WP PFC - Work package on “Preparation of efficient Plasma-Facing Component (PFC) operation for ITER and DEMO”

SP1 - Power and particle load studies and qualification (J.W. Coenen) – Report 2020

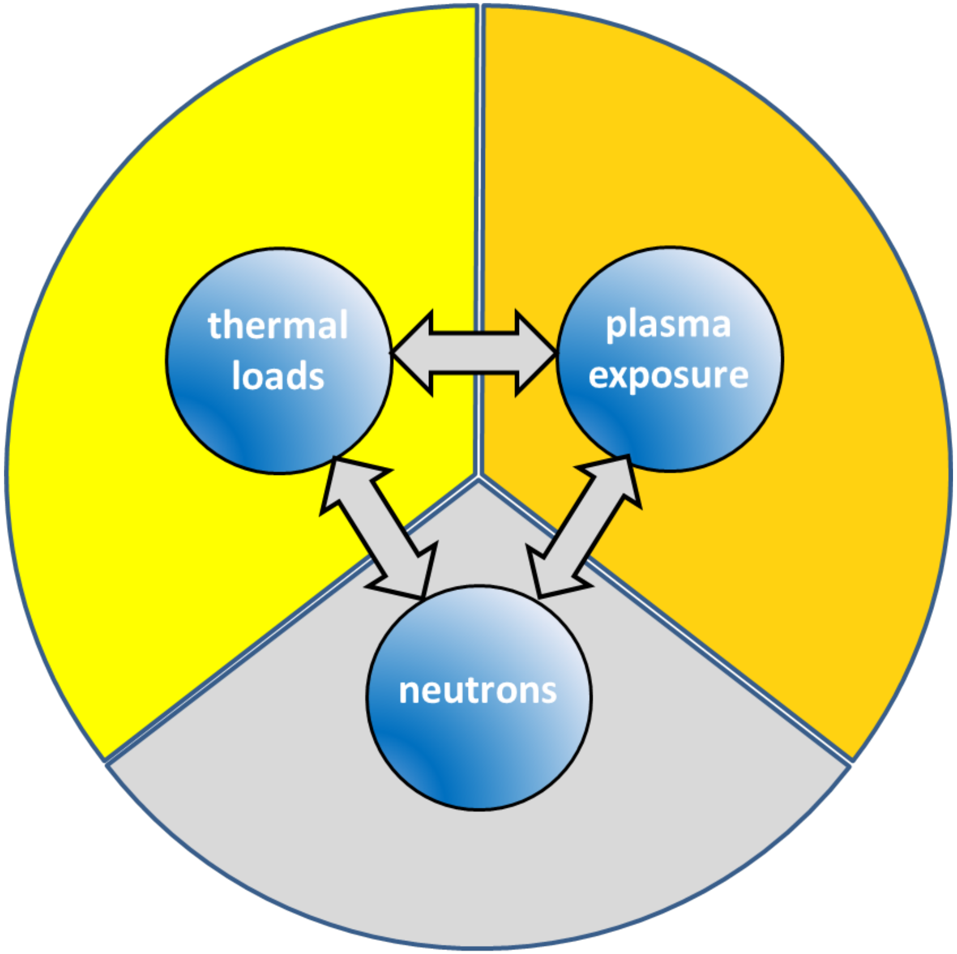
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.

Introduction

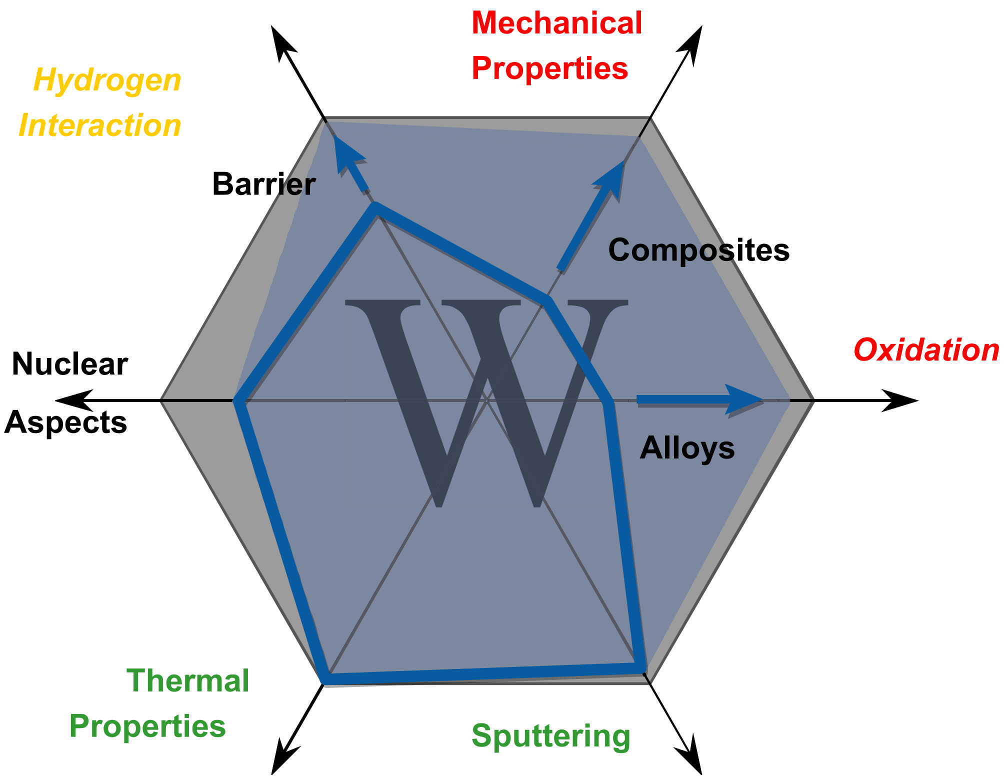
What is SP1 about

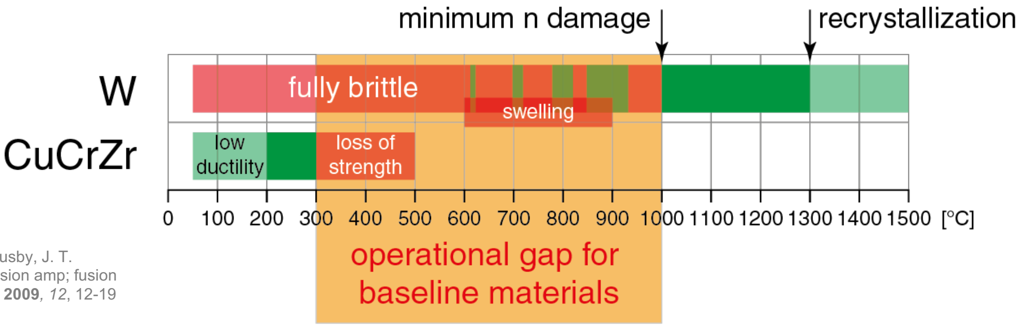
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.

Synergistic Loading



Tungsten as 1st Wall Material

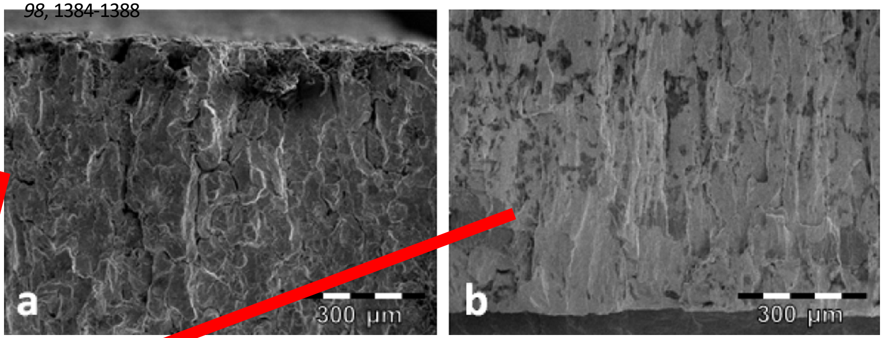


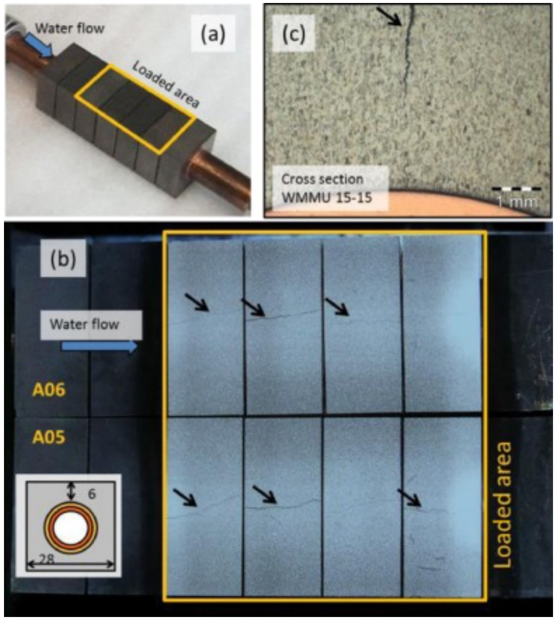


Based on: Zinkle, S. J. & Busby, J. T. Structural materials for fission amp; fusion energy *Materials Today* , **2009**, *12*, 12-19

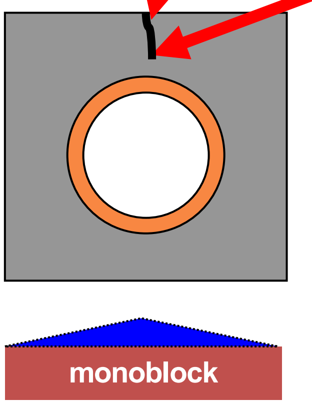
Cracking

Pintsuk, G.; Bednarek, M.; Gavila, P.; Gerzoskovitz, S.; Linke, J.; Lorenzetto, P.; Riccardi, B. & Escourbiac, F. Characterization of ITER tungsten qualification mock-ups exposed to high cyclic thermal loads *Fusion Engineering and Design, Elsevier,* **2015**, *98*, 1384-1388





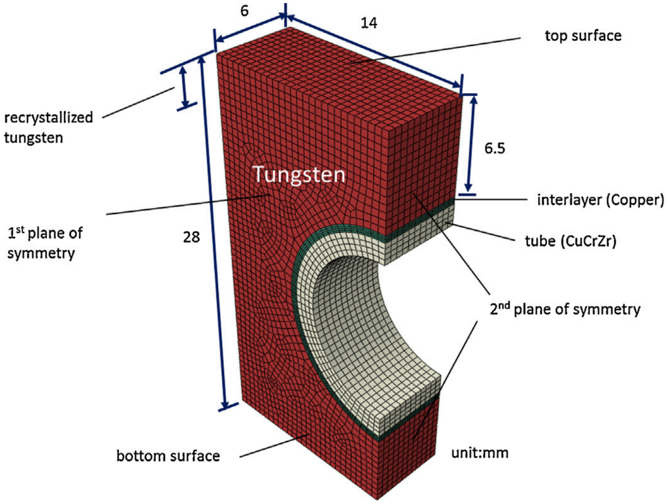
Hirai, T.; Panayotis, S.; Barabash, V.; Amzallag, C.; Escourbiac, F.; Durocher, A.; Merola, M.; Linke, J.; Loewenhoff, T.; Pintsuk, G.; Wirtz, M. & Uytdenhouwen, I. Use of tungsten material for the ITER divertor ,*Nuclear Materials and Energy, Elsevier BV,* **2016**, *9*, 616-622



From HHF facilities testing :

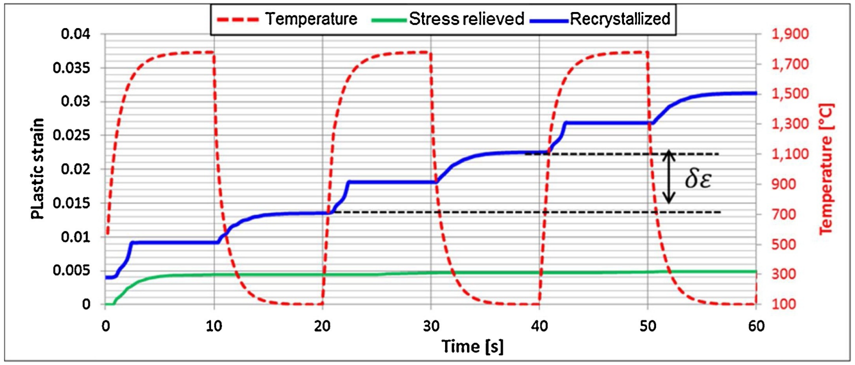
- crack network appear after a large number of ELM like transients
- macro cracks appear under high steady state heat flux (~20 MW/m2) above cooling channel due to plastic deformation and ductility decrease
- Perpendicular power handling not changed
- What changed wrt to thermo-mechanical properties and leading edges? (long term)

Recrystallisation



	20MW/m²	20MW/m²	15MW/m²
Rec. Depth	-	4mm	2mm
# cycles	4.2 × 105	86	617

Li, M. & You, J.-H. Interpretation of the deep cracking phenomenon of tungsten monoblock targets observed in high-heat-flux fatigue tests at 20 MW/m 2 *Fusion Engineering and Design, Elsevier BV*, **2015**, *101*, 1-8



Panayotis, S.; Hirai, T.; Barabash, V.; Amzallag, C.; Escourbiac, F.; Durocher, A.; Komarov, V.; Martinez, J. & Merola, M. Fracture modes of ITER tungsten divertor monoblock under stationary thermal loads *Fusion Engineering and Design, Elsevier BV,* **2017**, *125*, 256-262

Cracking Occurs after a given number of cycles for a given level of recrystallisation

Recrystallisation drastically changes the stress-strain behaviour inside the monoblock and leads to fatigue damage

EUROfusion

Subtopics

Delays / Covid related and others

JÜLICH Forschungszentrum IPP sck cen Belgian Nuclear Research Centre

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Differ

- Waiting to do follow up on SP1.1 experiments
- SP1.3 is delayed to 2021 best outcome experiments in Dec 2020

SCK - CEN

- Some activities are still going on (in particular, SEM on W-fibers on neutron irradiated KLST samples and first high temperature tests on KLST samples).
- The extra tests in 300-500C will be performed in DEC 2020 or JAN 2021. JUNE 2021 (currently considered as eligible period of execution of tasks).
- For WP-PFC, Transfer of HW to 2021.

IPP

- Gladis Tests in SP1.3

EUROfusion

Subtopics

PFC.SP1.1: Effects of tokamak-relevant loading conditions on W baseline materials: structure and damage

JÜLICH Forschungszentrum

IPP

sck cen Belgian Nuclear Research Centre

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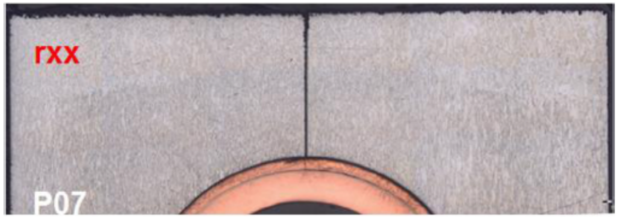
Differ Overview

Fracture of PFCs poses a threat to ITER

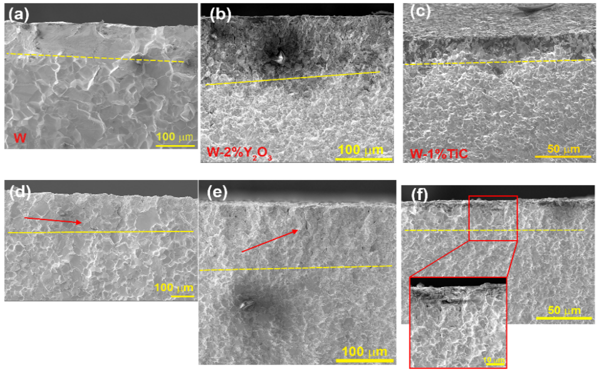


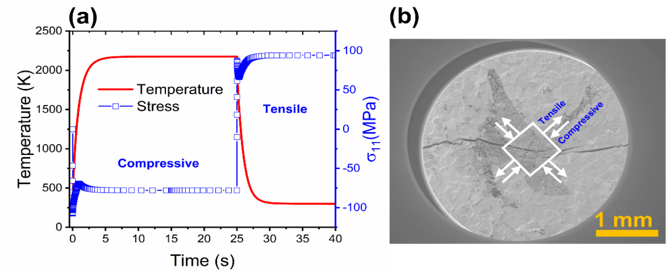
Pintsuk G., et al. 2013 Fusion Eng. Des. 88 1858

Step 1: surface cracking

Step 2: deep cracking

Yu Li, et al. 2020 Nucl. Fusion



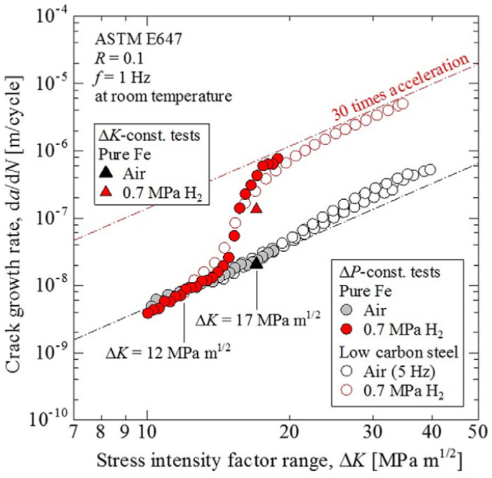


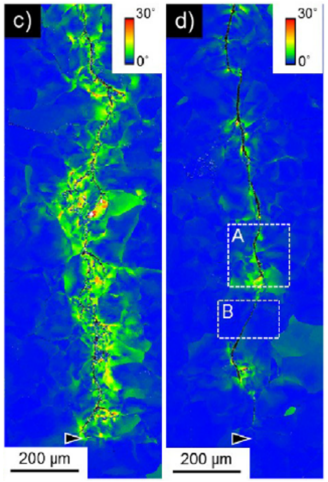
Crack propagation is controlled by crack tip plasticity

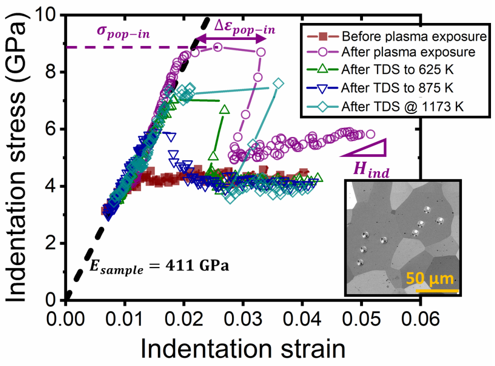
Ogawa Y. et al. 2017 Scr. Mater. ***140*** *13*

Question: What is the effect of hydrogen on fatigue in tungsten?

