., Rohde, V.,
FIB line marking as a tool for local erosion/deposition/fuzz formation measurements in ASDEX Upgrade during the He campaign.
Nuclear Materials and Energy 37, 101539.

Summary: 2020-2025 (VR)

Modelling of macroscopic metallic melt motion

Research line on modelling of the thermoelectric MHD response of PFCs to transient heat loads brought to maturity

- ✓ MEMOS-U physics model implemented in the modern computational tool MEMENTO.
- ✓ MEMENTO utilizes non-uniform and adaptive meshing along with sub-cycling in time enabled by the AMReX open-source framework.
- ✓ MEMENTO utilizes the AMReX built-in parallelization capabilities.
- ✓ Numerical algorithms and benchmarking exercises documented in open access publications.
- ✓ Multiple WPTE experiments with novel experimental constraints carried out in AUG and WEST have been successfully modelled by MEMENTO providing further model validation and predictive capabilities

Modelling of runaway-electron induced damage

New research line initiated on modelling of the thermomechanical response of PFCs to runaway electron impacts

- ✓ Rapid progress in the modelling of the volumetric heat loading by REs including the escaping particles.
- ✓ Rapid progress in the full thermomechanical modelling of RE-induced damage on brittle subliming PFCs: basic linear thermoelastic physics model supplemented by brittle failure criteria and fracture dynamics.
- ✓ Successful validation against deliberate DIII-D (graphite) and accidental WEST (boron nitride) experiments.
- ✓ Predictive thermal modelling for WEST and AUG to assist the design of novel W damage experiments.
- ✓ Modelling of the first controlled RE-induced damage experiment on W tiles in WEST (April 2025) is initiated.

2026-2027 activities will focus on expanding modelling of RE-induced damage to W PFCs



SPA-related VR publications 2020-2025

1. Wall damage due to oblique high velocity dust impacts

P. Tolias, M. De Angeli, D. Ripamonti, S. Ratynskaia et al, *Fus. Eng. Des.*, submitted, 2025 available at [arXiv:2509.18794](https://arxiv.org/abs/2509.18794).

2. Modeling of runaway electron induced damage on boron-nitride tiles in WEST

T. Rizzi, S. Ratynskaia, P. Tolias, et al., *Nucl. Mater. Energy*, submitted, 2025, available at [arXiv:2509.15821](https://arxiv.org/abs/2509.15821).

3. Roadmap: Runway electron-induced plasma facing component damage in tokamaks

S. Ratynskaia, M. Hoelzl, E. Nardon *plus 30 authors*, accepted to *Plasma Phys. Control. Fusion* (2025), currently available at [arxiv:2506.10411](https://arxiv.org/abs/2506.10411).

4. Scrape-off layer and divertor physics, Chapter 5 of special issue: On the path to tokamak burning plasma operation,

K. Krieger, S. Brezinsek, J. Coenen, H. Frerichs, A. Kallenbach, A. Leonard, T. Loarer, S. Ratynskaia, N. Vianello, N. Asakura, M. Bernert, D. Carralero, R. Ding, D. Douai, T. Eich, Y. Gasparyan, A. Hakola, Y. Hatano, M. Jakubowski, M. Kobayashi, S. Krashennikov, S. Masuzaki, T. Nakano, R. Neu, R. A. Pitts, J. Rapp, K. Schmid, O. Schmitz, D. Tskhakaya, L. Wang, T. Wauters, S. Wiesen, *Nucl. Fusion* **65**, 043001 (2025).

5. Modelling the brittle failure of graphite induced by the controlled impact of runaway electrons in DIII-D,

S. Ratynskaia, P. Tolias, T. Rizzi, K. Paschalidis *et al.*, *Nucl. Fusion* **65**, 024002 (2025).

6. Measurement of post-disruption runaway electron kinetic energy and pitch angle during final loss instability in DIII-D

E. Hollmann, C. Marini, D. Rudakov *et al.*, *Plasma Phys. Control. Fusion* **67**, 035020 (2025).

7. Plasma-wall interaction impact of the ITER re-baseline

R. A. Pitts, A. Loarte, T. Wauters *et al.*, *Nucl. Mater. Energy* **42**, 101854 (2025).

8. Normal high velocity solid dust impacts on tiles of tokamak-relevant temperature

M. De Angeli, P. Tolias, F. Suzuki-Vidal *et al.*, *Nucl. Mater. Energy* **41**, 101735 (2024).

9. The MEMENTO code for modeling of macroscopic melt motion in fusion devices

K. Paschalidis, F. Lucco Castello, S. Ratynskaia *et al.*, *Fus. Eng. Des.* **206**, 114603 (2024).

10. Metallic melt transport across castellated tiles

S. Ratynskaia, K. Paschalidis, K. Krieger *et al.*, *Nucl. Fusion* **64**, 036012 (2024).

11. Infrared detection of tungsten cracking on actively cooled ITER-like component during

high power experiment in WEST

Q. Tichit, A. Durif, J. Gaspar, Y. Anquetin *et al.*, *Nucl. Mater. Energy* **37**, 101537 (2023).

12. Testing of ITER-grade plasma facing units in the WEST tokamak:

Y. Corre, M. Aumeunier, A. Durif, J. Gaspar *et al.*, *Nucl. Mater. Energy* **37**, 101546 (2023).

13. Melt dynamics with MEMENTO—code development and numerical benchmarks

K. Paschalidis, S. Ratynskaia *et al.*, *Nucl. Mater. Energy* **37**, 101545 (2023).

14. Wall cratering upon high velocity normal dust impact

P. Tolias, M. De Angeli, D. Ripamonti *et al.*, *Fus. Eng. Des.* **195**, 113938 (2023).

15. Experiments and modelling on ASDEX Upgrade and WEST in support of tool development for tokamak reactor armour melting assessments

S. Ratynskaia, K. Paschalidis, P. Tolias *et al.*, *Nucl. Mater. Energy* **33**, 101303 (2022).

16. Analytical expressions for thermophysical properties of solid and liquid beryllium relevant for fusion applications

P. Tolias, *Nucl. Mater. Energy* **31**, 101195 (2022).

2

17. Sustained W-melting experiments on actively cooled ITER-like plasma facing unit in WEST

Y. Corre, A. Grosjean, J. P. Gunn *et al.*, *Phys. Scr.* **96**, 124057 (2021).

18. The MEMOS-U macroscopic melt dynamics code—benchmarking and applications

S. Ratynskaia, E. Thorén, P. Tolias *et al.*, *Phys. Scr.* **96**, 124009 (2021).

19. The MEMOS-U code description of macroscopic melt dynamics in fusion devices

E. Thorén, S. Ratynskaia, P. Tolias *et al.*, *Plasma Phys. Control. Fusion* **63**, 035021 (2021).

20. Resolidification-controlled melt dynamics under fast transient tokamak plasma loads

S. Ratynskaia, E. Thorén, P. Tolias *et al.*, *Nucl. Fusion* **60**, 104001 (2020).

Modelling of brittle material fragmentation

Linear thermo-elastic response successfully modelled to predict onset of failure in DIII-D experiment with graphite.