Crack Propagation / Perf. Experiment







Li Y.. et al 2020 Nucl. Fusion ***60*** *086015*

Sample Ar:

590 K

×100,000

Δ400 K

Ar plasma

Laser pulse

Sample H:

590 K

×100,000

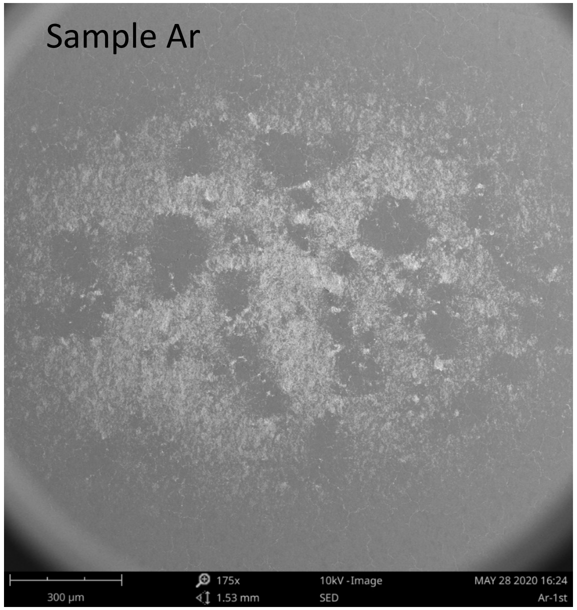
Δ400 K

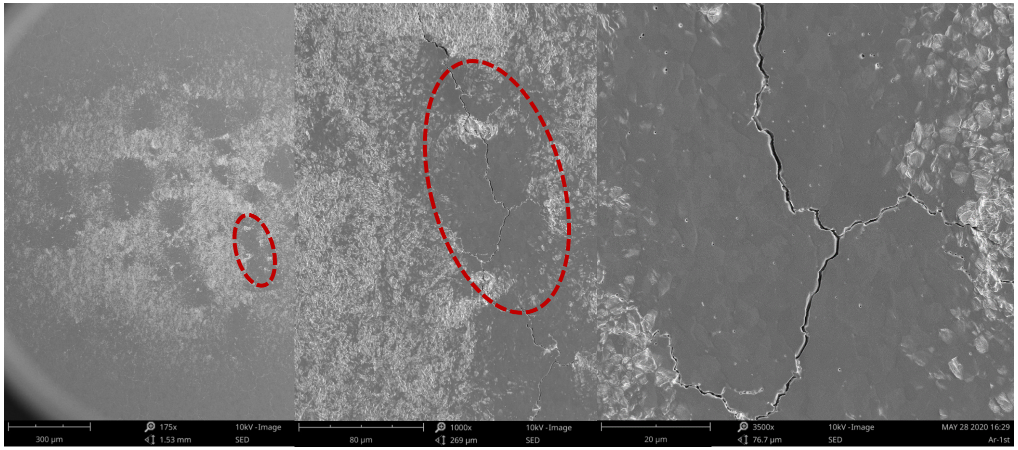
H plasma

Laser pulse

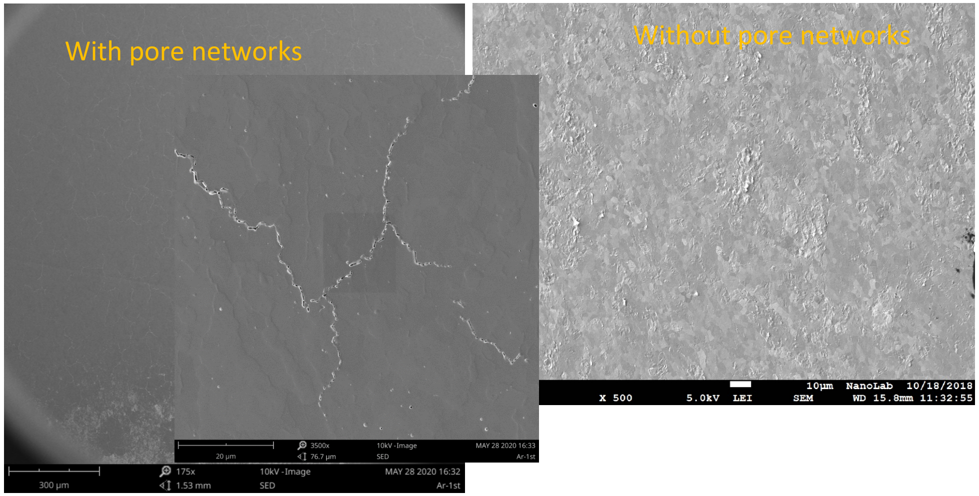
- Pre-existing pores from manufacturing develop into surface crack networks
- The sample with hydrogen plasma induced blistering showed more pronounced crack networks than the Ar plasma reference case; the mechanism needs further investigation

Key Results

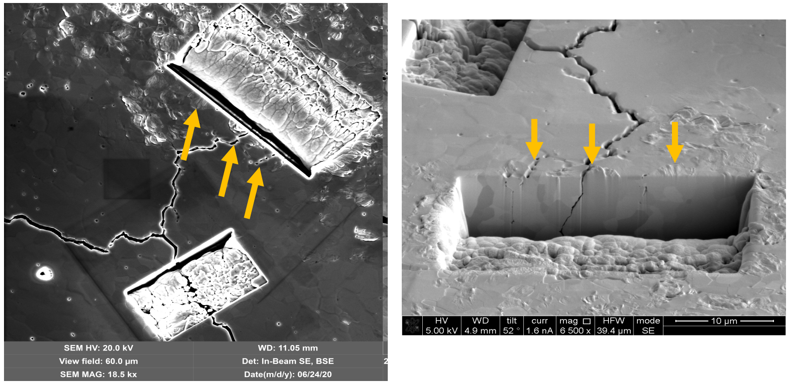




Key observation: Nonuniform damage

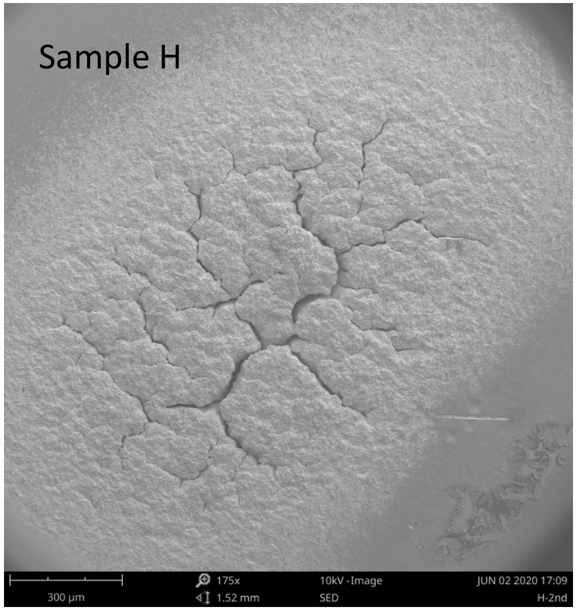


Pre-existing pore network develop into crack network

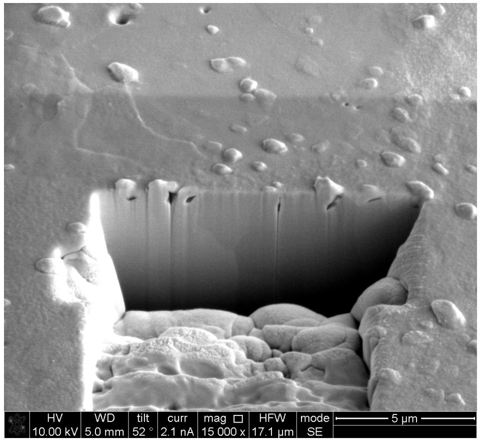


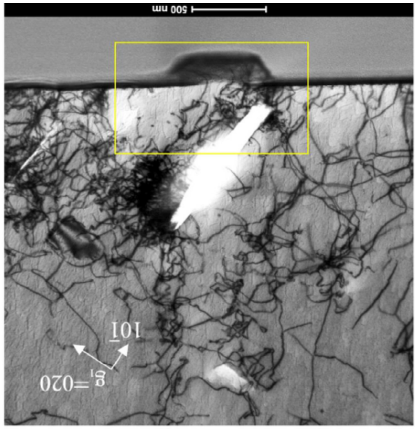
The developed crack networks are quite deep

Key Results



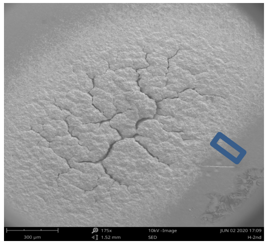
Sample H: blistering



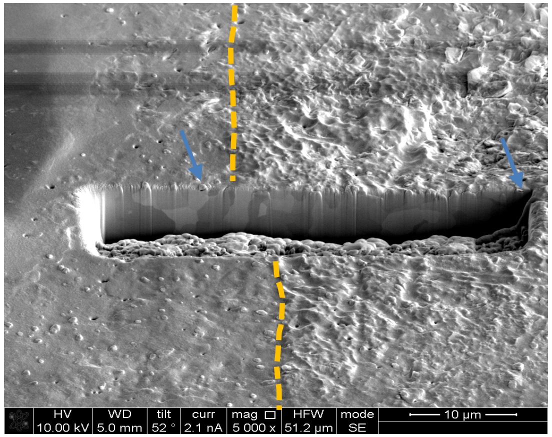


Chen W. Q., Wang X. Y., Chiu Y. L., Morgan T. W., Guo W. G., Li K. L., Yuan Y., Xu B. and Liu W. 2020 *Acta Mater.* **193** 19

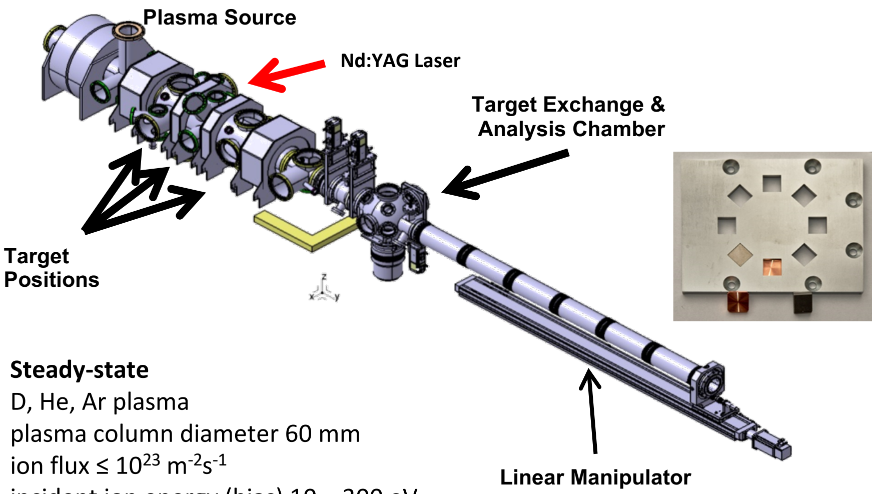
Sample H: cross-section



Cavity and deformation are of similar depth



Exposures in PSI-2



Base temperature of approximately 700 °C

Deuterium / Helium (6 %) plasma

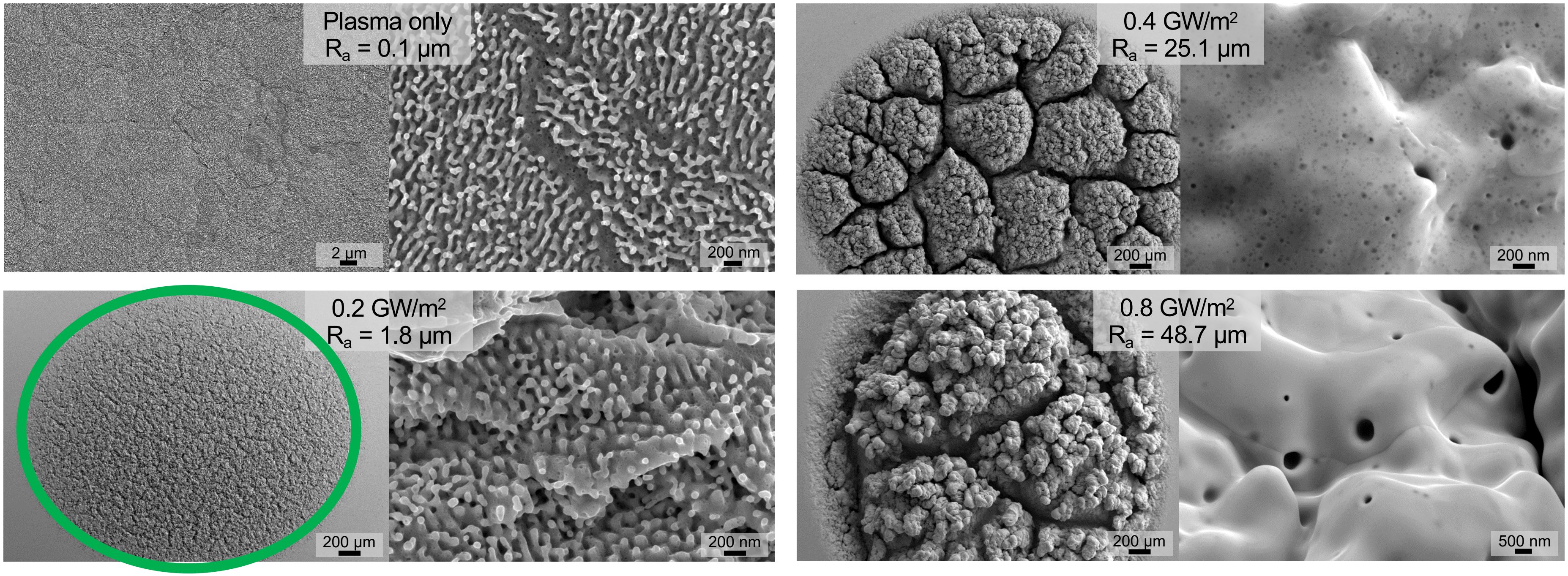
0.5 ms laser pulses with a frequency of 10-25 Hz

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

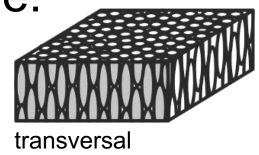
ELM-like heat pulse
Nd:YAG laser wavelength 1064 nm
laser energy 32 J

- Samples exposed to 10^5 thermal shock events of 0.4 GW/m² and higher show alarming surface damages such as cracking, melting, materials loss
- not tolerable during operation of a fusion power plant
- Exposure at 0.2 GW/m² and 10^6 thermal shock events w/o stationary plasma loading show clearly that the additional H/He plasma leads to an fast accumulation of damage (roughening due to plastic deformation)
- embrittlement due to H/He loading, nanoindentation tests are planned in order to quantify the impact on the material properties

Effects of high heat and particle loads

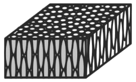


Microstructure:

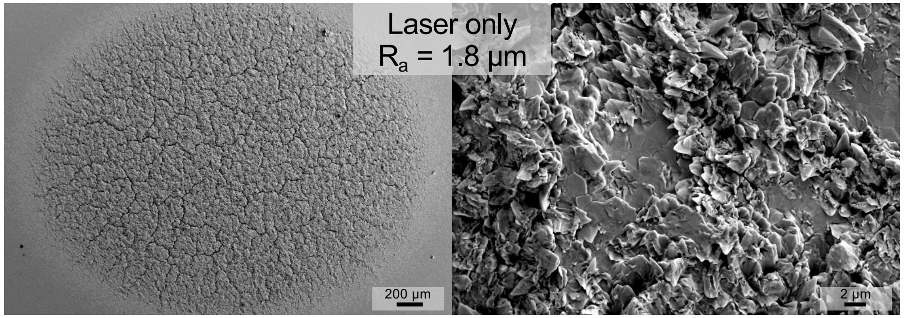


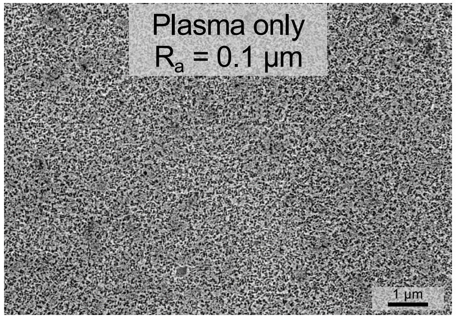
Flux = $6.0 \cdot 10^{21}\ \mathrm{m^{-2}s^{-1}}$
Fluence = $\sim 8 \cdot 10^{25}\ \mathrm{m^{-2}}$
Pulses = 10^5

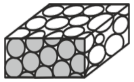
High pulse number tests, independent effects



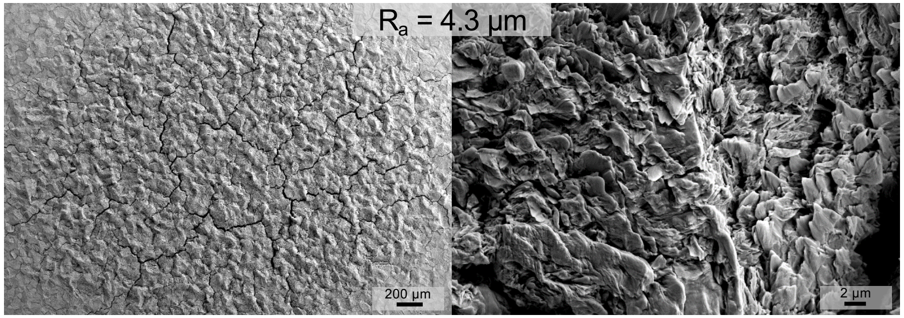
transversal

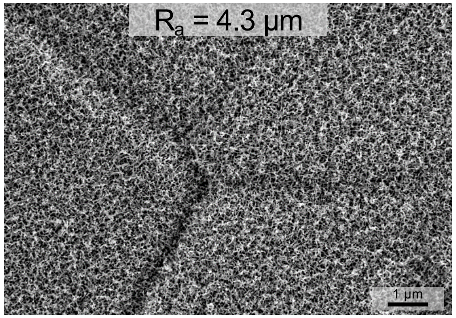






recrystallized

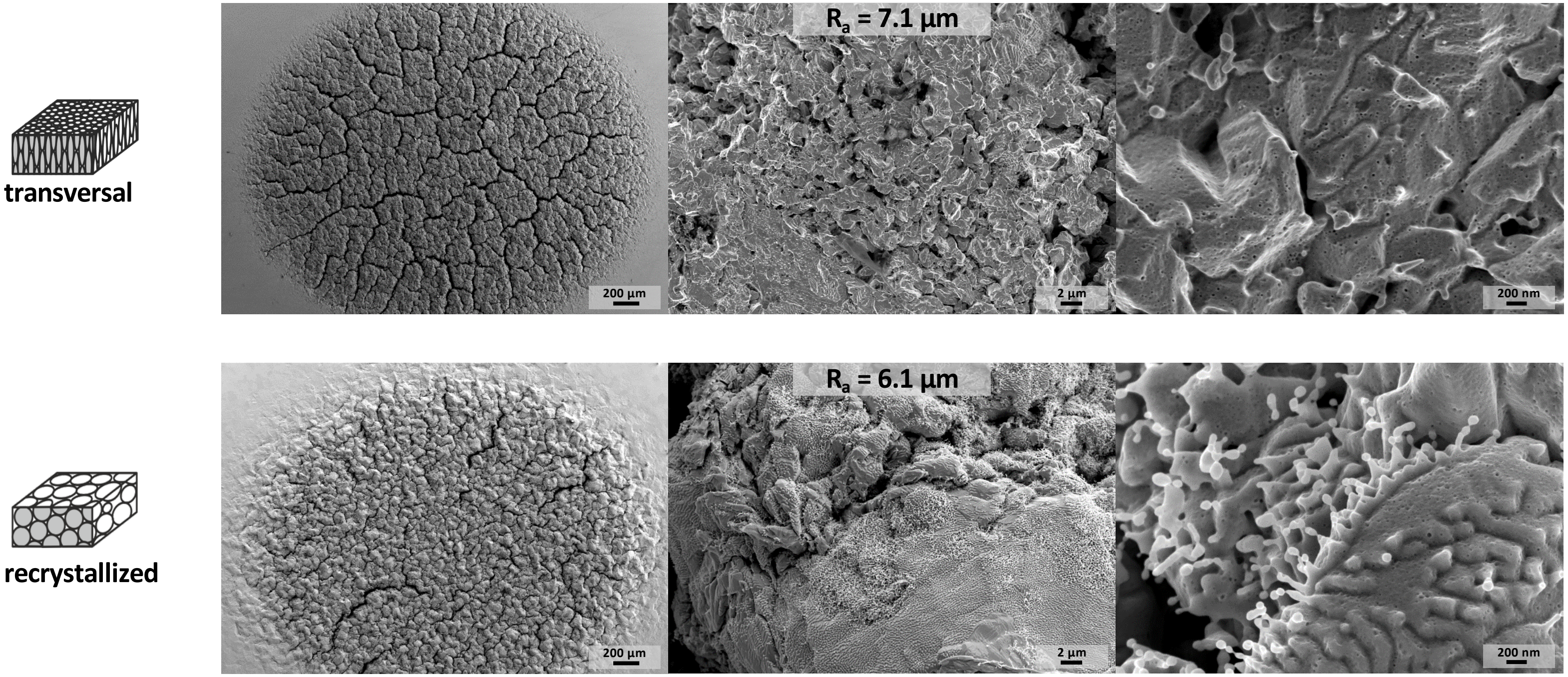




10^6 pulses, 25 Hz freq.
Power dens. = 0.2 GWm^{-2}

Flux = ~ $3.8\cdot10^{21}$ $m^{-2}s^{-1}$
Fluence = ~ $2\cdot10^{26}$ m^{-2}

High pulse number tests, synergistic effects



10^6 pulses, 25 Hz freq.
Power dens. = 0.2 GWm^{-2}

Flux = ~ $3.8 \cdot 10^{21}$ $m^{-2}s^{-1}$
Fluence = ~ $2 \cdot 10^{26}$ m^{-2}

GLADIS contributions to WP-PFC SP 1.1 in 2020

PFC SP 1.1: **“Effects on tokamak-relevant loading conditions on W baseline materials structure and damage”**

Qualification of W baseline materials for ITER and beyond

1. Quality assessment and lifetime estimation of ITER like W monoblock divertor components for WEST

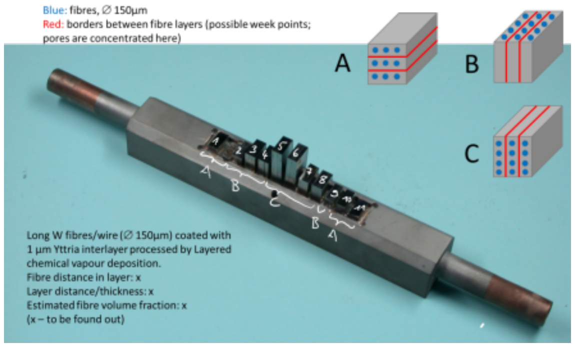
- Assessment of the quality of industrial manufactured PFUs on the basis of the surface temperature evolution of the individual W monoblocks during 100 cycles at 10 MW/m²
- **Result: QA performed at 9 series elements, no remarkable features, surface impurities complicate the thermal analysis 14 operating days spent, ~ 15 days analysis**