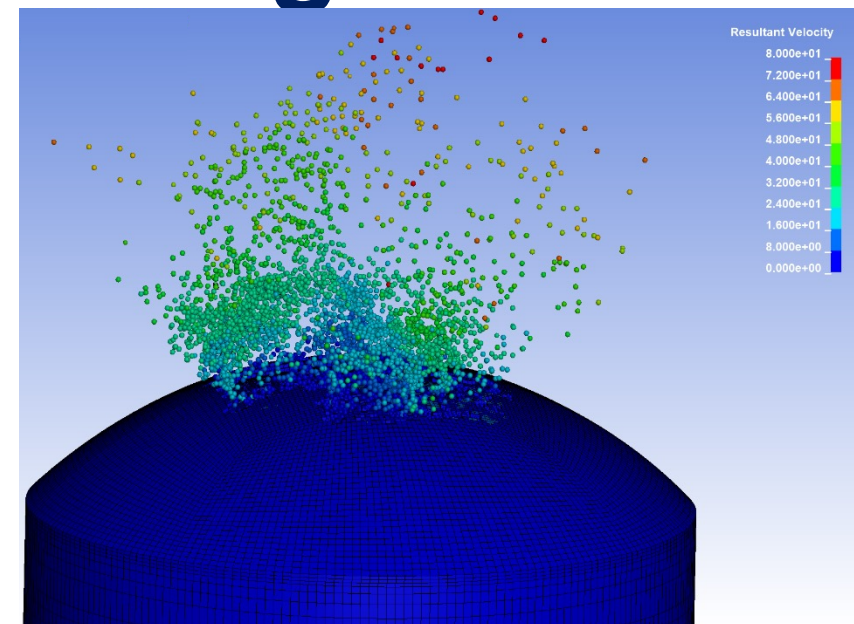
Workflow: KORC + Geant4 + COMSOL.

S. Ratynskaia et al, Nucl. Fusion Letter 65 (2025)

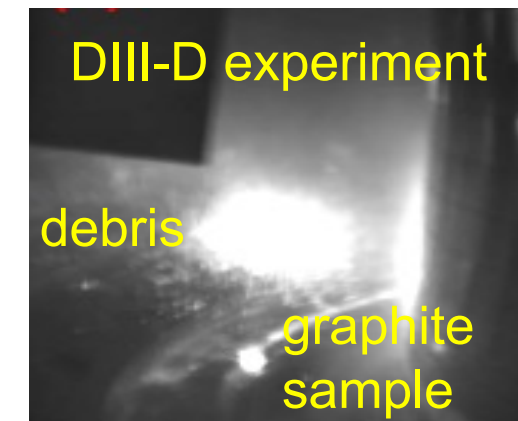
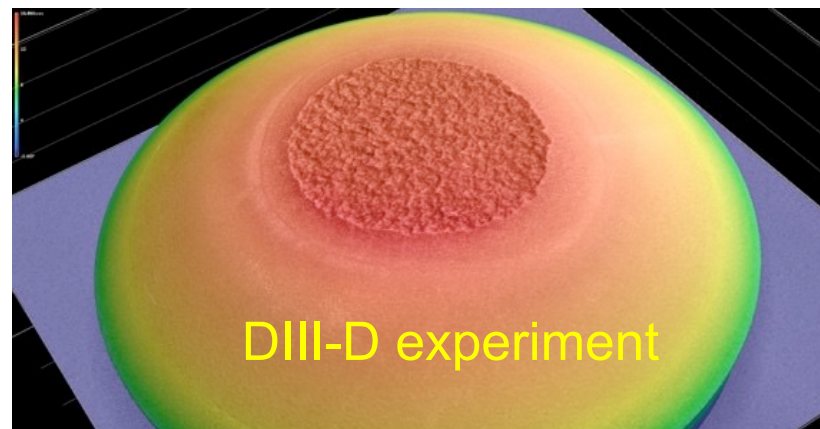
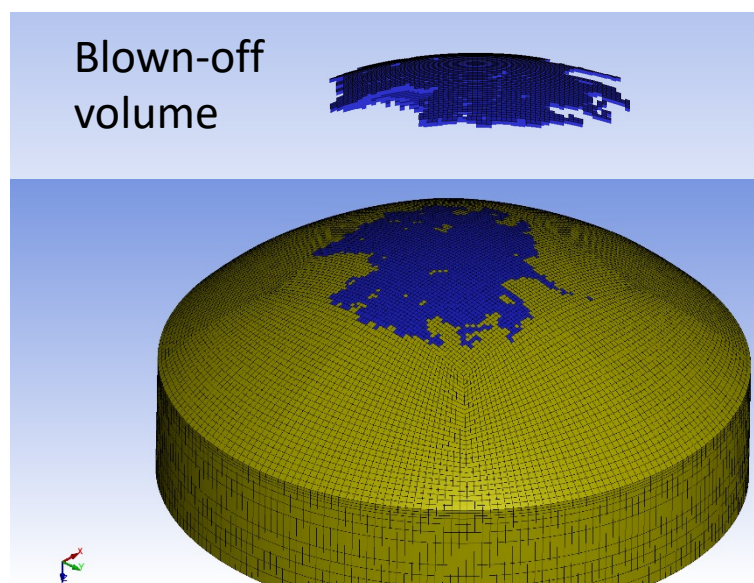
Now developing full nonlinear response model capable of predicting also release of debris

Work-flow : Geant4 + LS-DYNA.

LS-DYNA simulations are based on FEM + SPH approach
(SPH: *Smoothed Particle Hydrodynamics*)



MC (Geant4) + FEM / SPH (LS-DYNA)
work-flow calculations of the DIII-D
ATJ graphite sample response to REs



Modelling of brittle failure: BN in WEST

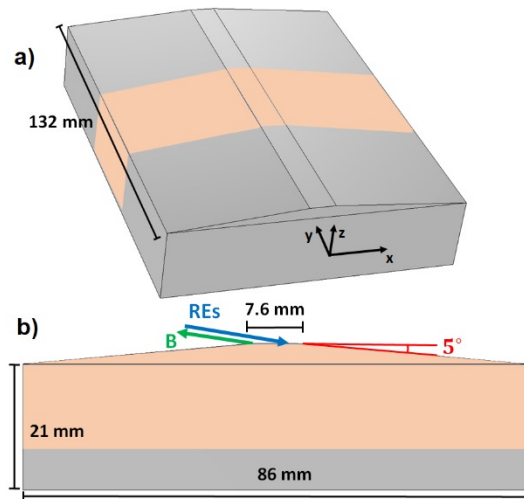
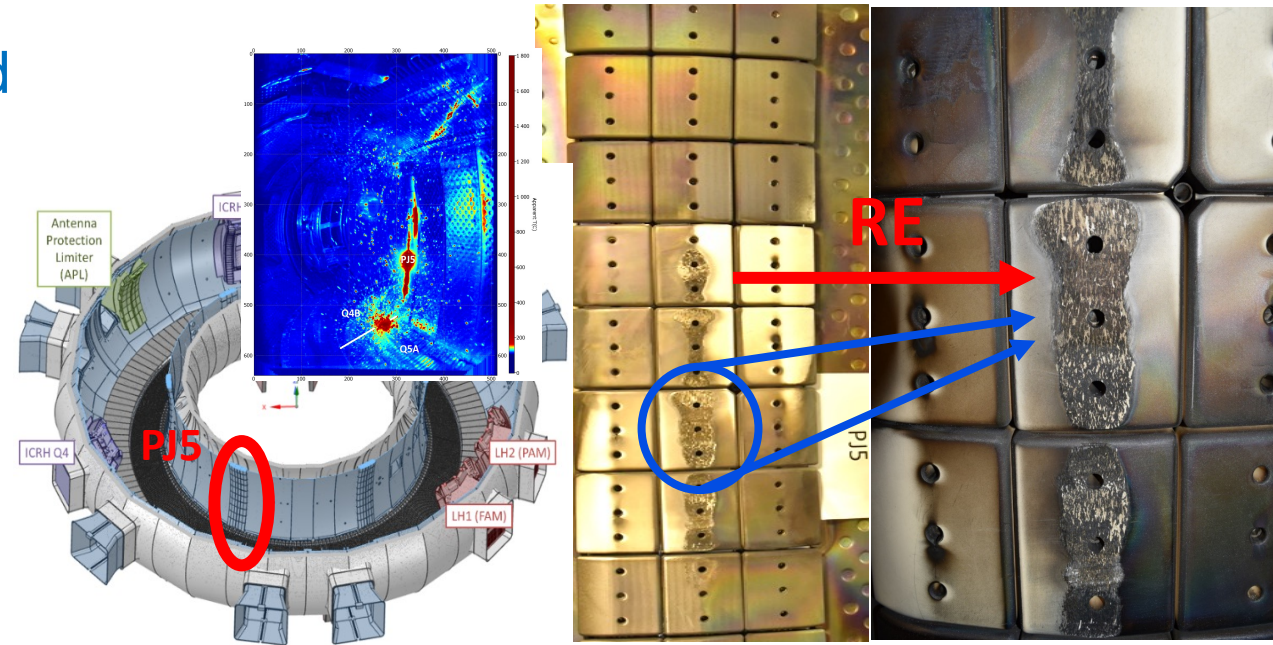
The developed work-flow is successfully applied to BN tiles in WEST (accidental damage)