Image provided by CEA

2. Investigation of material structure of W_fW mock-ups, manufactured in collaboration by FZJ & IPP

Intention of the HHF test campaign:

- 15 MW/m² loading, resulting in material temperatures close to 3000°C
- **Results: HHF tests performed within the WP-MAT project**
    - **mock-up PM W_fW B01 survived in good condition**
    - **CVD W_fW B01 partially damaged, tiles removed before cycling**


Blue: fibres, ∅ 150µm
Red: borders between fibre layers (possible week points; pores are concentrated here)

Long W fibres/wire (∅ 150µm) coated with 1 µm Yttria interlayer processed by Layered chemical vapour deposition.
Fibre distance in layer: x
Layer distance/thickness: x
Estimated fibre volume fraction: x
(x – to be found out)

Subtopics

PFC.SP1.3: Material parameters of tungsten materials used and considered for fusion applications before and after tokamak relevant exposition

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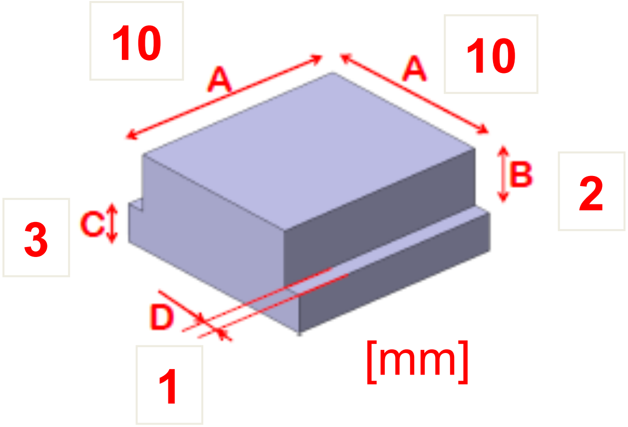
Fabrication of tungsten samples via PIM

Fabrication of tungsten samples for testing @ PSI-2 via PIM



Dimension of the sample

#	Material	No of samples
11	W-1TiC	42
12	W-2Y2O3	56
43	W-3Re-1TiC	56
40	W-3Re-2Y2O3	60
38	W-1HFC	56
18	W-1La2O3-1TiC	14

Delivery of 284 samples (see table) to M. Wirtz (FZJ) in February 2020 ✓

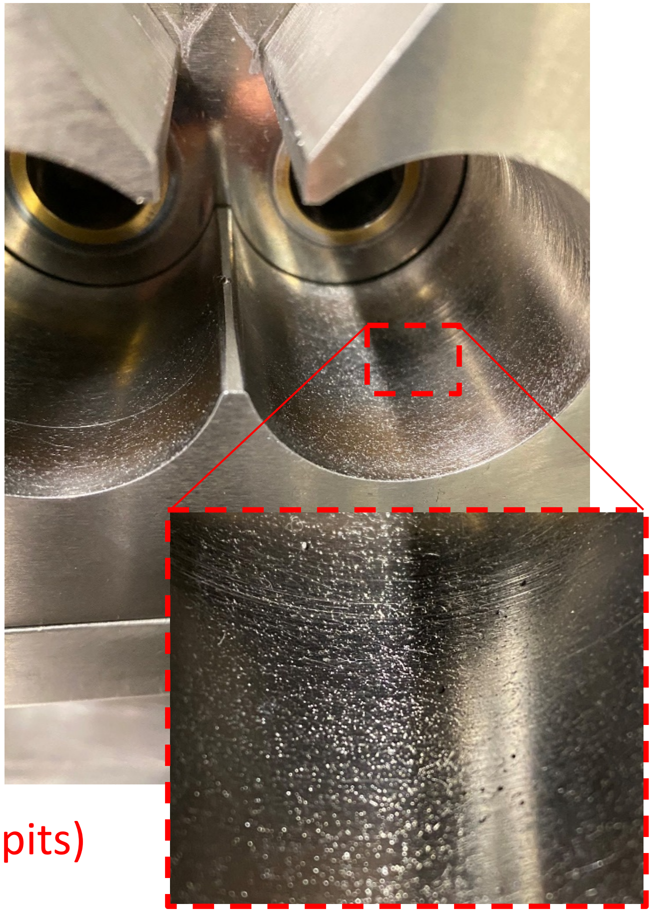
More samples on request.

Fabrication of tungsten samples via PIM

WfW Feedstock preparation and fabrication of samples via PIM

WfW Powder + Fibres
(J. Coenen, FZJ)

WfW Feedstock after kneading



Damage of the wear resistant surface (grooves, scratches and pits) of the kneader during kneading of WfW feedstock).

No futher tests on the PIM machines.

GLADIS contributions to WP-PFC SP 1.3 in 2020

PFC SP 1.3: "Material parameters of tungsten materials used and considered for fusion application before and after loading"

Investigation of heavy alloy W(90-95%) -Cu-(Ni) composite materials

Intention of the assessment:

- Assessment of the suitability as divertor or baffle plasma-facing material for W7-X to substitute bulk W
- Material characterization before/ after HHF loading
- HHF test to explore the thermal limits (actively cooled)

Investigation of W coatings on metallic and non-metallic substrates

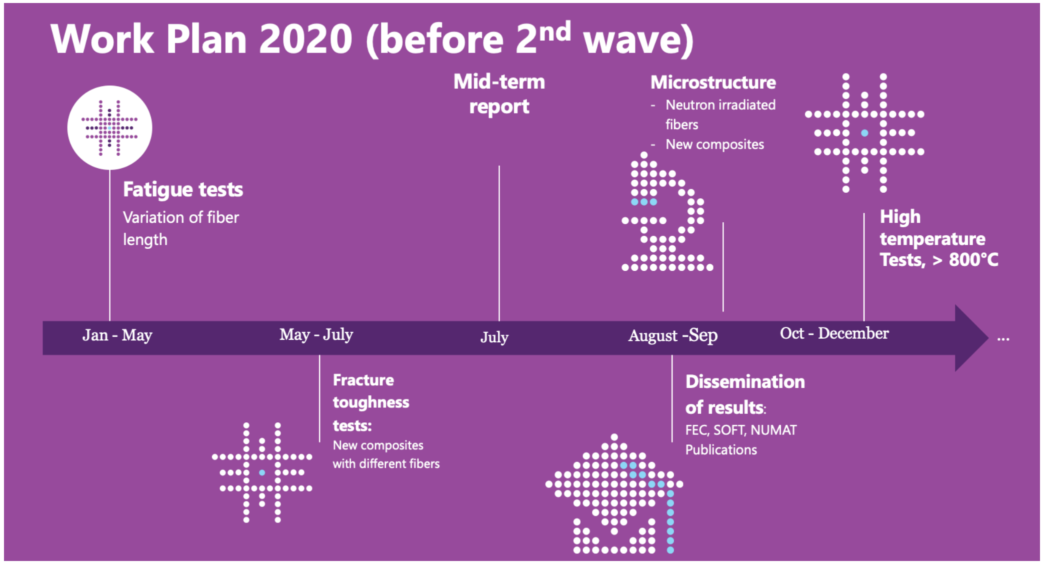
Intention of the assessment:

- Qualification test and characterization of W coatings as plasma-facing material
  - W7-X
  - JT-60 SA

- **Result: no HHF experiments have been performed so far**

Test matrix in 2020

- Assessment of cyclic fatigue load (in tension) on W fibers
  - Reveal effect of fiber length, consider L = 30 mm : 15 mm : 6 mm
  - Reference tensile tests + Fatigue tests + Microstructural characterization
- Assessment of fracture toughness of Wf-W composites
  - Long fibers (used in neutron irradiation LOT B)
  - Short fibers (used in neutron irradiation LOT B)
  - Chinese fibers – supplied by FZJ (J. Coenen)
  - OSRAM fibers – supplied by FZJ (J. Coenen)
  - 1900C 60 Mpa 4 min – supplied by FZJ (J. Coenen)
  - Plansee tungsten (reference): T-L and L-T orientations
- Microstructural characterization of W fibers tested after neutron irradiation
  - Long & Short KLST fracture toughness samples



Work Plan 2020 (before 2nd wave)

Fatigue tests
Variation of fiber length

Mid-term report

Microstructure
- Neutron irradiated fibers
- New composites

High temperature Tests, > 800°C

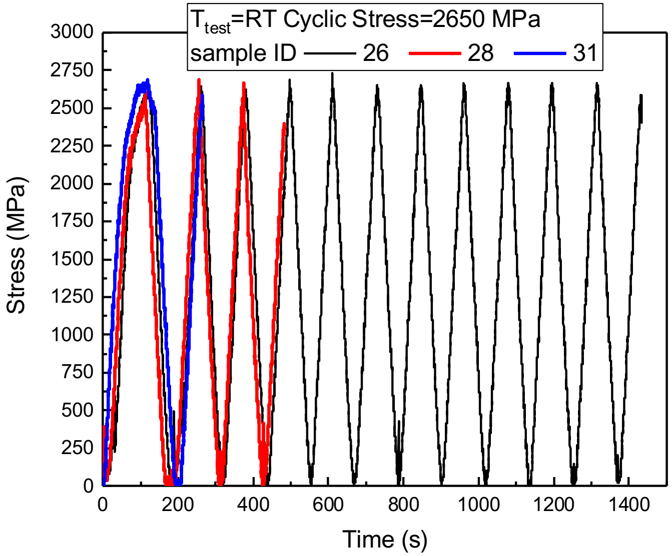
Jan - May · May - July · July · August -Sep · Oct - December · ...

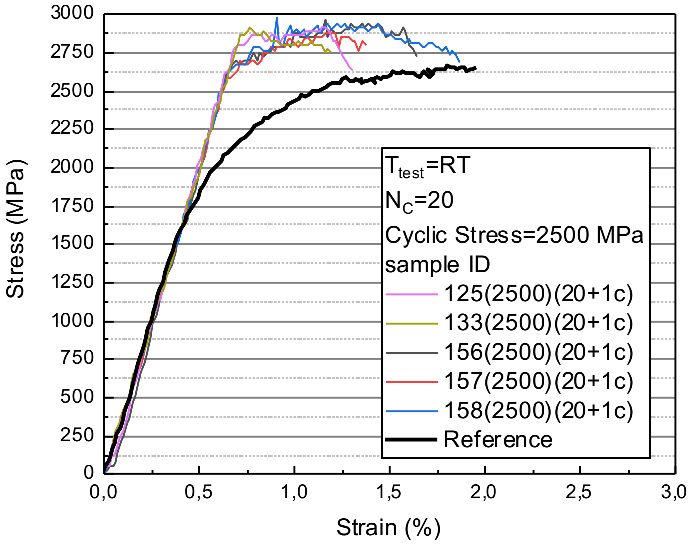
Fracture toughness tests:
New composites with different fibers

Dissemination of results:
FEC, SOFT, NUMAT
Publications

High cycle fatigue of wires

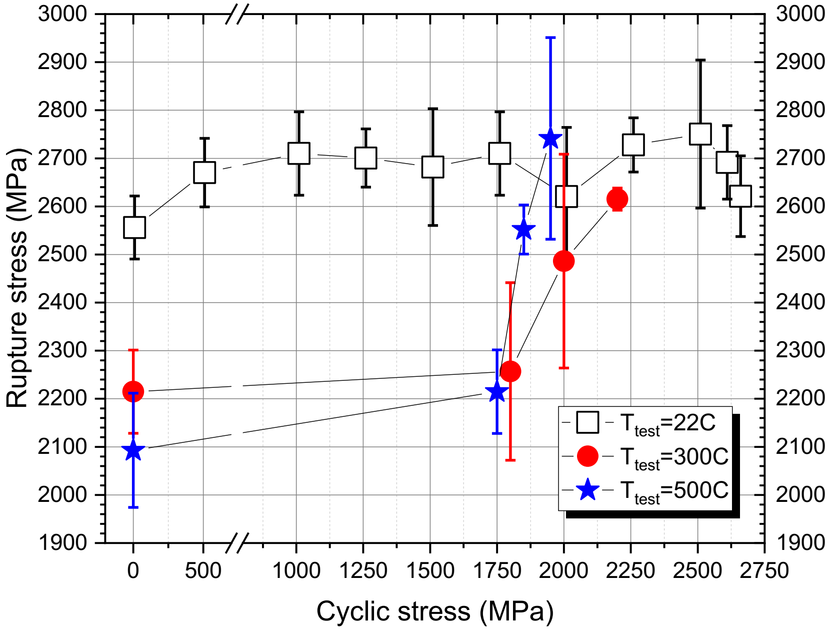
- Increasing stress amplitude > 2600 MPa leads to failure of wire within < 100 cycles
- Making full tensile tests after 10/20/50 cycles: yielded to the same result





High cycle fatigue of wires

- UTS after cyclic load strongly increases if σ_{cyc} > 1750 MPa
- Fracture mechanism of reference and fatigued fibers remains the same



Task_2020_1:

- Confirm the observed trend using shorter wires, which are more representative of PFC component

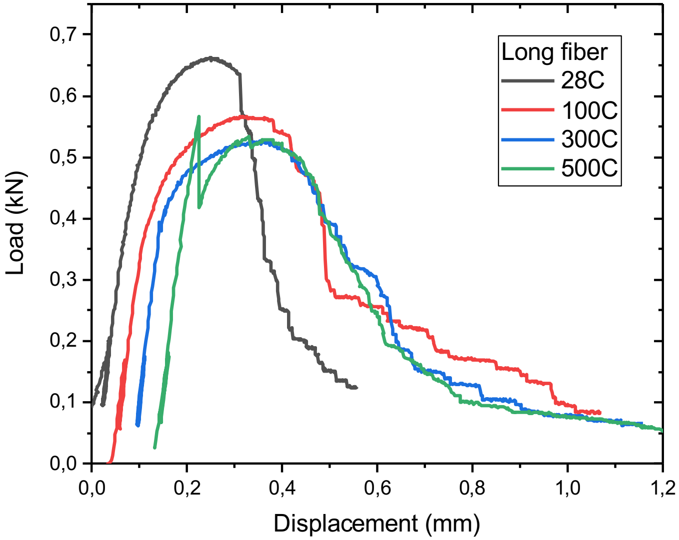
Wire strength is linked to toughness (KQ)

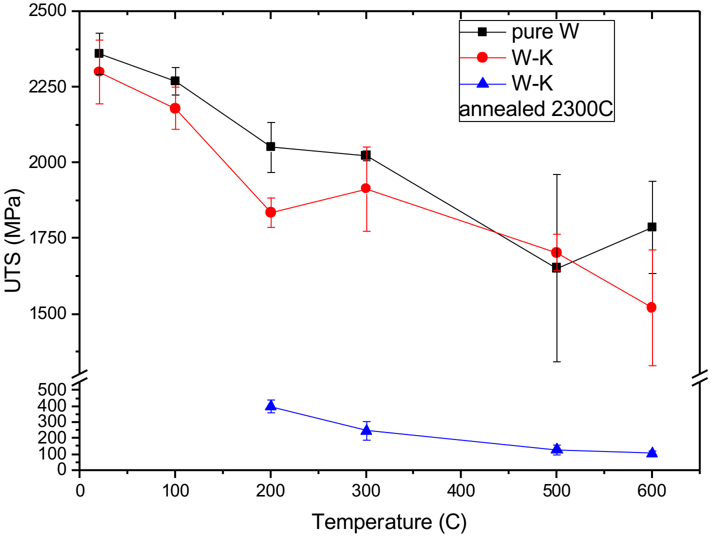
- Conditional fracture toughness goes down with Ttest
- Consistently with the reduction of the wire strength

Task_2020_2:

- Perform fracture toughness tests for KLST samples with other fibers at 300C, 600C and higher T

K_Q_RT/K_Q_500C = 1.33; UTS_RT/UTS_500C = 1.35



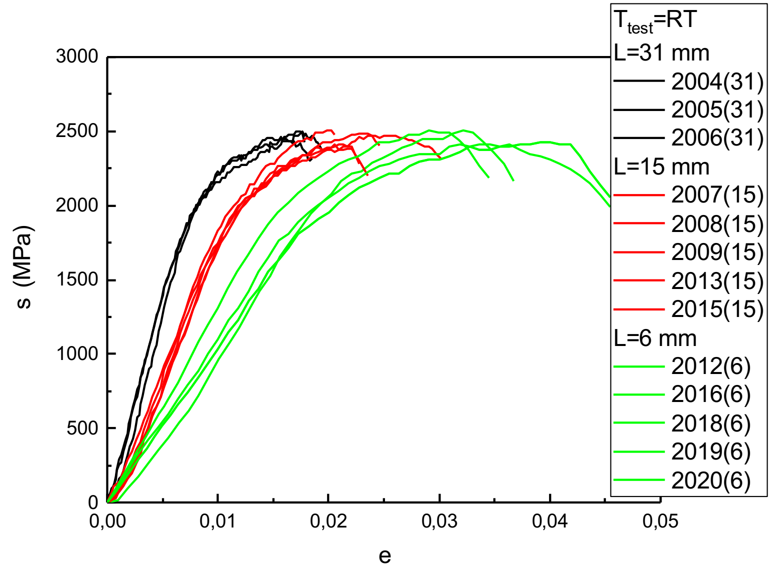


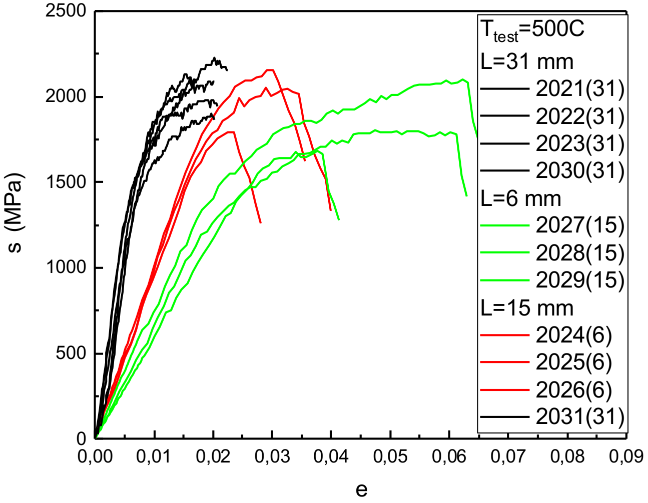
Task_2020_3:

- Perform fracture toughness tests for KLST samples after neutron irradiation

Tensile strength for shorter fibers

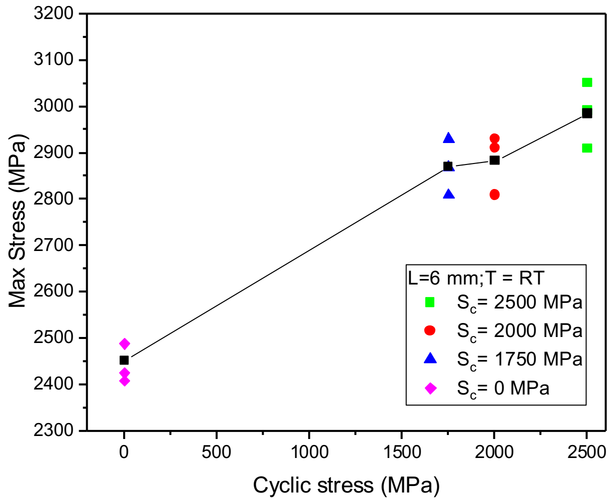
- L= 30mm, 15mm and 6 mm were tested
- Reduction of wire length to 6 mm does not lead to any significant effect on UTS and total elongation as compared L=30 mm

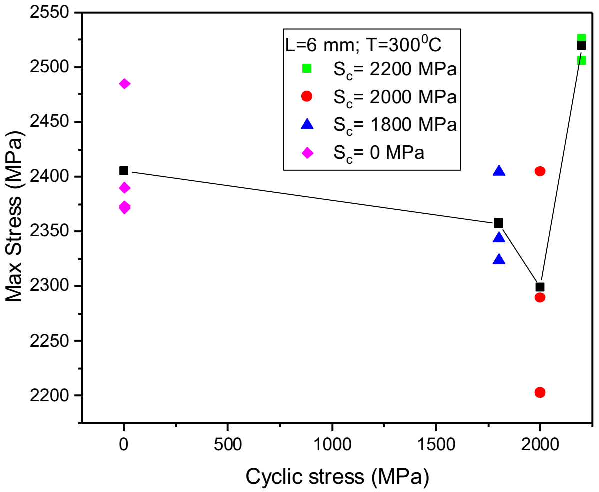




High cycle fatigue of wires

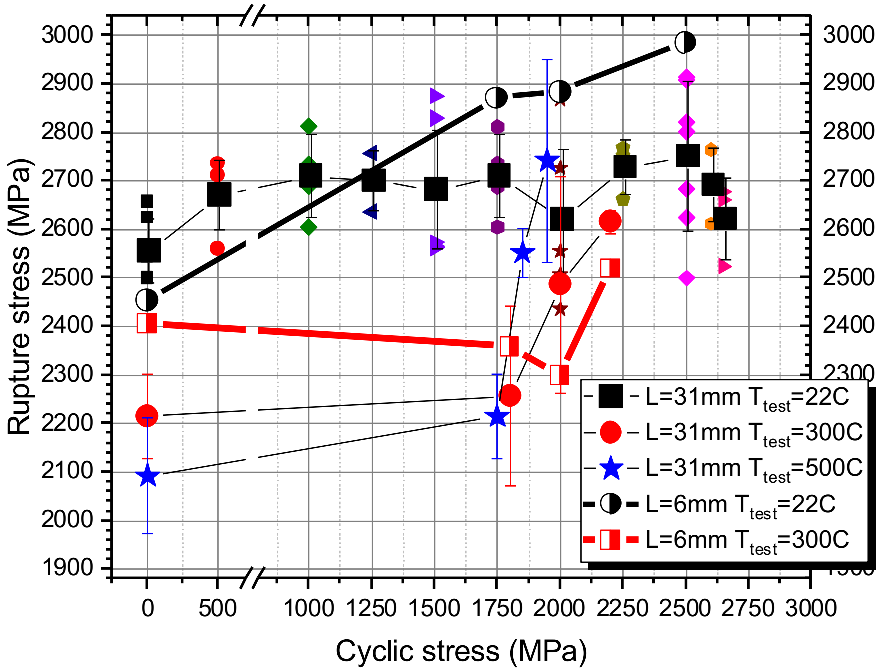
- @RT: the increase of UTS of the pre-fatigued wire occurs as in the case of 30 mm wire
- @300C: the increase of UTS of the pre-fatigued wire occurs above 2000 MPa as in the case of 30 mm wire





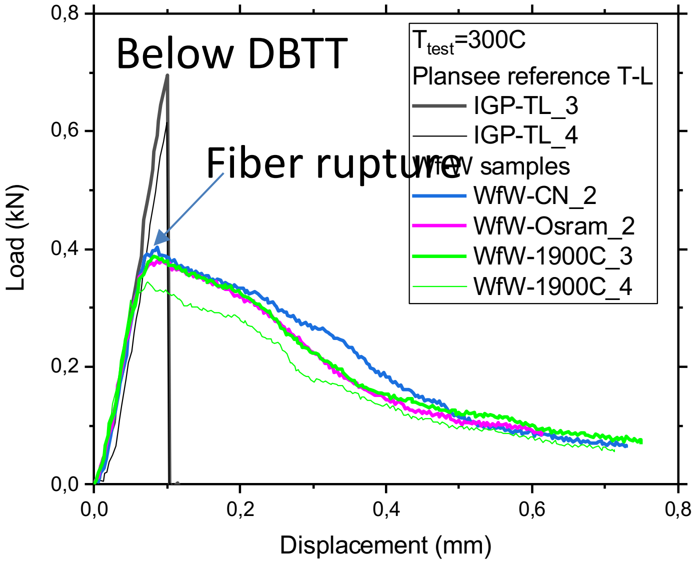
High cycle fatigue of wires

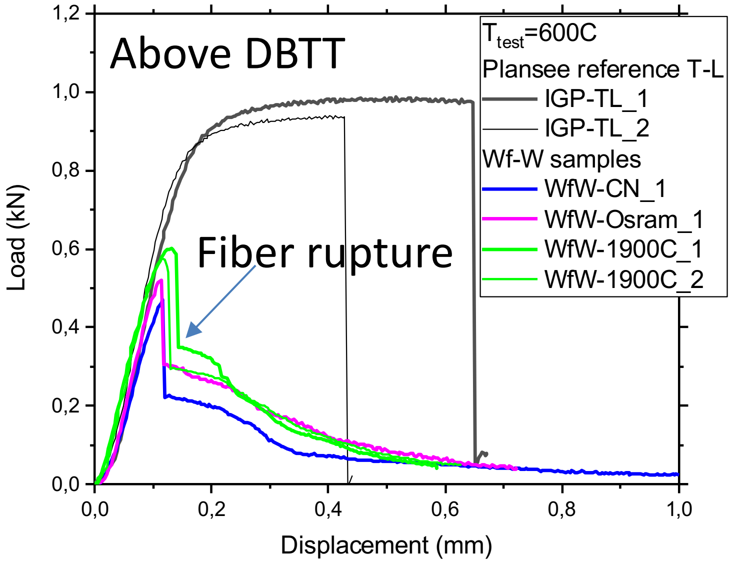
- Shorter wire exhibits steeper increase of the UTS due to pre-fatigue



Fracture toughness tests non-irradiated samples

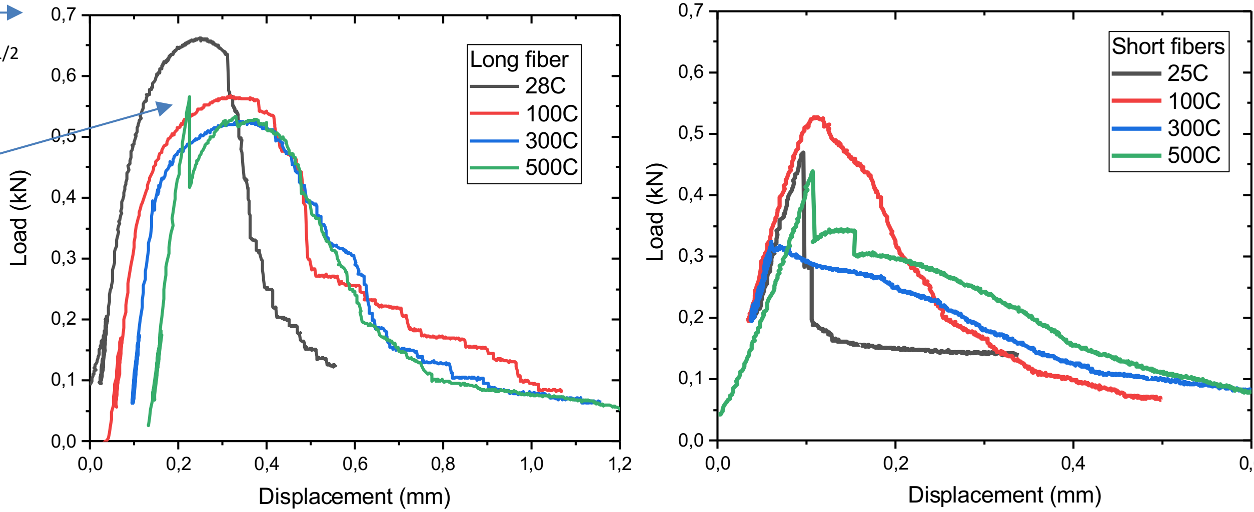
- All samples with new wires exhibit similar behavior
- Wire's strength decreases with raising test temperature





Fracture toughness tests non-irradiated samples

- K_{IC} fracture toughness of long fibers is comparable to that of IGP W in T-L orientation in the lower shelf
- Short fibers exhibit lower K_{IC} and less pronounced toughening effect

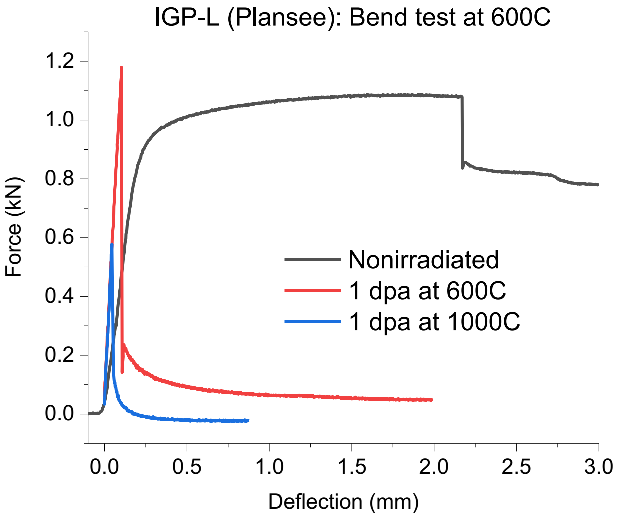


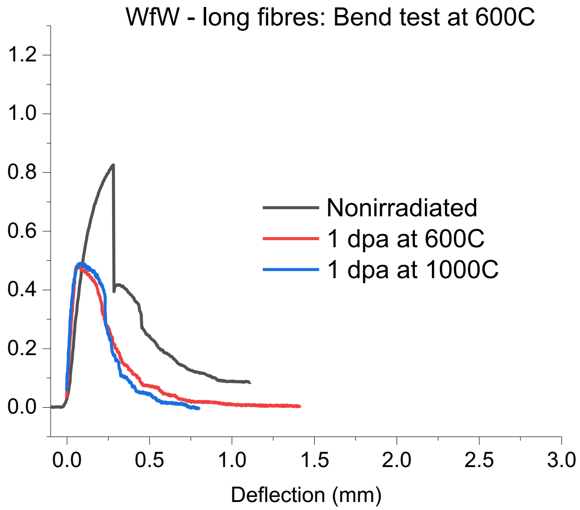
K_{IC}=10 MPa·$m^{1/2}$

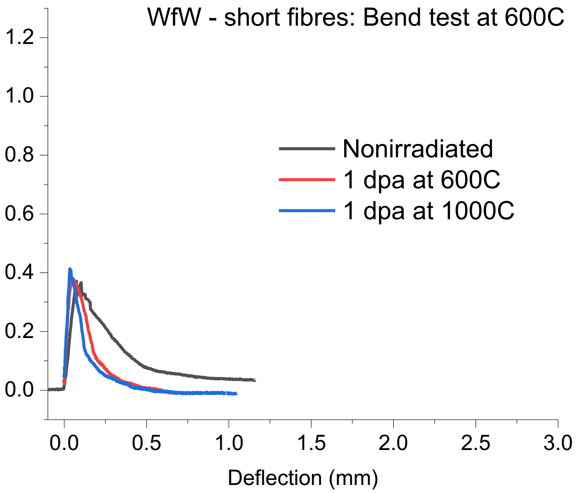
Matrix ductility

Fracture toughness tests: irradiated samples

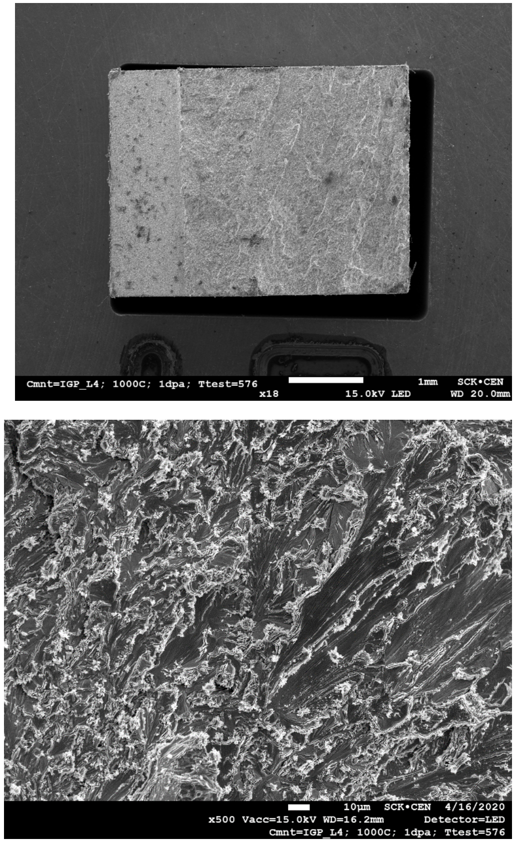
- long-fiber samples: matrix ductility is reduced by irradiation, wire strength remains the same
- short-fiber samples: wire strength remains the same (matrix is brittle as fore irradiation)


IGP-L (Plansee): Bend test at 600C

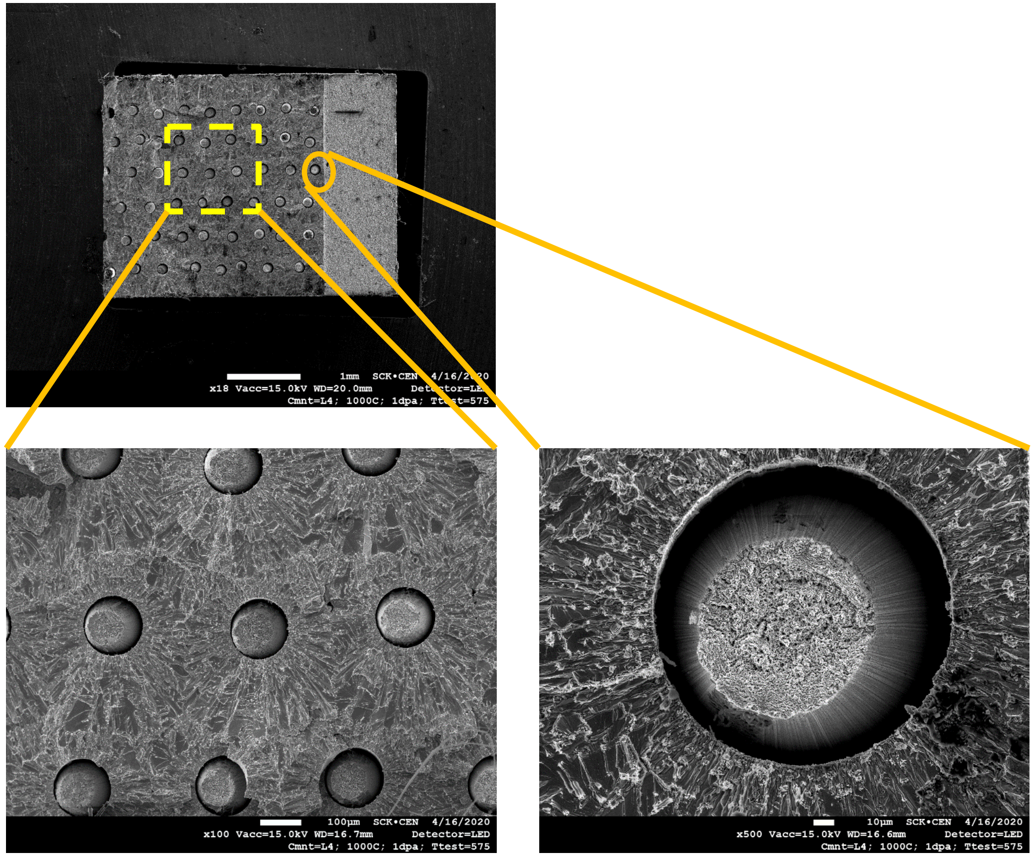

WfW - long fibres: Bend test at 600C


WfW - short fibres: Bend test at 600C

Fracture toughness tests: irradiated samples



IGP



WfW (long fibres)

WfW (long fibres)

EUROfusion

Subtopics

PFC.SP1.8: High power test of plasma-facing components in QPSA and in comparison with other facilities (2018)

NATIONAL SCIENCE CENTRE "KHARKOV INSTITUTE OF PHYSICS & TECHNOLOGY" ХФТИ

IPP

NSC KIPT, Kharkiv, Ukraine
Institute of Plasma Physics

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.

Tasks completed in 2020

1. Studies of damage propagation for misaligned tungsten edges under disruption-like heat loads and included irradiation by plasmas of mixture of different gasses (H+He and H+Ar)

2. Qualification of W and advanced materials at ELM-like and disruption-like loading (in collaboration with FZJ, CCFE, IPP)

3. Comparison of different type of loadings in heat-load and plasma loading facilities including exposes of samples common for WP PFC in LHD devices (as part of activity within WP S1. Material to be specified with SP1 and LHD)

- Plasma shield formation in front of the surface was studied in QSPA –M
  - Pure hydrogen
  - Plasma mixture of hydrogen (95%) and helium (5%)
- Studies of damage propagation for misaligned tungsten edges in QSPA Kh-50
- Analysis of collected erosion products ejected from castellated W targets
- Post-mortem analysis of targets irradiated during joint QSPA - LHD experiment

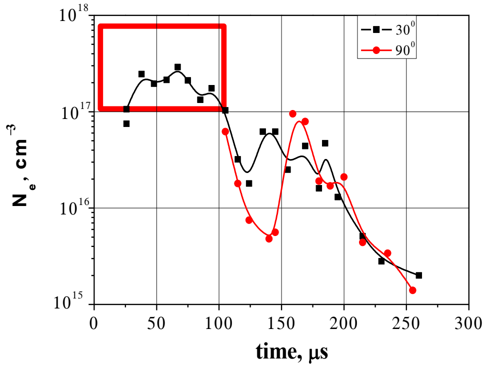
QSPA-M *Evolution of plasma density near surface*

Parameters	
Plasma stream energy density [MJ/m^2]	0.75
Load duration [ms]	0.1
Average heat flux [GW/m^2]	7.5
Heat flux factor [MWs$^{1/2}$/m^2]	75
Magnetic field, T	1

I.E. Garkusha *et al 2017 Nucl. Fusion 57, 116011;*
I.E. Garkusha *et al 2019 Nucl. Fusion 59, 086023*

- Experiments were performed with pure hydrogen plasma
- Experiments were performed with plasma mixture of hydrogen (95%) and helium (5%).
  - H+He Plasma parameters were similar to pure H plasma
- Plasma shield formation in front of the surface has been studied

Pure hydrogen



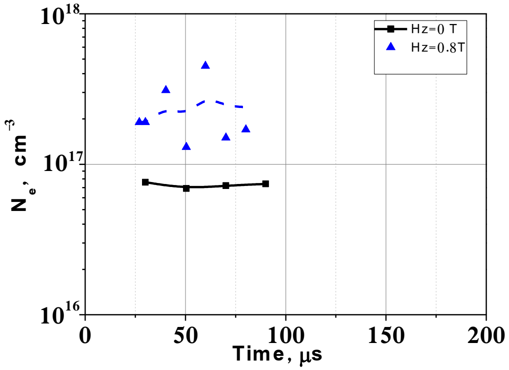
The time distributions of the plasma density were measured from the linear Stark broadening of the spectral line H_β 486.1 nm.

The density of the shielding layer was measured in a magnetic field H = 0.8 T in front of perpendicular (red line) and oblique target (black line).

Maximal density is Ne>3×10^{17} cm^{-3} at normal irradiation (red rectangular).

The broadening of the line exceeds the capabilities of the recording system.