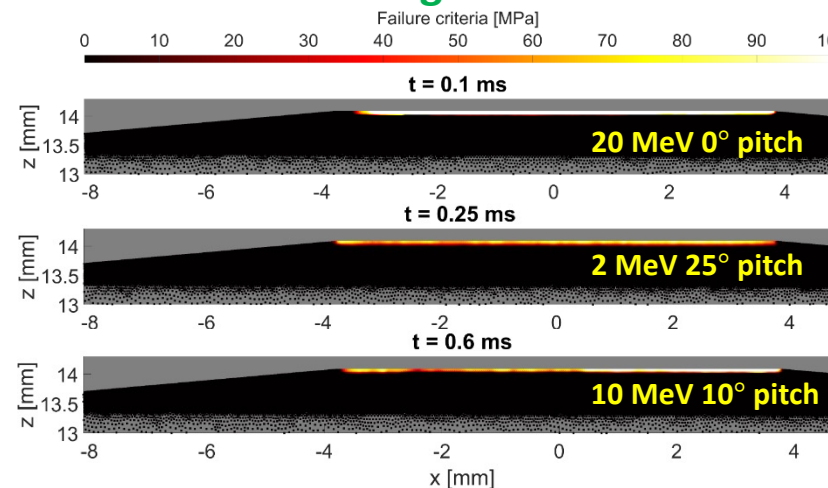
Modeling of runaway electron induced damage on boron-nitride tiles in WEST

T. Rizzi *et al*, submitted to NME 2025

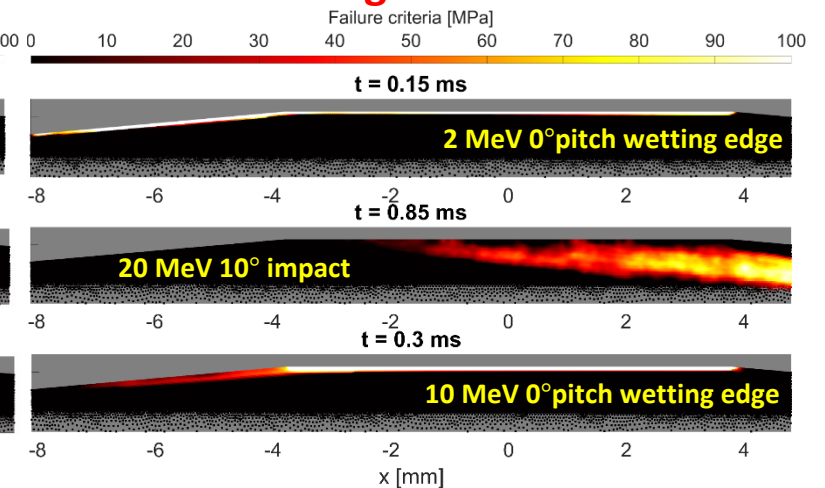
arXiv:2509.15821



Matching observations



Not matching observations



Modelling of accidental W damage on WEST

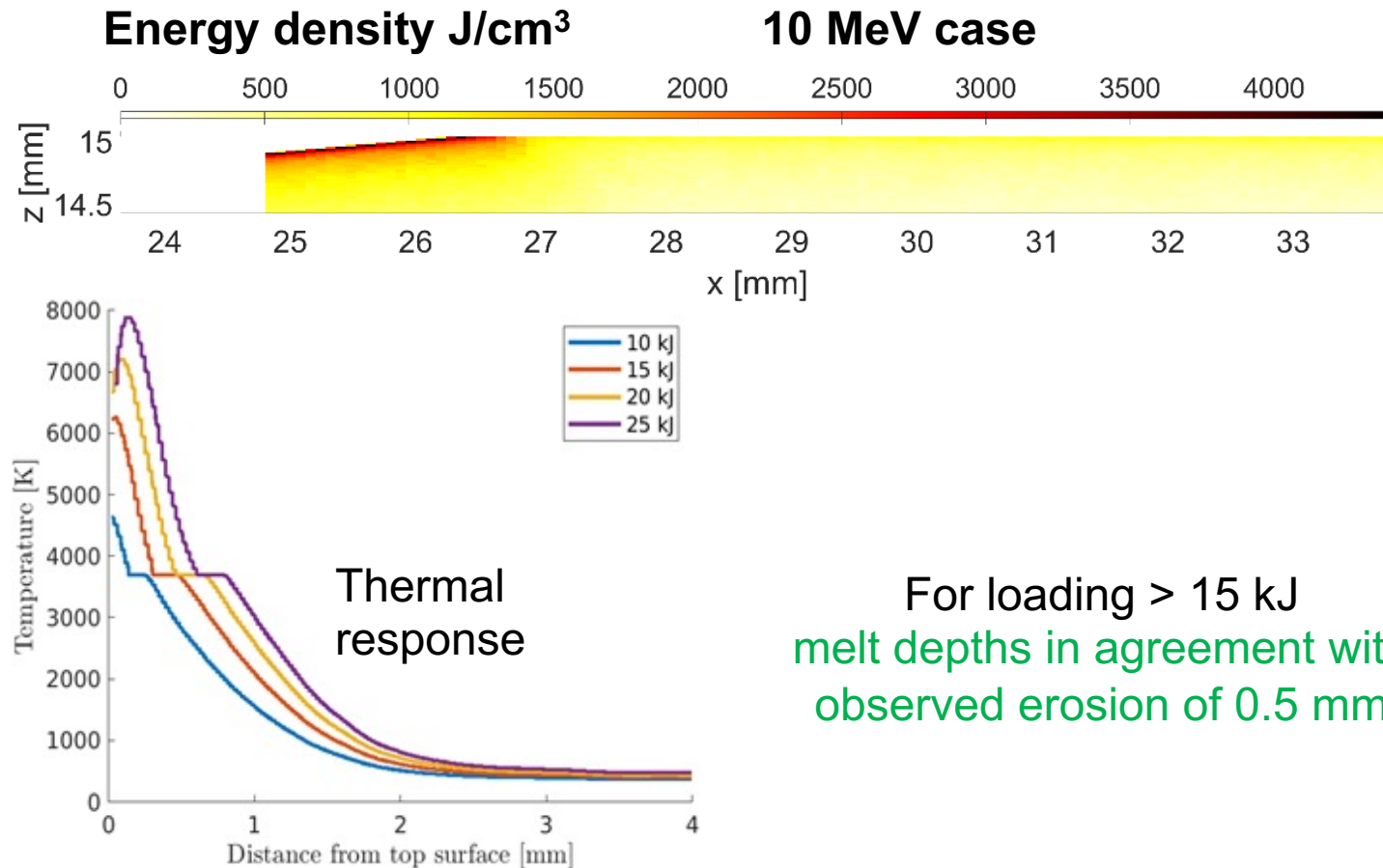
RE impact parameters & loading :