Plasma mixture of hydrogen (95%) and helium (5%)



The duration of the luminosity of HeII line does not exceed 100 µs. Density increased at with growing magnetic field

External magnetic field Hz=0 and Hz= 0.8 T

The plasma density was evaluated by the line of HeII (468.5 nm). t_{ex} =10 µs

Damage propagation for misaligned tungsten edges

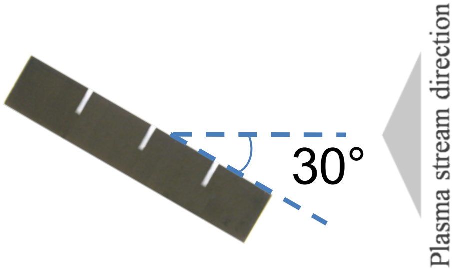
QSPA Kh-50

Parameters	Crack.	Melt.		Evap.
Target Heat Load [MJ/m²]	0.3	0.6	0.9	1.1
Plasma load duration [ms]	0.25	0.25	0.25	0.25
Surface Heat factor [MW×s$^{1/2}$×m^{-2}]	19	38	57	69.6

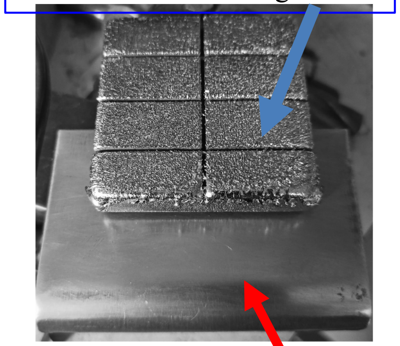
1) Surface of castellated target was exposed with 200 plasma pulses at normal incidence (2018).
2) Additional plasma exposures with 300 plasma pulses were applied at inclined plasma incidence. (2019)

Heat load of 0.9 MJ/m^2 causes pronounced melting of exposed surfaces. (unmitigated ITER ELMs Type I)

Irradiation scheme

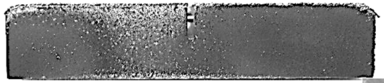


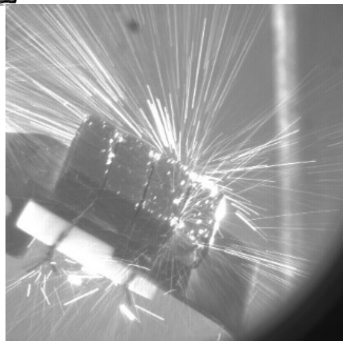
Castellated tungsten target 5x5x1 cm³ with slits. The size of each target unit is 2.4x1.2cm² which is close to divertor reference design



Copper plate to collect erosion products of an irradiated target

Top part of W target was sharp

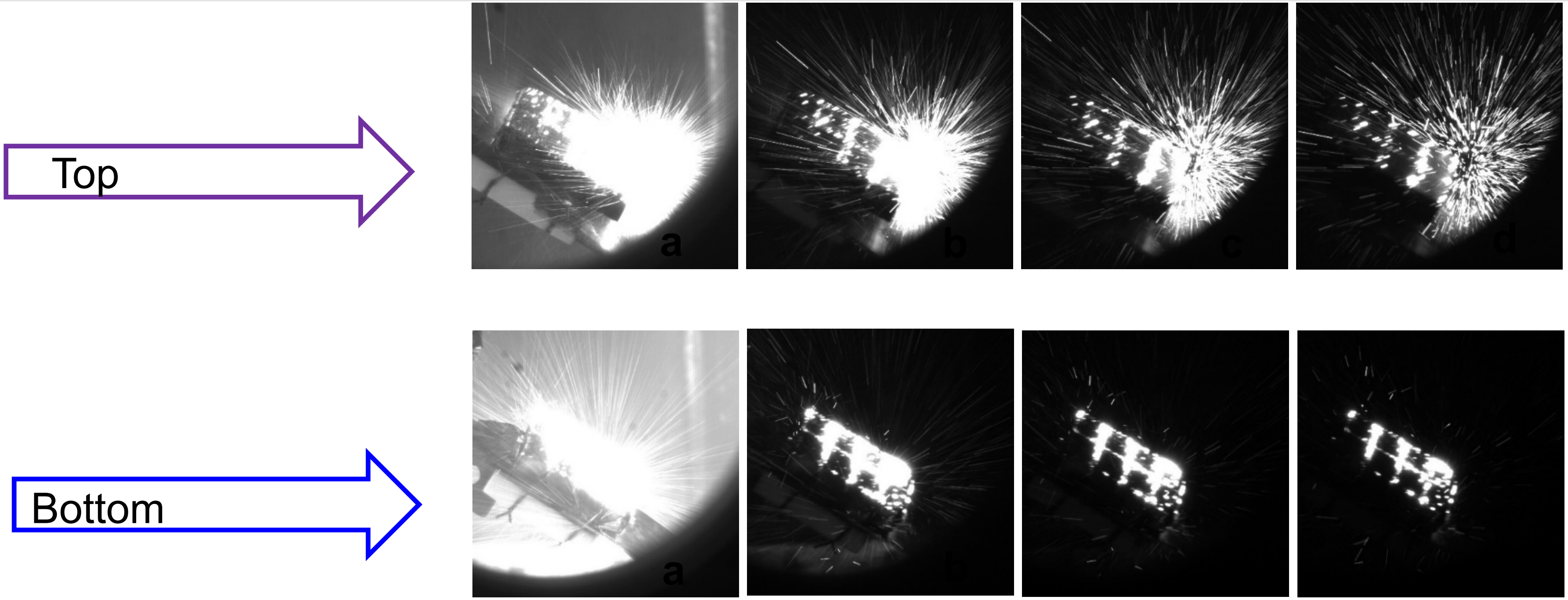




Top and Bottom parts of W target were faced to plasma during irradiation

Bottom part of W target was smoothed

The particle ejection during PSI

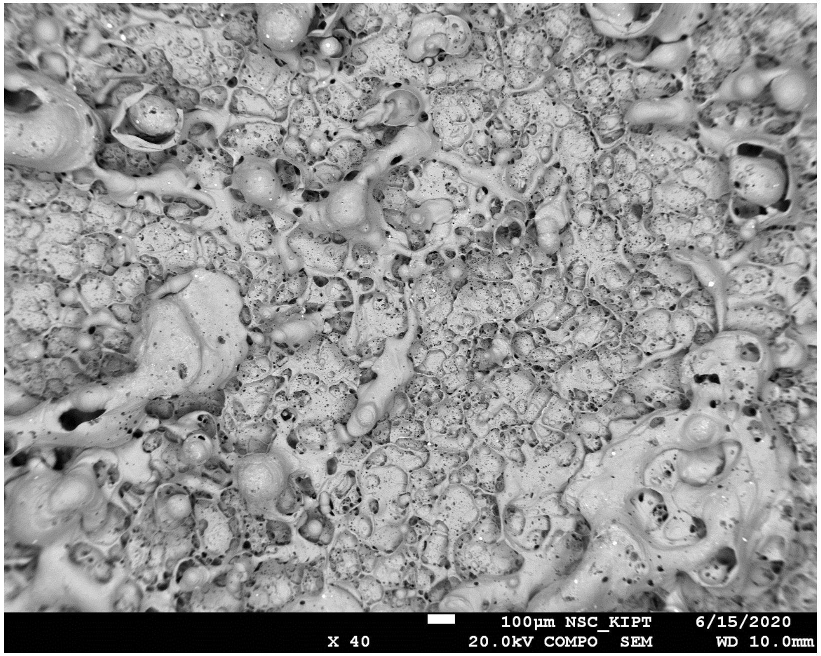


Top and Bottom parts of W target were faced to plasma during irradiation

Images of droplet traces after plasma pulse corresponding to 1.2–2.4ms (a), 2.4–3.6ms (b) 3.6–4.8 ms (c) 4.8–6.0 ms (d) after the start of the plasma–surface interaction (t_{exp}=1.2ms).

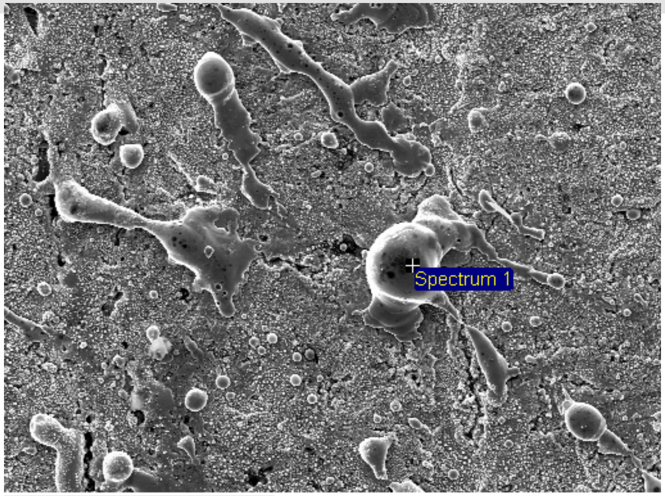
➢The sharp leading edges of castellated W target caused pronounced erosion products ejection during PSI.

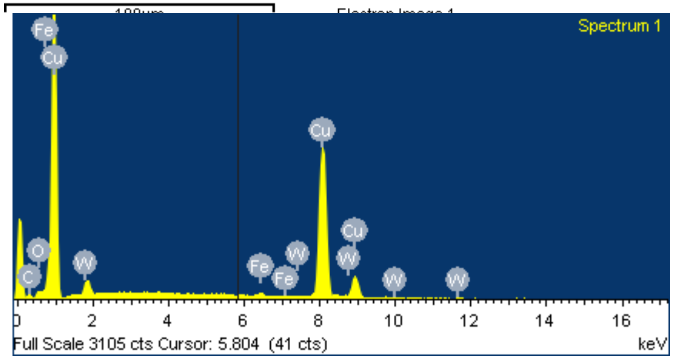
Analysis of collected erosion products



SEM (BSE) image of damaged collecting Cu plate

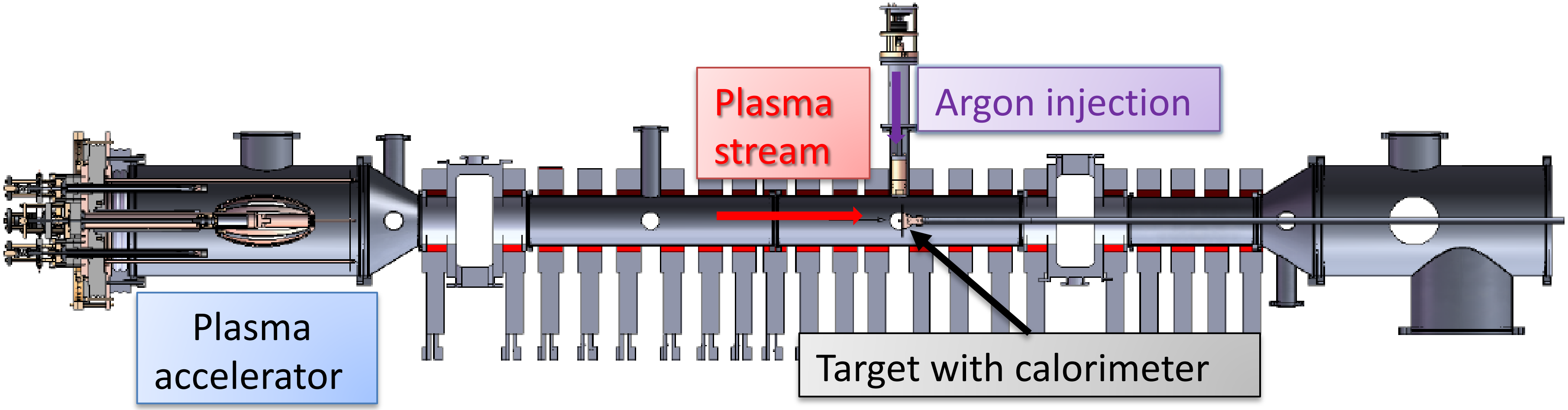
- SEM, XRF analyzes showed the occurrence of deposited layer containing W
- Deposited particles could be mixed with material of collecting plate during plasma irradiation.
- Large particles could fly away after next pulses.



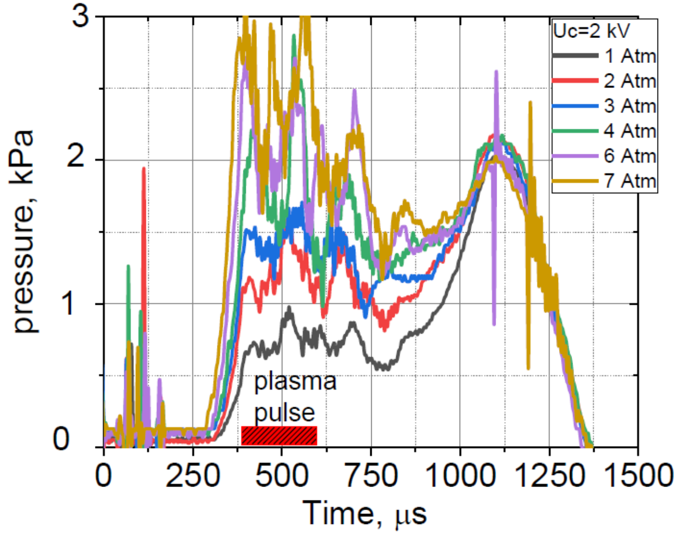


Element	Weight%	Atomic%
O K	1.76	6.93
Fe K	0.68	0.77
Cu K	91.10	90.10
W M	6.45	2.21
Totals	100.00	

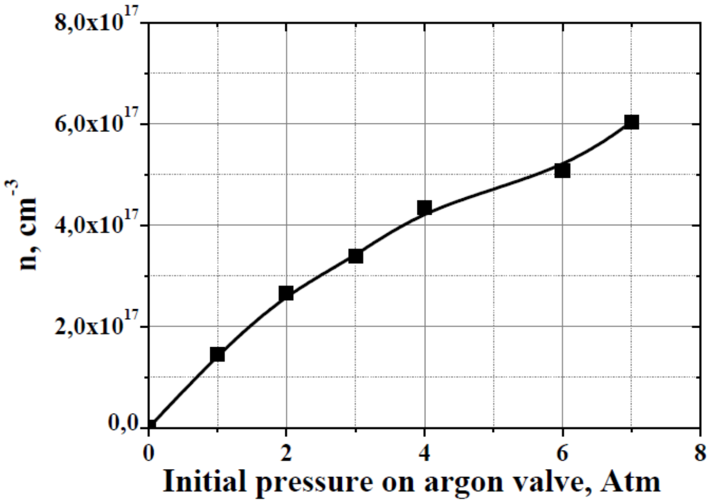
QSPA-M: Injection of Ar along target surface



Special additional gas injector was designed for injection of Ar along target surface.



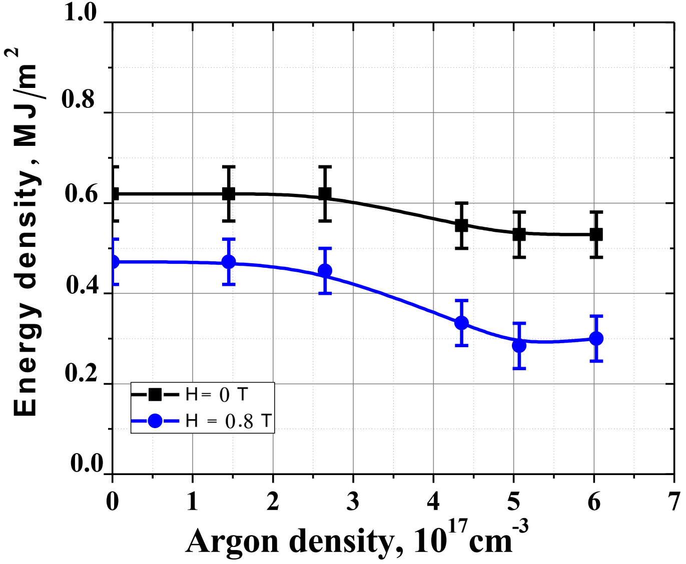
Time distributions of argon pressure near surface depend on initial gas pressure in gas injector



Estimated average density of neutral gas near target at the moment of plasma surface interaction

Energy transfer thought plasmas H+Ar

Energy density absorbed surface

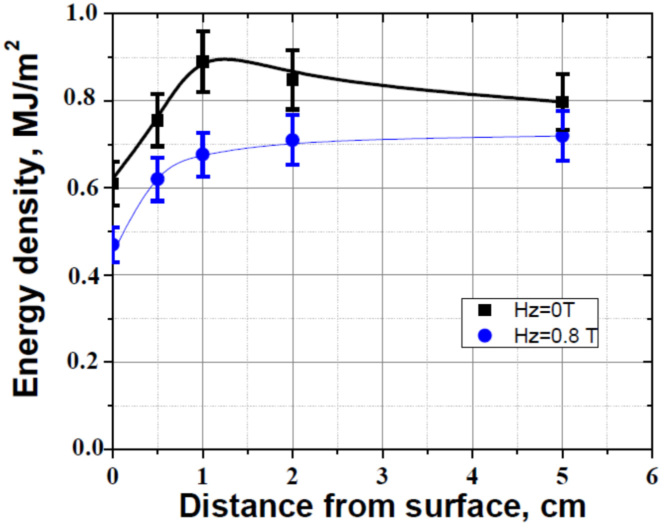


An increase of the neutral gas density in front of the surface leads to a decrease of energy delivered to the target surface.

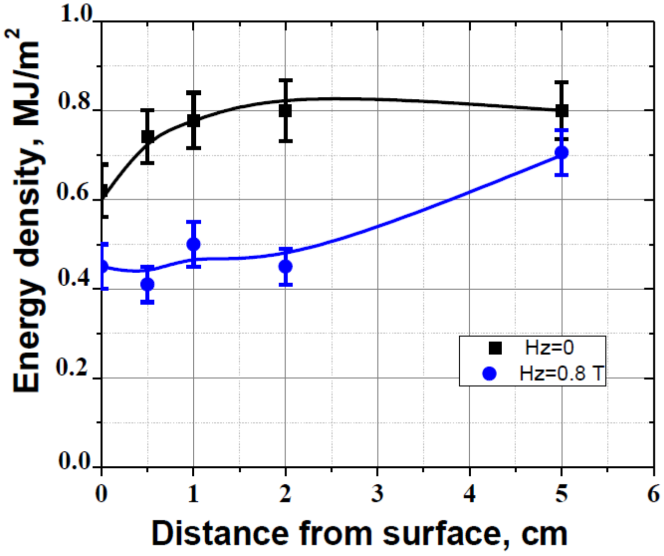
In magnetic field, part of energy dissipated in shielding layer increased.

The thickness of the screening layer is increases at local Ar injection.

Pure hydrogen



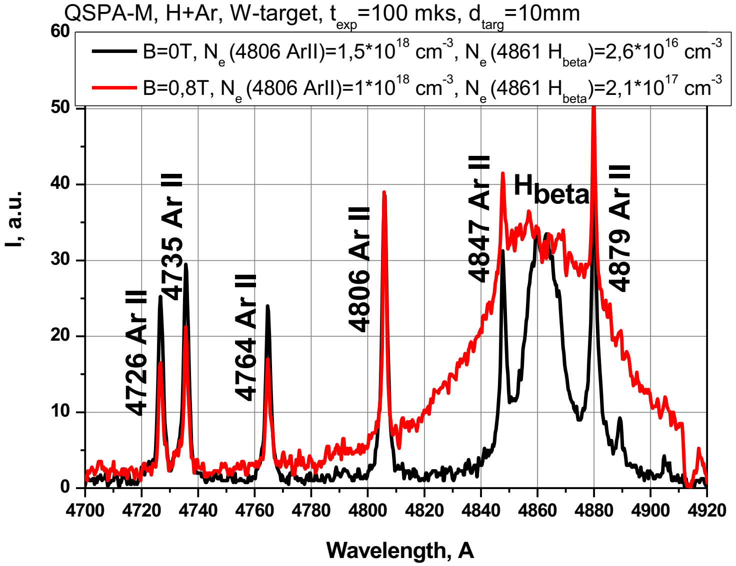
Addition Local Ar injection $n_{Ar}=2.6\times10^{17}$ cm^{-3}



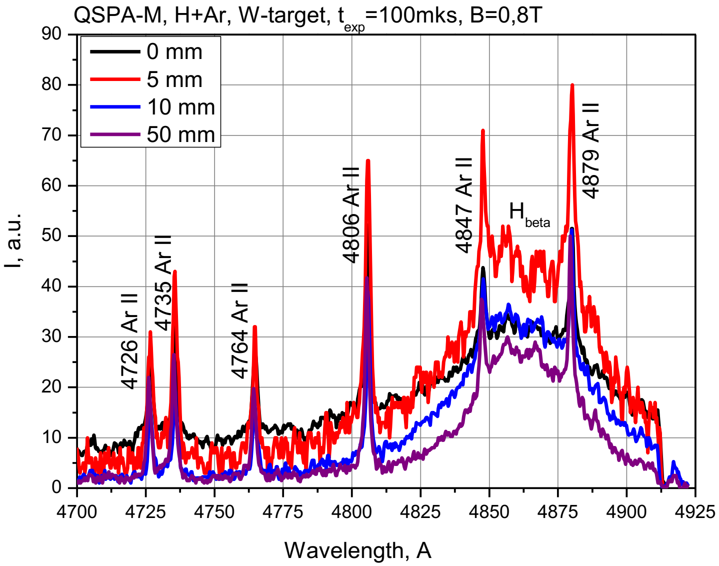
Part energy dissipated in shielding layer increased in magnetic field

Plasma shield formation

Argon is injected along target surface.



Intensity of spectra at H=0.8T (red) and B=0T (black),

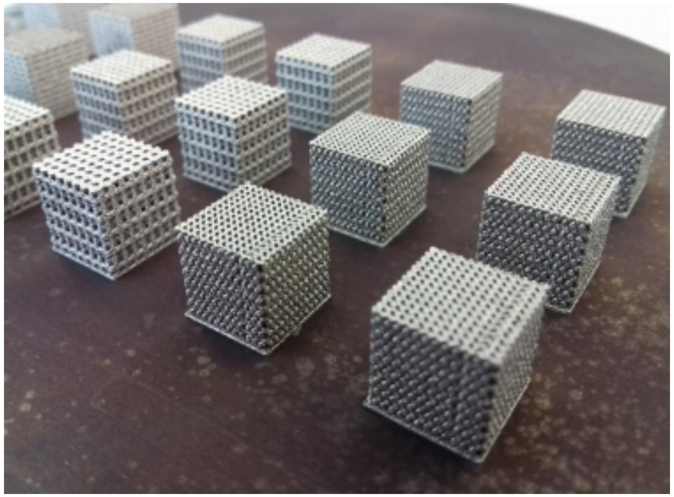


Intensity of spectra versus distance from target, H=0.8T

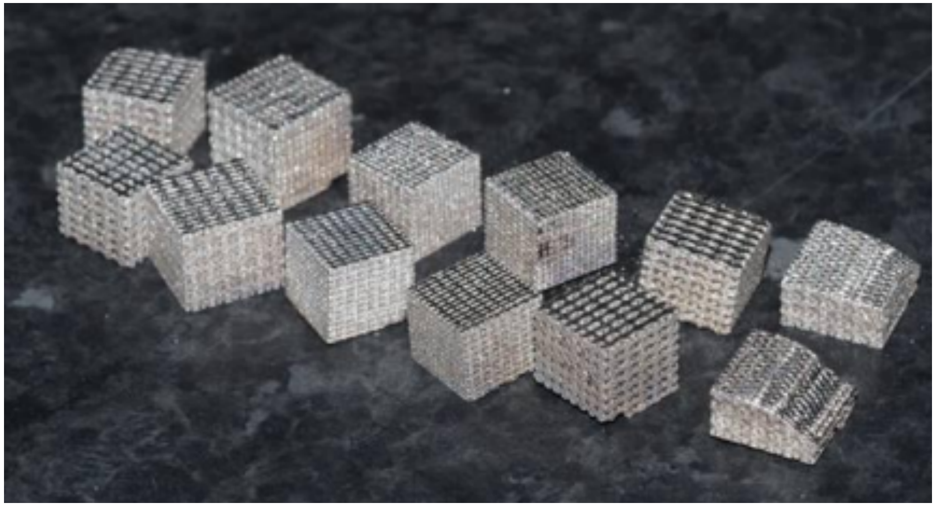
Local injection of Ar leads to increase of electron density of N_e(4806A) up to (1-3)×10^{18} cm^{-3} .
Electron density was estimated from broadening of Ar II (4806A) spectral line.
The influence of magnetic field on half-widths of Ar II spectral lines (i.e. electron density) is not substantially.
The duration of Ar II spectral lines observed during ~ 20 μs only at 30-40 μs from the start plasma surface interaction.