RE energies: 1 MeV, 10 MeV or exp. distrib. RE pitch: zero

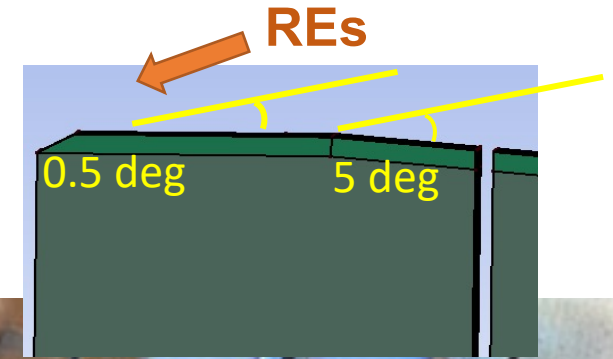
B field inclination - see the sketch

Wetted area: to match experimental damage

Energy loaded: scan 10-25 kJ per apex, over 1 ms



**Outer
bumpers
(C9)**



Overview of work on thermal stability 2021 to 2025

Rolled tungsten from  **A.L.M.T. Corp.**

- Thermal stability of rolled tungsten (IGW, CLW, CHW)
- Qualification of new baseline material

W_f/W composites by CVD 

- Single fiber: microstructural evolution during annealing
- Multifibre: microstructure and bending tests

Powder metallurgical W_f/W composites from 

- Continuous vs. short fibers in dense vs. porous matrix
- Microstructural evolution during annealing

Publications DTU 2021-2025

1. Ciucani, U.M., L. Haus, H. Gietl, J. Riesch, W. Pantleon, Microstructural evolution in single tungsten fiber-reinforced tungsten composites during annealing: recrystallization and abnormal grain growth, *J. Nucl. Mater.* **543** (2021) 152579:1-11.
2. Ciucani, U.M., L. Haus, H. Gietl, J. Riesch, W. Pantleon, Cyclic ring fiber textures in single fiber-reinforced tungsten composites, *IOP Conf. Ser.: Mater. Sci. Eng.* **1121** (2021) 012024:1-6.
3. Tarras Madsen, D., U.M. Ciucani, A. Hoffmann, W. Pantleon, Strong rotated cube textures in thin cold-rolled potassium-doped tungsten sheets during annealing up to 1300 °C, *IOP Conf. Ser.: Mater. Sci. Eng.* **1121** (2021) 012018:1-6.
4. Pantleon, W., Thermal stability of the microstructure in rolled tungsten for fusion reactors, *Phys. Scr.* **96** (2021) 124036:1-8.
5. Tarras Madsen, D., U.M. Ciucani, A. Hoffmann, W. Pantleon, Thermal stability of thin rolled potassium-doped tungsten sheets during annealing up to 1400 °C, *Nucl. Mater. Energy* **30** (2022) 101126:1-7.
6. Larsen, T., K. Chmelar, B.L. Larsen, P. Nagy, K. Wang, W. Pantleon, Thermal stability of differently rolled pure tungsten plates in the temperature range from 1125 °C to 1250 °C, *Fusion Eng. Design* **192** (2023) 113581:1-6. (Corrigendum *Fusion Eng. Design* **192** (2025) 114818:1).
7. Wartacz, D.A.H., J. Riesch, K. Pantleon, W. Pantleon, Recrystallization and grain growth in single tungsten fiber-reinforced tungsten composites, *J. Phys. Conf. Ser.* **2635** (2023) 012034:1-8.
8. Wartacz, D.A.H., J. Riesch, K. Pantleon, W. Pantleon, Tungsten fiber-reinforced tungsten composites and their thermal stability, *J. Nucl. Mater.* **592** (2024) 154951:1-8.
9. Wartacz, D.A.H., H. Becker, S. Antusch, N. Ordás, C. Gundlach, O.V. Mishin, W. Pantleon, Microstructure of additive manufactured materials for plasma-facing components of future fusion reactors, *IOP Conf. Series: Mater. Sci. Eng.* **1310** (2024) 012004:1-8.
10. Pantleon, W., Fiber textures revisited, *Mater. Char.* **223** (2025) 114900:1-11.
11. Wartacz, D.A.H., J. Riesch, K. Pantleon, W. Pantleon, Restoration in drawn tungsten wires of tungsten fiber-reinforced tungsten composites, *Fus. Eng. Design* **216** (2025) 115038:1-8.
12. Wartacz, D.A.H., T. Höschen, J. Riesch, K. Pantleon, W. Pantleon, Thermal stability of multi-fiber tungsten fiber-reinforced tungsten composites and their mechanical integrity after high temperature annealing, *Fus. Eng. Design* **222** (2026) 115438:1-12.