Qualification of W advanced materials (WPDIV)

Collaboration with CCFE (Mantel, Nicolas) and IPP Garching (Jeong-Ha You , Von Müller Alexander)



Pure W AM lattices



W-6% AM lattices

Advanced material "build trials" at Fraunhofer Augsburg (directed by IPP Garching) and Renishaw PLC (directed by CCFE) have produced nominal 1 cm cubes of lattice material in W and W-6% Ta at a range of lattice parameters, designed by Uni Tuscia

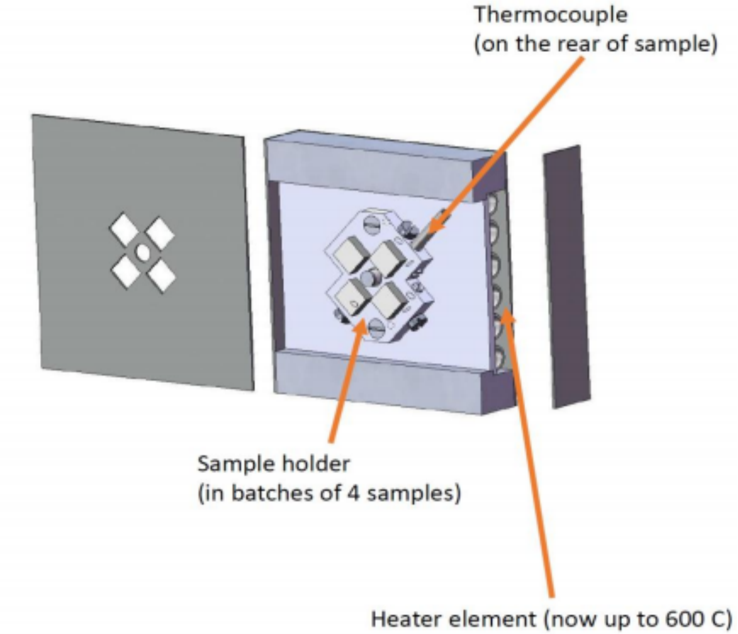
Applied plasma stream energy density, MJ/m^2	Expected result
1.8	Melting
2.3	Strong melting/start evaporation
Up to 3	Pronounced evaporation

- Tests of W advanced materials were performed in QSPA Kh-50

  Larger number of ejected particles is observed under plasma irradiation of lattice W targets with energy density causing strong melting/pronounced evaporation.

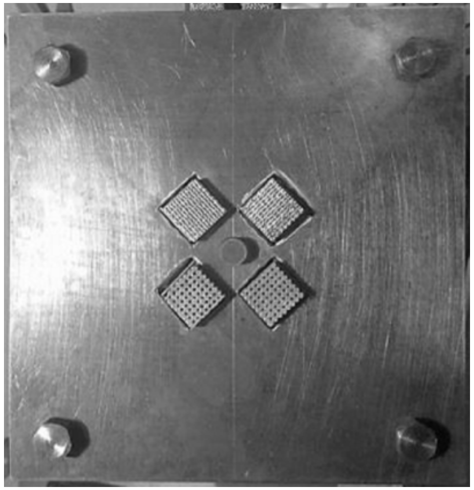
Values of absorbed energy by solid and lattice targets are equal within the measurement accuracy.

Qualification of W advanced materials (WPDIV)



Test condition In QSPA Kh-50	
Plasma load	Above tungsten melting/evaporation
Pulse duration, ms	0.25
Base temperature, C	≈500°C (above DBTT)
Number of pulses	Up to 10

General view of irradiated target



Four cube samples mounted around a central moveable colorimeter will be used in each test bath. Preferable all samples are identical for uniform shielding effect.

- ✓ Energy transfer to different exposed surface will be studied.
- ✓ Comparative analysis of damaging lattice as well as solid tungsten will be performed.

EUROfusion

Subtopics

Management Aspects

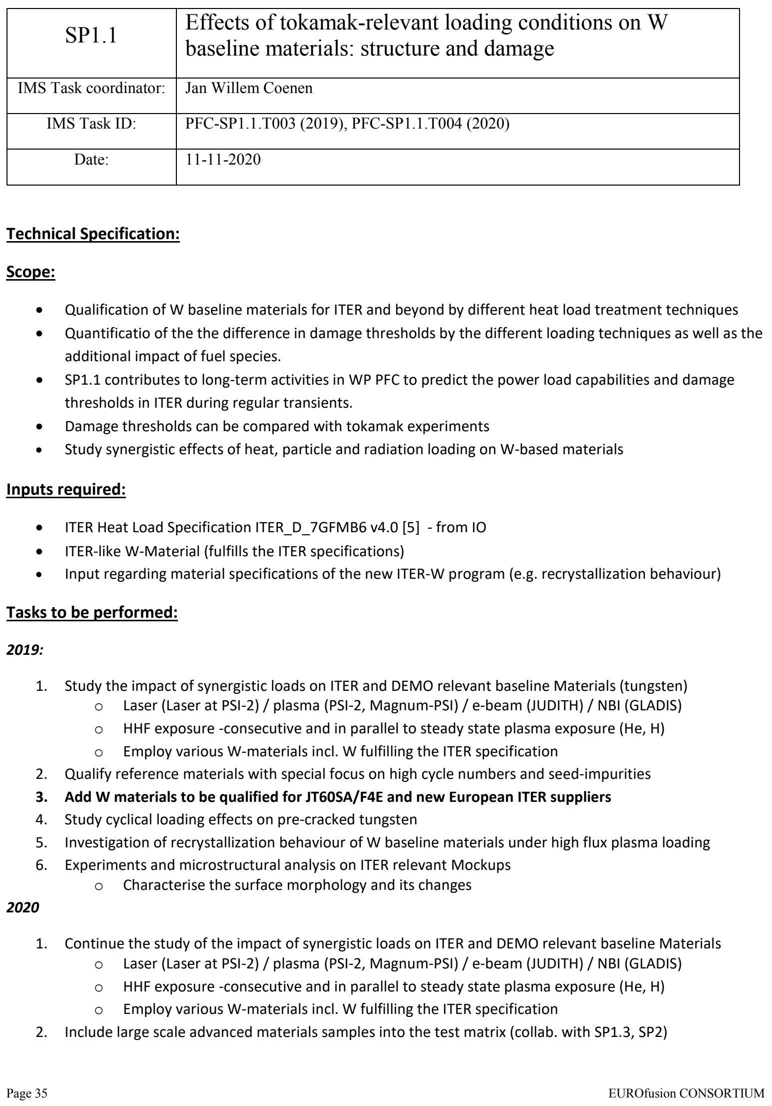
JÜLICH Forschungszentrum

IPP

sck cen Belgian Nuclear Research Centre

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

SP1.1



SP1.1	Effects of tokamak-relevant loading conditions on W baseline materials: structure and damage
IMS Task coordinator:	Jan Willem Coenen
IMS Task ID:	PFC-SP1.1.T003 (2019), PFC-SP1.1.T004 (2020)
Date:	11-11-2020

Technical Specification:

Scope:

- Qualification of W baseline materials for ITER and beyond by different heat load treatment techniques
- Quantificatio of the the difference in damage thresholds by the different loading techniques as well as the additional impact of fuel species.
- SP1.1 contributes to long-term activities in WP PFC to predict the power load capabilities and damage thresholds in ITER during regular transients.
- Damage thresholds can be compared with tokamak experiments
- Study synergistic effects of heat, particle and radiation loading on W-based materials

Inputs required:

- ITER Heat Load Specification ITER_D_7GFMB6 v4.0 [5] - from IO
- ITER-like W-Material (fulfills the ITER specifications)
- Input regarding material specifications of the new ITER-W program (e.g. recrystallization behaviour)

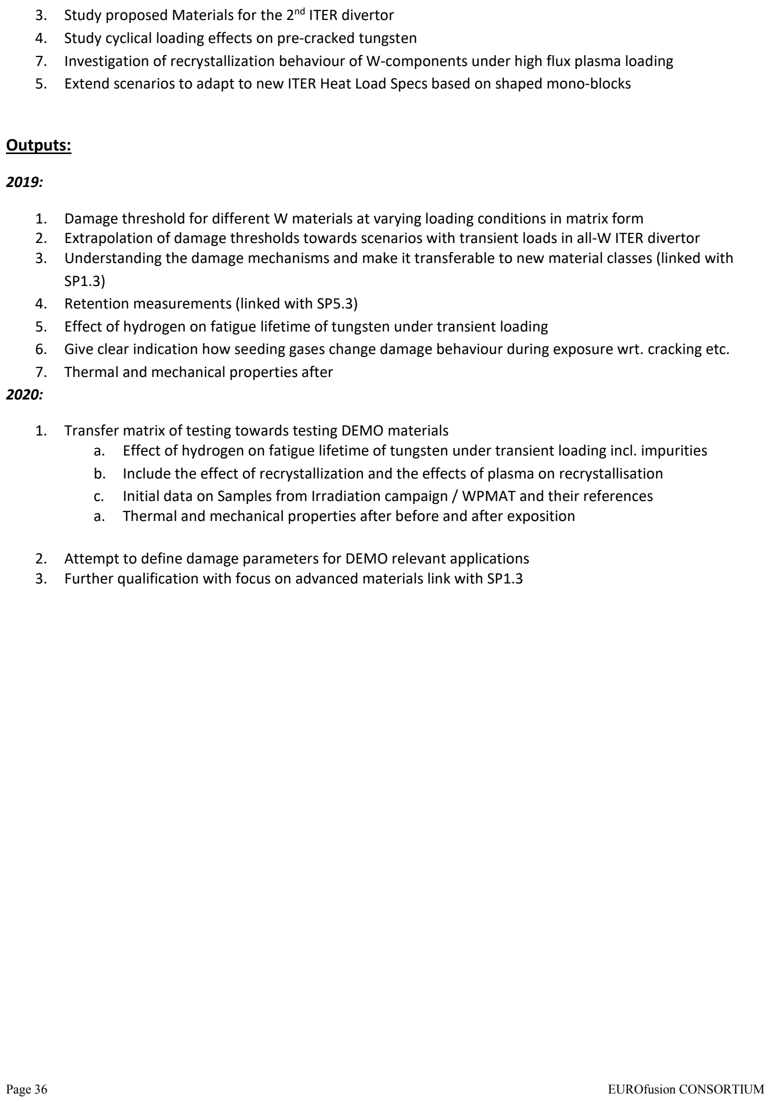
Tasks to be performed:

2019:

1. Study the impact of synergistic loads on ITER and DEMO relevant baseline Materials (tungsten)
    - Laser (Laser at PSI-2) / plasma (PSI-2, Magnum-PSI) / e-beam (JUDITH) / NBI (GLADIS)
    - HHF exposure -consecutive and in parallel to steady state plasma exposure (He, H)
    - Employ various W-materials incl. W fulfilling the ITER specification
2. Qualify reference materials with special focus on high cycle numbers and seed-impurities
3. **Add W materials to be qualified for JT60SA/F4E and new European ITER suppliers**
4. Study cyclical loading effects on pre-cracked tungsten
5. Investigation of recrystallization behaviour of W baseline materials under high flux plasma loading
6. Experiments and microstructural analysis on ITER relevant Mockups
    - Characterise the surface morphology and its changes

2020

1. Continue the study of the impact of synergistic loads on ITER and DEMO relevant baseline Materials
    - Laser (Laser at PSI-2) / plasma (PSI-2, Magnum-PSI) / e-beam (JUDITH) / NBI (GLADIS)
    - HHF exposure -consecutive and in parallel to steady state plasma exposure (He, H)
    - Employ various W-materials incl. W fulfilling the ITER specification
2. Include large scale advanced materials samples into the test matrix (collab. with SP1.3, SP2)



3. Study proposed Materials for the 2nd ITER divertor
4. Study cyclical loading effects on pre-cracked tungsten
7. Investigation of recrystallization behaviour of W-components under high flux plasma loading
5. Extend scenarios to adapt to new ITER Heat Load Specs based on shaped mono-blocks

Outputs:

2019:

1. Damage threshold for different W materials at varying loading conditions in matrix form
2. Extrapolation of damage thresholds towards scenarios with transient loads in all-W ITER divertor
3. Understanding the damage mechanisms and make it transferable to new material classes (linked with SP1.3)
4. Retention measurements (linked with SP5.3)
5. Effect of hydrogen on fatigue lifetime of tungsten under transient loading
6. Give clear indication how seeding gases change damage behaviour during exposure wrt. cracking etc.
7. Thermal and mechanical properties after

2020:

1. Transfer matrix of testing towards testing DEMO materials
    a. Effect of hydrogen on fatigue lifetime of tungsten under transient loading incl. impurities
    b. Include the effect of recrystallization and the effects of plasma on recrystallisation
    c. Initial data on Samples from Irradiation campaign / WPMAT and their references
    a. Thermal and mechanical properties after before and after exposition

2. Attempt to define damage parameters for DEMO relevant applications
3. Further qualification with focus on advanced materials link with SP1.3

Deliverables of the task PFC-SP1.1.T003 (2019):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.1.T003-D001	01.01.19	31.12.19	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
MPG	2.0	GLADIS	8				
FZJ	17.0	JUDITH	20	PSI-2	13		
FOM-DIFFER	3.0			MAGNUM-PSI	5		
Total PM:	22.0	Total cost / k€:	142.000	Total cost / k€:	135.760	Total cost / k€:	0.000

Deliverables of the task PFC-SP1.1.T004 (2020):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.1.T004-D001	01.01.2020	31.12.2020	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
MPG	2	GLADIS	8				
FZJ	17	JUDITH	20	PSI-2	15		
FOM-DIFFER	3			MAGNUM-PSI	5		
Total PM:	22,0	Total cost / k€:	142,000	Total cost / k€:	142,800	Total cost / k€:	0,000

Acceptance criteria for these tasks:

The tasks shall be carried out along the lines defined in the technical specification. Achieved Deliverables to be reported and approved through EUROfusion IDM (https://idm.euro-fusion.org)

SP1.3

SP1.3	Material parameters of tungsten materials used and considered for fusion applications before and after tokamak relevant exposition
IMS Task coordinator:	Jan Willem Coenen
IMS Task ID:	PFC-SP1.3.T003 (2019), PFC-SP1.3.T004 (2020)
Date:	11-11-2020

Technical Specification:

Scope:

- Develop qualification methods for advanced materials (e.g. W_f/W, self-passivating alloys, powder injection moulding (PIM) tungsten, ultrafine grain (UFG) tungsten, W laminates etc.) to be used beyond ITER by different heat load treatment techniques. Quantifying the difference in damage thresholds by different loading techniques as well as the additional impact of fuel species. Contributes to long-term activities in WP PFC to predict the power load capabilities and damage thresholds in ITER and beyond during regular transients.
  - Apply advanced test and characterisation techniques to also validate advanced materials
  - Damage thresholds can be compared with tokamak experiments.

Inputs required:

- ITER Heat Load Specification ITER_D_7GFMB6 v4.0 [5] - from IO
- Bulk samples and modell systems of advanced material concepts or parts of them ready for (micro)mechanical testing and or plasma exposure: W_f/W / SMART W etc
- Input regarding material specifications of the new ITER-W program (e.g. recrystallization behaviour)
- Materials from EUROPEAN ITER monoblock candidate suppliers and WPMAT candidates for DEMO

Tasks to be performed:

2019

1. Study the impact of synergistic transient loads on Advanced W- materials
   - Laser (Laser at PSI-2) / plasma (PSI-2, Magnum-PSI) / e-beam (JUDITH) / NBI (GLADIS)
   - HHF exposure -consecutive and in parallel to steady state plasma exposure (He, H)
   - Characterise the surface morphology and its changes
   - Lifetime estimates for PFCs
   - Link with SP2/SP3 when determining impact on retention under various conditions
   - Plasma tests of model systems
2. Combined tests with SP1.1 in cases where viable HHF samples are available
3. High temperature mechanical tests (up to 2000˚C) on relevant materials
   - Impact of high temperature annealing and recrystallization (occurring simultaneously with the deformation).
4. Test Advanced Materials for the second ITER divertor
5. Extend testing scenarios to adapt to new ITER Heat Load Specs based on shaped monoblocks

6. Include the effect of recrystallization and the effects of plasma on recrystallization & helium effects on new advanced materials
7. Assessment of cycle fatigue lifetime of Advanced Materials before and after plasma irradiation
8. Study effect of irradiation damage on mechanical properties of W wire

2020

1. Study the impact of synergistic transient loads on Advanced W- materials
   a. Laser (Laser at PSI-2) / plasma (PSI-2, Magnum-PSI) / e-beam (JUDITH) / NBI (GLADIS)
   b. HHF exposure -consecutive and in parallel to steady state plasma exposure (He, H)
   c. Characterise the surface morphology and its changes
   d. Lifetime estimates for PFCs
   e. Link with SP2/SP3 when determining impact on retention under various conditions
   f. Plasma tests of model systems
2. Experiments and microstructural analysis on DEMO relevant Mockups
   a. Characterise the surface morphology and its changes
   b. Compare irradiated (self-damage or neutrons) samples of advanced materials with their baseline counterparts.
3. Do Combined tests with SP1.1 in those cases where viable HHF samples are available
4. Determination of the hydrogen retention in W wire used in W_f/W composites and of its effect on mechanical properties.
5. Include the effect of recrystallization and the effects of plasma on recrystallization & helium effects on new advanced materials

Outputs:

2019:

- Mechanical properties of ion damaged W wire
- Damage threshold for different W materials at varying loading conditions in matrix form
- Extrapolation of damage thresholds towards scenarios with transient loads in all-W ITER divertor
- Understanding the damage mechanisms and make it transferable to new material classes (linked with SP1.3)
- Give clear indication how seeding gases during exposure change damage behaviour with respect to cracking etc.
- Mechanical properties of ion damaged W wire

2020:

- Initial outcome of PFC tests including neutron damaged materials
- Select candidates for a potential second ITER or first DEMO divertor and/or link with WPMAT for DEMO materials or design specifications

Deliverables of the task PFC-SP1.3.T003 (2019):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.3.T003-D001	01.01.19	31.12.19	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
MPG	6.0	GLADIS	2				
FZJ	4.0	JUDITH	10	PSI-2	5	Sample	2.000
FOM-DIFFER	2.5			MAGNUM-PSI	5		
LPPERM-KMS	12.0						
KIT	2.5						2.000
Total PM:	**27.0**	**Total cost / k€:**	**61.000**	**Total cost / k€:**	**107.600**	**Total cost / k€:**	**4.000**

Deliverables of the task PFC-SP1.3.T004 (2020):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.3.T004-D001	01.01.2020	31.12.2020	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
MPG	6	GLADIS	2				
FZJ	4	JUDITH	10	PSI-2	5		2,000
FOM-DIFFER	2,5			MAGNUM-PSI	5		
LPPERM-KMS	12					Experiments in hotcells	20,000
KIT	2,5						2,000
Total PM:	**27,0**	**Total cost / k€:**	**61,000**	**Total cost / k€:**	**107,600**	**Total cost / k€:**	**24,000**

Acceptance criteria for these tasks:

The tasks shall be carried out along the lines defined in the technical specification. Achieved Deliverables to be reported and approved through EUROfusion IDM (https://idm.euro-fusion.org)

SP1.8

SP1.8	High power test of plasma-facing components in QPSA and comparison with other facilities
IMS Task coordinator:	Jan Wilem Coenen
IMS Task ID:	PFC-SP1.8.T003 (2019), PFC-SP1.8.T004 (2020)
Date:	11-11-2020

Technical Specification:

Scope:

- Study the damage propagation of misaligned tungsten edges. Simulate the ITER W case of individual monoblock alignment.
- Influence of shallow recrystallization on crack formation and propagation on ITER-grade W material.
- Comparison of different type of loadings in heat-load and plasma loading facilities. Characterisation of QSPA in comparison with other HHF in SP1
- Qualification of W and advanced materials at disruption like loading as expected in DEMO (with WP PMI)

Inputs required:

- Reference sample material from SP1
- Sample material produced at KIPT
- Comparative experiments / results from other high heat flux facilities in SP1
- Comparative experiments / results from WEST
- Expected conditions and materials in DEMO to simulate in QSPA (from WP PMI)

Tasks to be performed:

2019/2020

1. Studies of damage propagation for misaligned tungsten edges under disruption-like heat loads included irradiation by plasmas of mixture of different gasses (H+He and H+Ar)
2. Qualification of W and advanced materials at ELM-like and disruption-like loading
3. Comparison of different type of loadings in heat-load and plasma loading facilities included exposes of samples common for WP PFC in LHD devices (as part of activity within WP S1. Material to be specified with SP1 and LHD)

Outputs:

2019/2020

- Characterisation of the damage propagation of misaligned tungsten edges in comparison to WEST experiments
- Analysis of crack formation on shallow recrystallized tungsten and comparison to exposures at other HHF f in SP1.
- Characterisation of QSPA in comparison with other HHF in SP1 f
- Analysis of the effects of disruption-like heat loading on tungsten and advanced materials
  Select candidates for a potential second ITER or first DEMO divertor and/or link with WPMAT for DEMO materials or design specifications

Deliverables of the task PFC-SP1.8.T003 (2019):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.8.T003-D001	01.01.2019	31.12.2019	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
KIPT	60,5	QSPA	20			Samples	11,000
KIPT	12	QSPA	20				
Total PM:	**72,5**	**Total cost / k€:**	**65,000**	**Total cost / k€:**	**0,000**	**Total cost / k€:**	**11,000**

Deliverables of the task PFC-SP1.8.T004 (2020):

IMS Deliverable ID	Start date	End date	Deliverable Owner:
PFC-SP1.8.T004-D001	01.01.2020	31.12.2020	Sebastijan Brezinsek

RU	PM 50%	Accelerators	days	EUROfusion facilities	days / sessions	Hardware	cost / k€
KIPT	60,5	QSPA	20			Samples	8
Total PM:	**60,5**	**Total cost / k€:**	**65,000**	**Total cost / k€:**	**0,000**	**Total cost / k€:**	**8,000**

Acceptance criteria for these tasks:

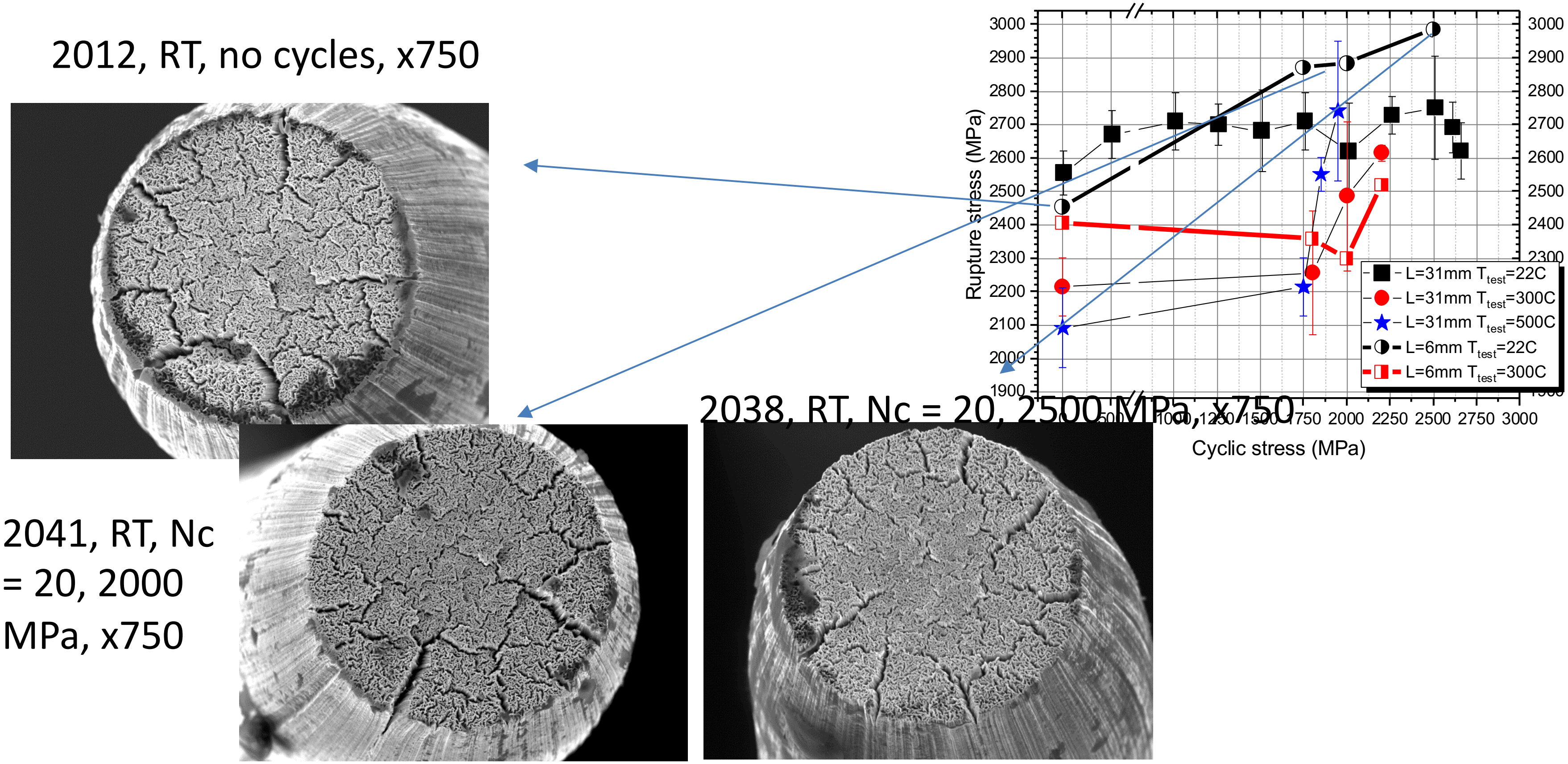
The tasks shall be carried out along the lines defined in the technical specification. Achieved Deliverables to be reported and approved through EUROfusion IDM (https://idm.euro-fusion.org)

Add Ons

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.

High cycle fatigue of wires

- Reference and pre-fatigued T_{test}=RT



2012, RT, no cycles, x750

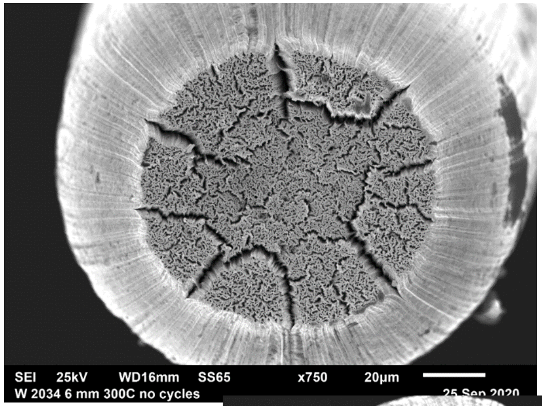
2041, RT, Nc = 20, 2000 MPa, x750

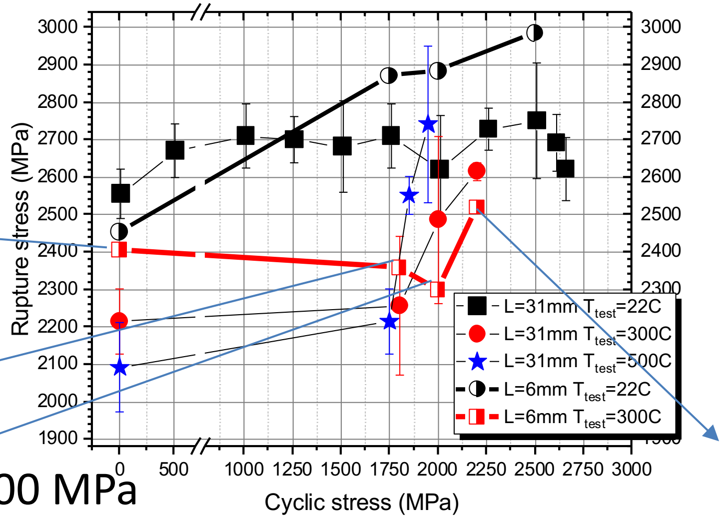
2038, RT, Nc = 20, 2500 MPa, x750

High cycle fatigue of wires

- Reference and pre-fatigued T_{test}=300 °C

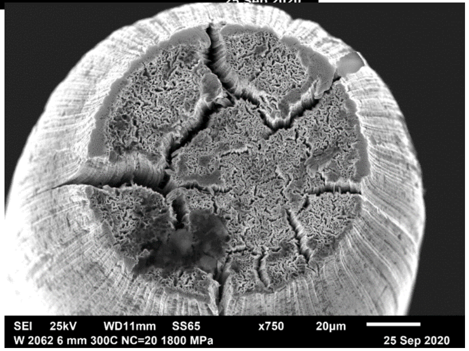
2034, 300C, no cycles, x750

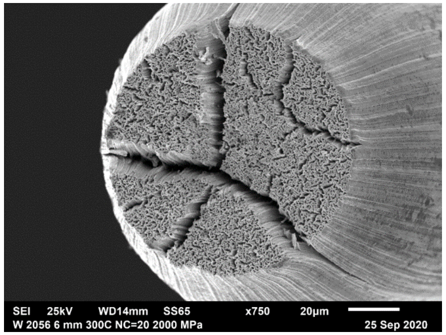


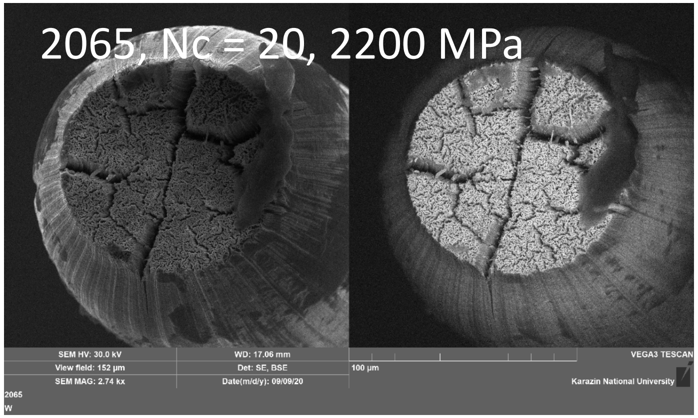


2056, Nc = 20, 2000 MPa

2062, RT, Nc = 20, 1800 MPa, x750






2065, Nc = 20, 2200 MPa

Tests of AM W/W Ta samples in QSPA Kh-50

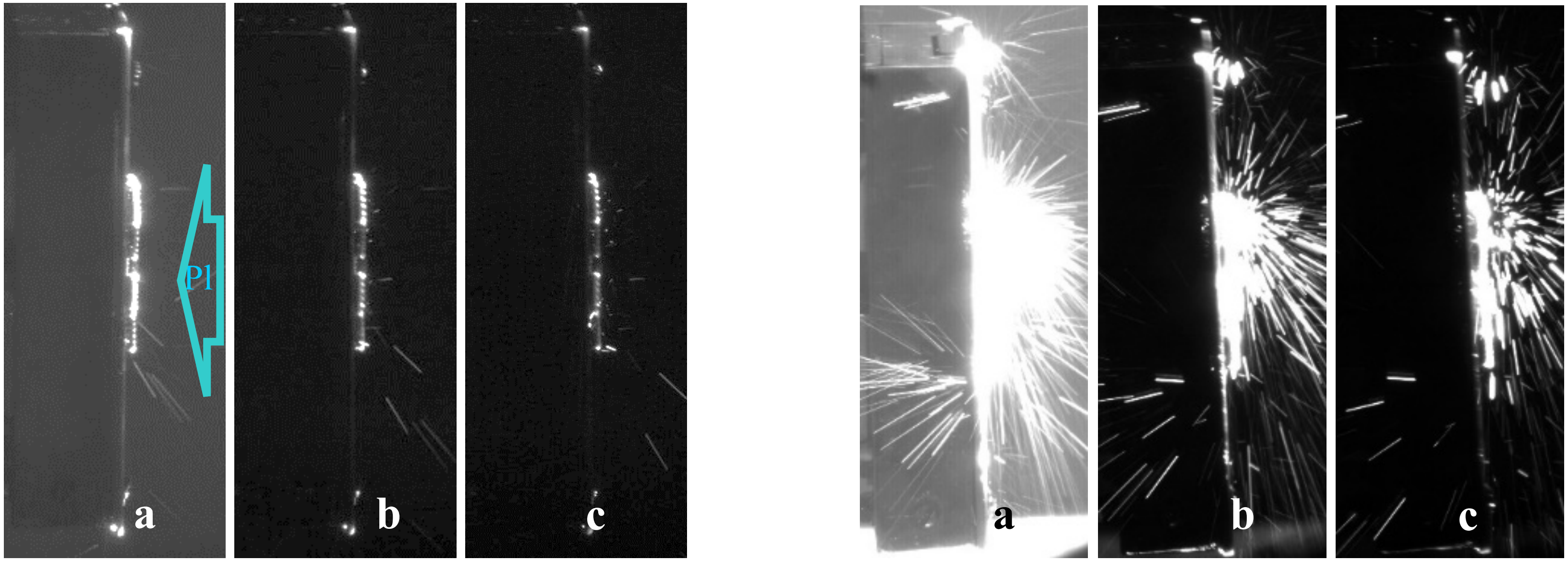
DONE in 2020

	Plasma load by	Number of pulses	T_{base}	Applied plasma stream energy, MJ/m^2	Sample origin
Lattice W Ta L6 Not polished	QSPA Kh-50	5	500 °C	1.8	CCFEx4
				2.3	CCFEx4
				Up to 3	CCFEx4
Lattice W Ta L6 Polished				1.8	CCFEx4
				2.3	CCFEx4
				Up to 3	CCFEx4
Lattice W L6 Polished				2.3	IPPx4
Solid W Not polished				1.8	IPPx2, CCFEx2
				2.3	IPPx2, CCFEx2

The particle ejection during PSI

Not polished latticed samples. Applied plasma stream energy density,

1.8 MJ/m^2 3 MJ/m^2



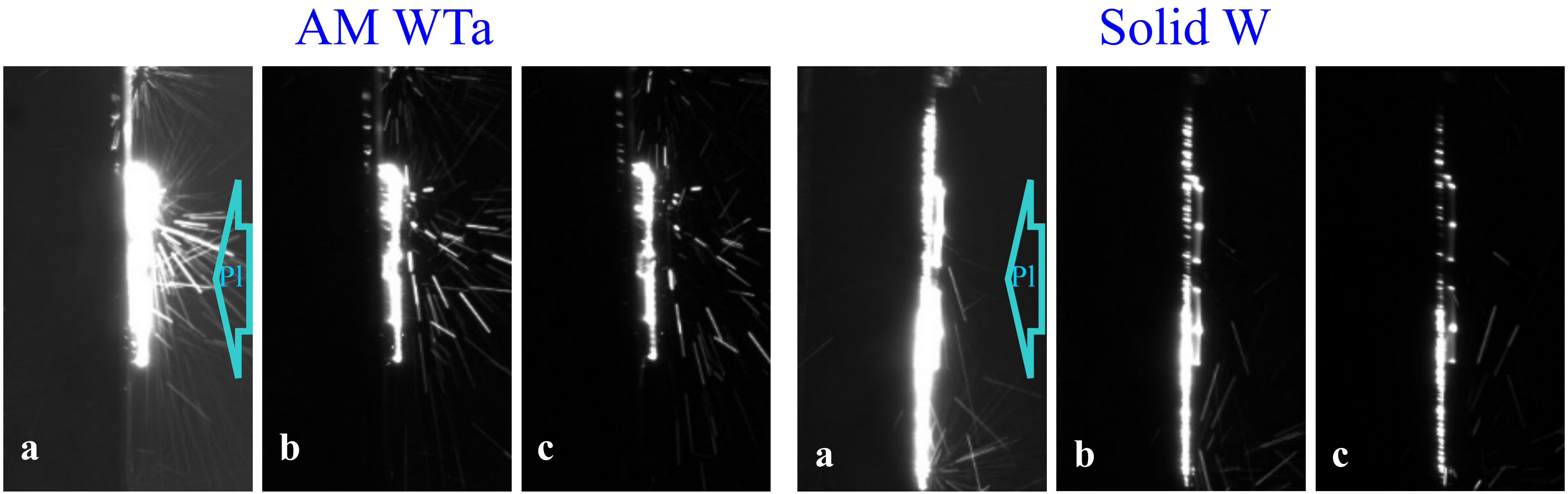
Images of droplet traces after plasma pulse corresponding to 1.2–2.4ms (a), 2.4–3.6ms (b) 3.6 – 4.8 ms (c) after the start of the plasma–surface interaction (t_{exp}=1.2ms).

- The plasma surface interaction is accompanied by particles emitted from the exposed target surfaces
- Larger number of ejected particles is observed under plasma irradiation with energy density causing strong melting/pronounced evaporation

The particle ejection during PSI

Not polished latticed and solid samples

Applied plasma stream energy density, 2.3 MJ/m^2



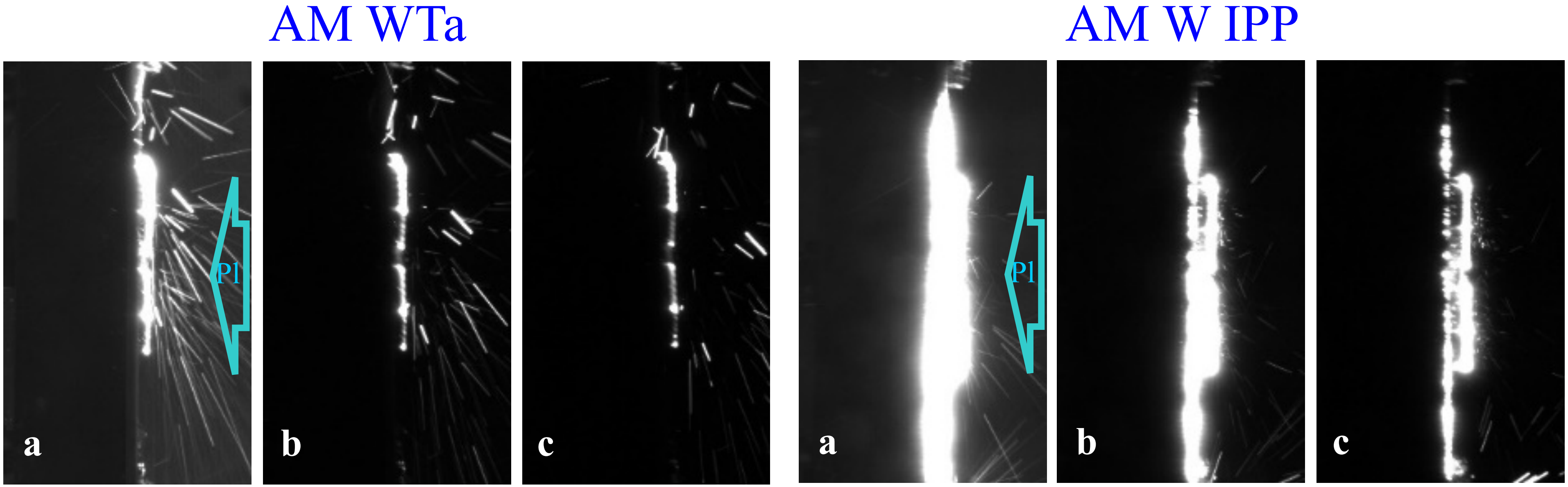
Images of droplet traces after plasma pulse corresponding to 1.2–2.4ms (a), 2.4–3.6ms (b) 3.6 – 4.8 ms (c) after the start of the plasma–surface interaction (t_{exp}=1.2ms).