WP PWIE SPA 5

Report for 2025 & Overview



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+6	D007
James Paterson	UKAEA	4	D008, D009
Total		39	

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

- Microscopy – 10+10 k€ - IPPLM
- Hive + Lab – 75k€ - UKAEA

Task under SP A5 include the preparatory work on assessing and analysing the material candidates for COMPASS-U this includes particularly heat flux performance as well as material evolution on microstructure, and surface condition. The work is based on a comprehensive pre-characterization of the 9 candidate W materials (IPPCR) with a potential down-selection to main suppliers, Plansee, ALMT, AT&M. Exposures will be performed in JUDITH, PSI-2(FZJ), OLMAT (CIEMAT) and Magnum (DIFFER). As an example, disruption simulation on the surface and at edges of COMPASS-U W armor will be performed at OLMAT. The damage threshold in terms of power density and number of pulses will be determined, especially critical at edges. The damage at maximum power densities, $\sim 7 \text{ GW/m}^2$, will also be studied to determine the damage of mild or partially mitigated disruptions in DEMO (expected at a minimum of 30 GW/m^2).

Pre- and post-Characterization including various techniques as highlighted in the deliverables will be performed (FZJ, CIEMAT, DIFFER, ENEA, IPPLM). A new addition here is particular the *detection of nano-cracking in the surface layer of the first wall as it can be crucial for reducing D/T fuel retention in the wall. CW IR laser heating and IR camera scanning of heated area allows the rapid detection of nano-cracking in the top layer of the first wall (CU). Comparative analysis for the various materials will be performed also including comparing multiple analysis techniques*

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 sposed 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
D008	Establish a round robin test with other HHF Test Facilities to Benchmark HIVE (UKAEA without EUROfusion funding)
D009	Tungsten High Temperature testing.

WP PWIE SPA Outlook

A few comments



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.





Future Plans for 2026-2027 KIPT

Works to be performed in 2026-2027 (A1)

- The influence of sequential steady-state plasma and transient loading on cracking/melting thresholds will be studied for preheated tungsten surfaces.
- The main damage mechanisms of exposed surfaces will be identified and evaluated.

Works to be performed in 2026-2027 (A3)

- Investigations will focus on advanced materials (various types of tungsten, etc.) subjected to high-flux transient plasma loads.
- High-flux testing of different coatings (including boron) deposited on materials such as austenitic and RAFM steels, copper, tungsten, etc. will be carried out, followed by surface analysis.

Works to be performed in 2026-2027 (A4)

- The influence of melt motion on surface damage and modification of reference materials will be studied.
- The evaluation of tungsten surface damage at heat loads near the recrystallization threshold will be carried out for samples that exhibit melt motion effects after the pre-damaging stage.



Prospects for 2026-27 CEA

- Follow-up (topic A & B) strengthening the current investigations :
 - Finalize crack understanding for actively cooled W divertor (HADES testing ?)
 - Perform a second 3He campaign with various conditions (material, implantation temperature, self-irradiation) and related characterizations
 - Perform FEM modeling considering the impact of the evolution of the tungsten thermo-mechanical properties due to presence of light impurities (H, He) (FEM + T-REX modelling?)
- **Additional topic** : W limiters - Provide a preliminary feedback regarding WEST operation

EUROfusion support expected (9 pm in 2025): **12pm/year in 2026-27 + 1 Week/year of HADES HHF tests):**



General Remarks

- Deliverables will be defined soon – some input already
 - Part Continuation
 - Part concentration





FAIRNESS



Transparency
Collaboration
Loyalty

OPENNESS



Open doors
Open hearts
Open minds
Open ears

COMMITMENT



Ownership
Critical thinking
Determination
Respect

DIVERSITY



Cooperation
Equal opportunities
Inclusion