- Decreased number of the ejected particles is observed for Solid W

The particle ejection during PSI

Polished latticed samples

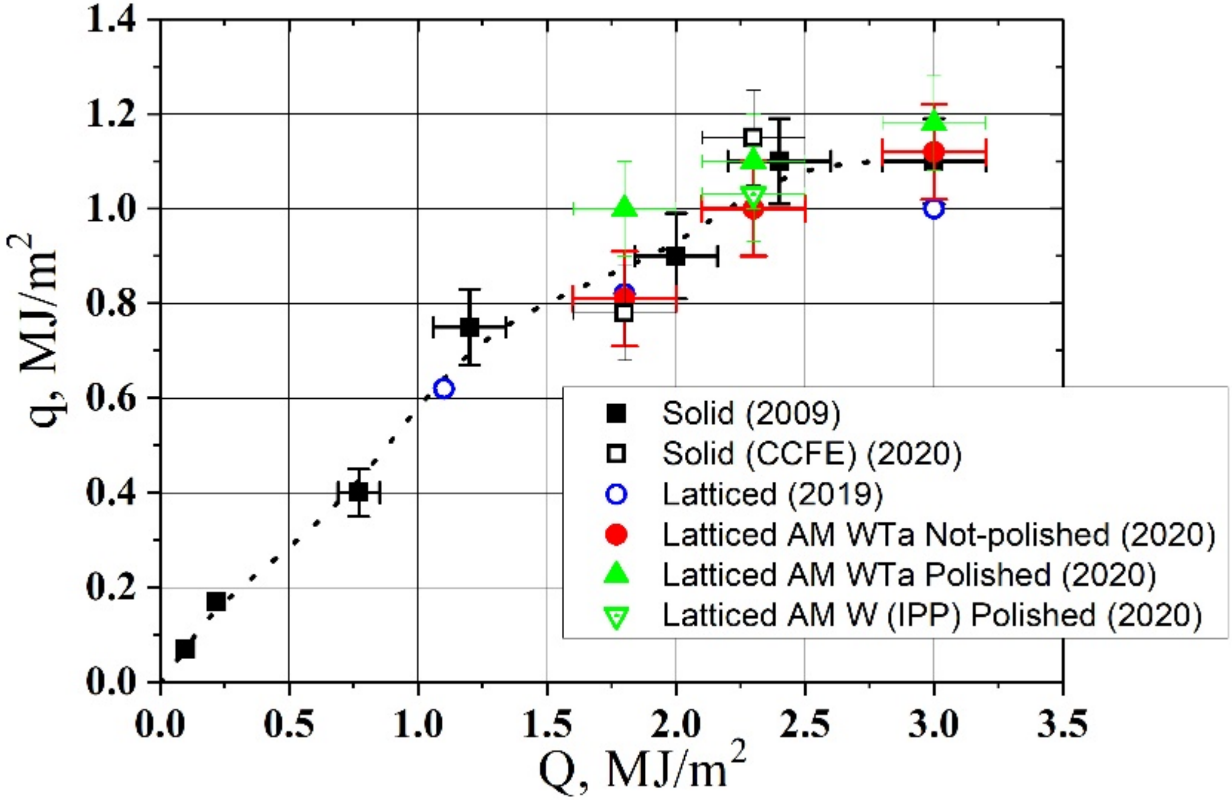
Applied plasma stream energy density, 2.3 MJ/m^2



Images of droplet traces after plasma pulse corresponding to 1.2–2.4ms (a), 2.4–3.6ms (b) 3.6–4.8 ms (c) after the start of the plasma–surface interaction (t_{exp}=1.2ms).

- Decreased number of the ejected particles is observed for both types of polished latticed samples

Energy density absorbed by the target surface



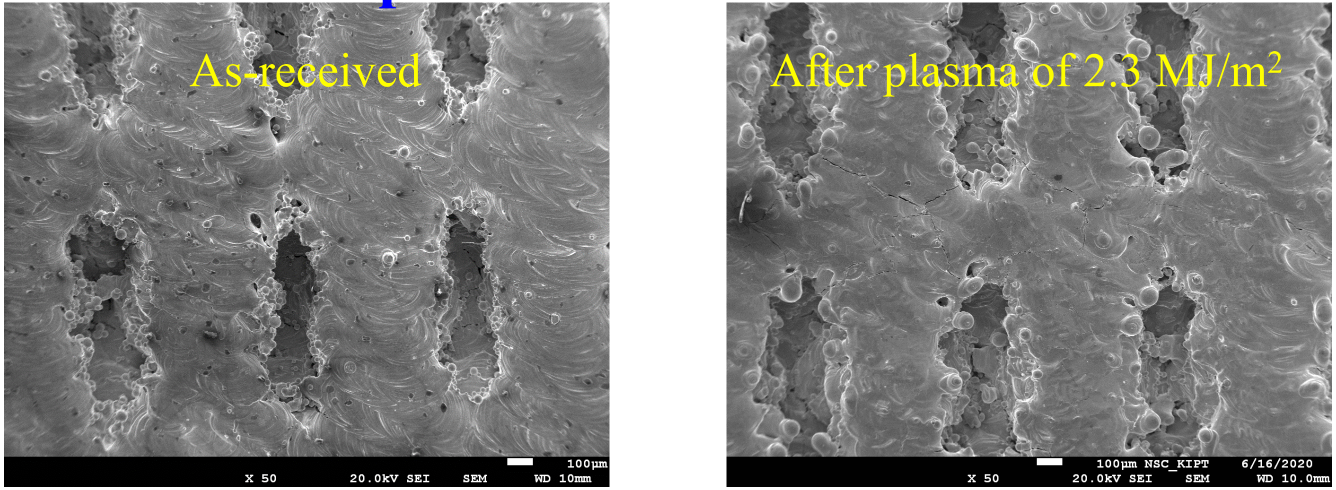
Energy density (q) absorbed target surface vs the energy density (Q) of impacting plasma stream.

Values of absorbed energy by solid and lattice targets are equal within the measurement accuracy.

[black square: I.E. Garkusha et al. / J of Nucl. Mat. 390–391 (2009) 814–817]

SEM analysis

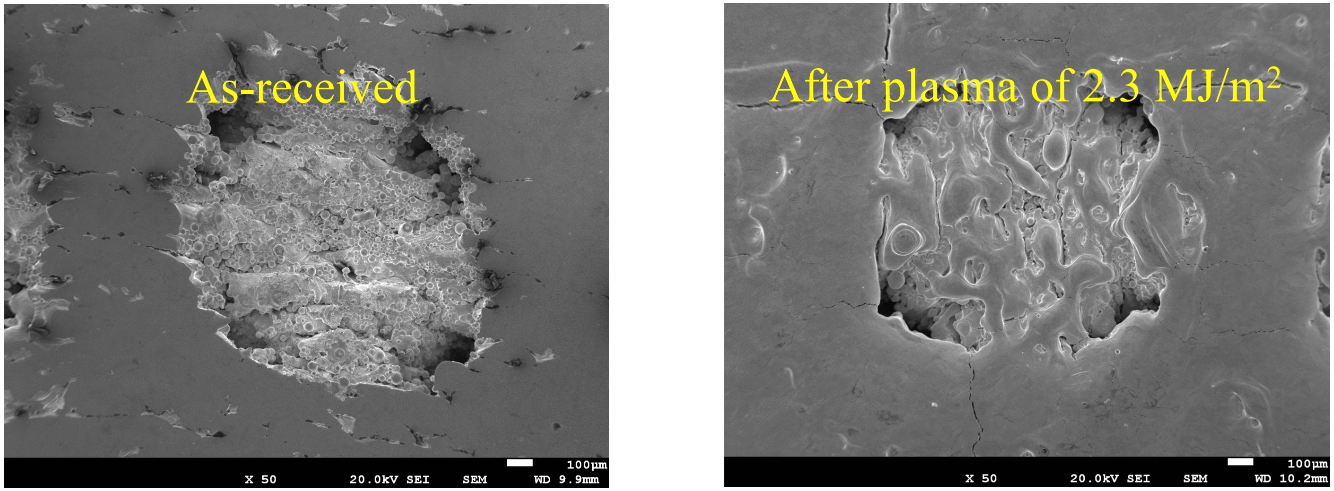
Not polished latticed AM WTa



As-received

After plasma of 2.3 MJ/m^2

Polished latticed AM WTa



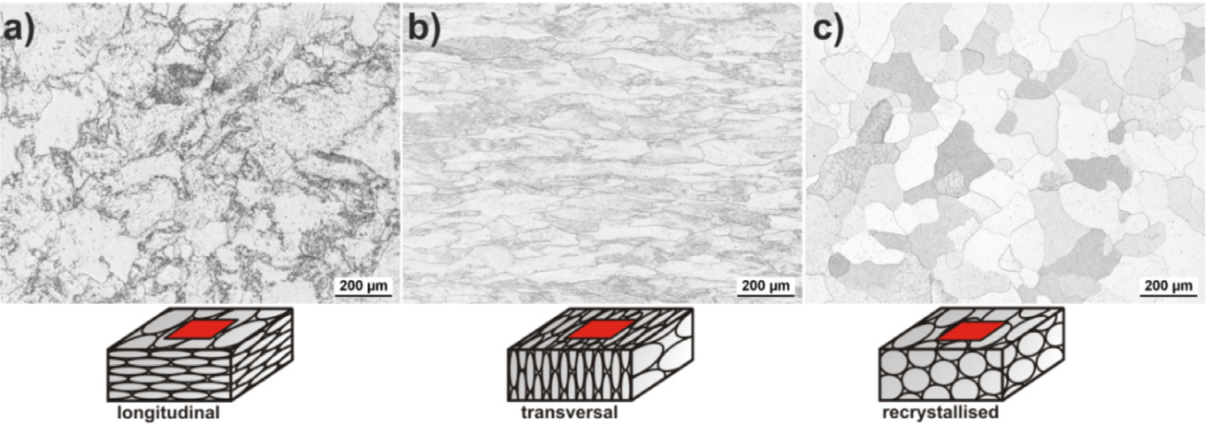
As-received

After plasma of 2.3 MJ/m^2

- Pores, cracks, balls, cause particle ejection

Joint QSPA - LHD experiment

Qualification of W materials



In collaboration with FZJ (M. Wirtz)

Tungsten samples were supplied by Plansee AG (Austria), prepared and delivered from Forschungszentrum Julich (Germany). Samples have sizes of 12 ×12 ×5 mm^3.
the longitudinal (L) transversal (T) grain orientation and in the recrystallized (R) state.

Continuation studies of influence of different type of loadings in heat-load and plasma loading facilities including exposes of samples common for WP PFC in LHD devices (as part of activity within WP S1. Material to be specified with SP1 and LHD)

In collaboration with NIFS (S. Masuzaki)

Tasks completed in second half of 2020

- Plasma shield formation in front of the surface was studied during heavy gas (Ar) injection along target surface in QSPA –M (first results). Argon was injected surface by means of special gas injector.

- Qualification of W advanced materials in QSPA Kh-50
- Latticed W/WTa targets
    - » Polished
    - » Non-polished
- Solid W target
    - » Non-polished

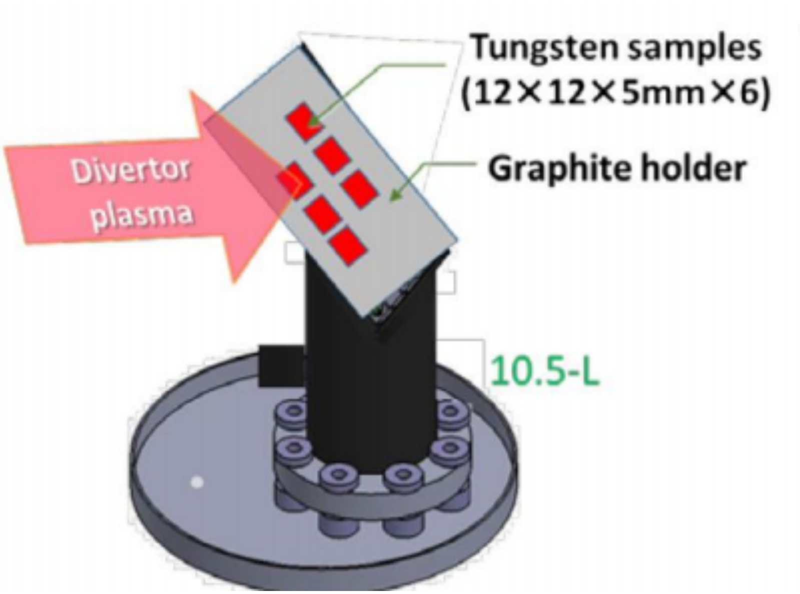
Joint QSPA - LHD experiment

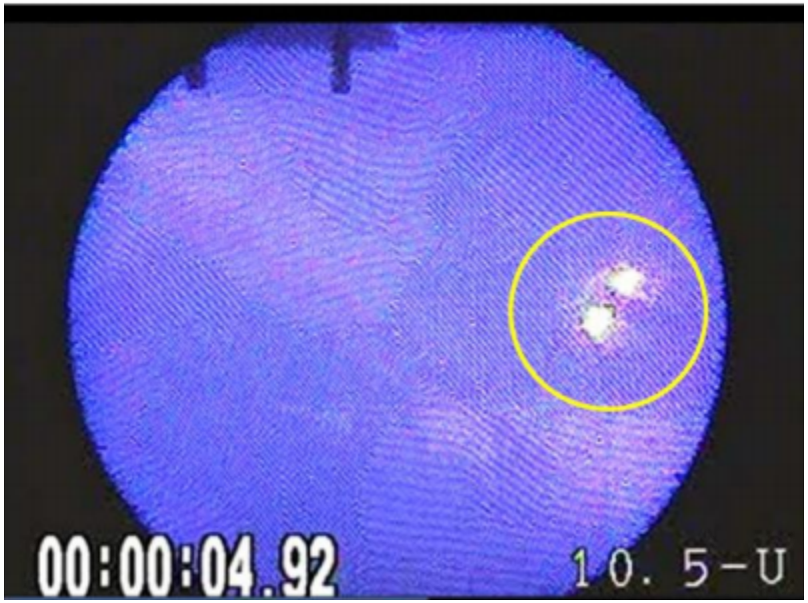
Comparative analysis of samples common for WP PFC irradiated by pulsed plasma load (QSPA); plasma fluxes in divertor region of LHD and consequent powerful pulsed plasma loads and plasma fluxes in divertor region of LHD.

Targets : TLR tungsten sample

1. Pre-loaded procedure at QSPA: 200 QSPA pulses to each sample (T_{base} = RT; 200 pulses, $q_{(surf)}$.=0.1 MJ/m^2, τ_{pulse}=0.25 ms ; 6.3 MWsqr(s) m^{-2}) (Done);
2. Preliminary analysis of initial and Pre-loaded samples (3 – initial, 3 – after QSPA loads): SEM+EDS, and TEM analysis of samples before LHD exposition (Done).
3. Exposure of initial and pre-loaded at QSPA samples within LHD divertor region (Done).
4. Post-mortem analysis. (Done)

Exposure to the LHD divertor plasma

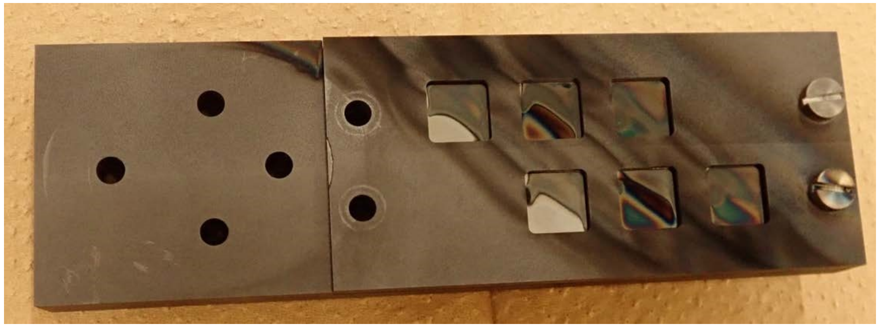




View of CCD camera

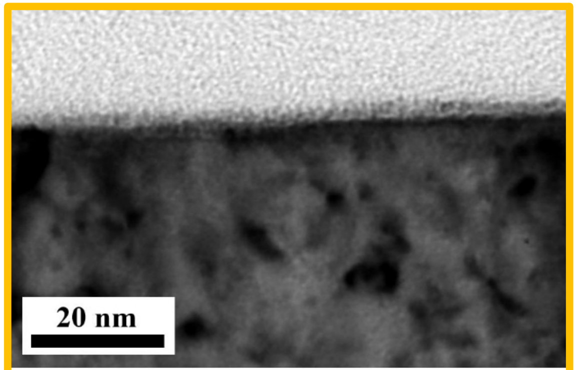
Average heat flux [MW m^{-2}]	≤ 10
Average ion flux [10^{23} m^{-2} s^{-1}]	3.7
Average electron density [10^{19} m^{-3}]	1.1
Average electron temperature [eV]	16
Pulse duration [s]	2
Number of pulses	5

Langmuir probe data at the divertor plate near the W sample

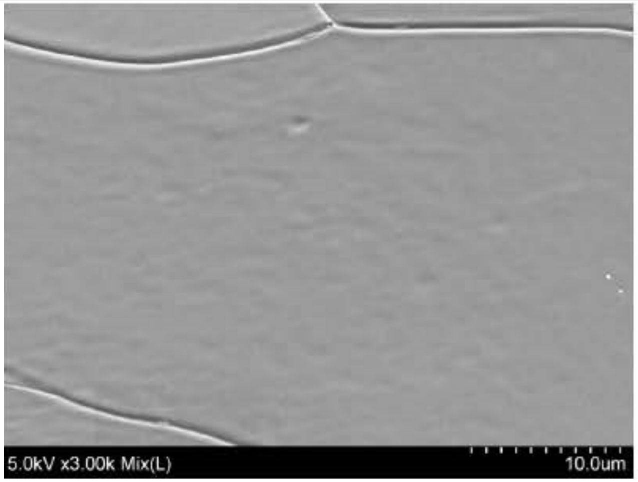


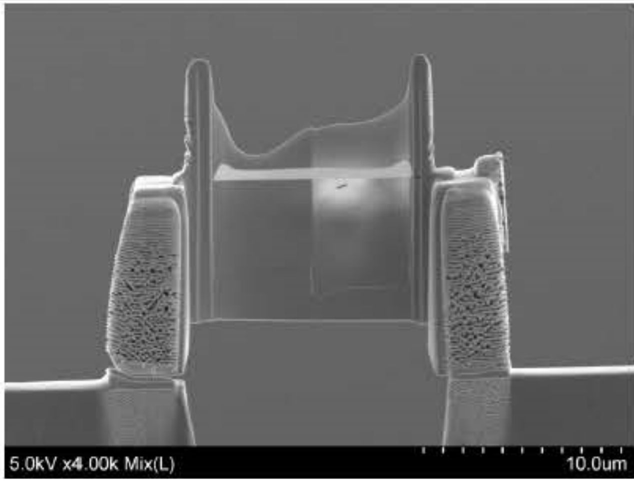
Samples after stage of irradiation in the LHD

TEM observation

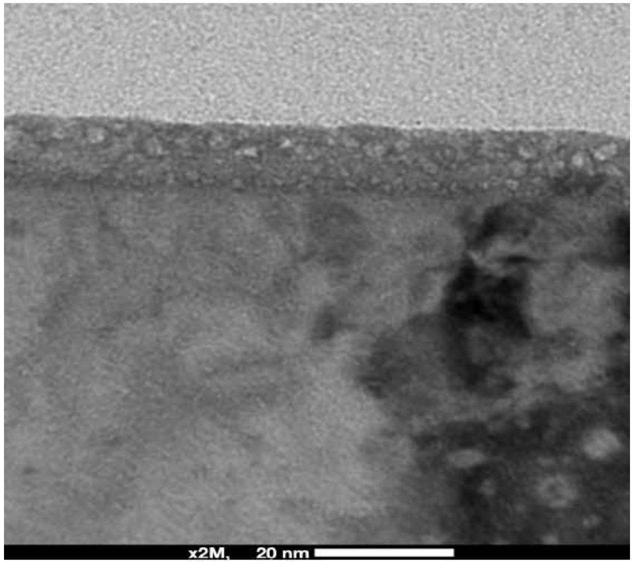


Before the installation into the LHD





- **No damage/Surface modification was observed** on the surfaces irradiated at QSPA Kh-50 plasma.
- LHD divertor fluxes is contributed to formation of damaged layer with approximately 10 nm thickness on surfaces of all samples.
- Bubbles/blisters were recognised in this plasma affected layer.
- These bubbles look to be generated by helium irradiation. A possible reason of the bubbles generation is helium in hydrogen plasma (<15%).



We thank for the TEM analysis Dr. R. Sakamoto, NIFS

Changes between 2019 / 2020 version of PMP

Activity	Year	RU	Description of change	Resources change	Budget change [Consortium Contribution]
SP2.2 Qualification of ammonia production mechanisms	**2019**	ENEA	Increased resources to 3 PM	+1 PM	+3,125 k€
SP3.1 Qualification of the impact of seeding gases (Ar and N) on fuel retention and fuel release	**2020**	FZJ	Removed task “D-retention in the Be-W system”	-1,1 PM and -5 days accelerator	-9,954 k€
		MPG	Removed task “D influence on W recrystallization”	-2,2 PM	-10,349 k€
		MPG	Removed task “Permeation W layer on Fe”	-2,2 PM	-10,349 k€
SP4.1 Plasma-background and plasma-sheath modelling	**2020**	IPP.CR	Reduced resources to 2 PM	-3,0 PM	-4,859 k€
SP4.2 Plasma-surface interaction and transport modelling	**2020**	ENEA	Increased resources to 3 PM for GyM ERO modelling	+ 1,0 PM	+3,125 k€
SP5.1 Material migration in tokamaks	**2020**	FZJ	Increased resources to 5 days of accelerator operation	+5 days accelerator	+5,000 k€
SP7.4 Characterization of fusion-relevant plasma	**2020**	ENEA	Added task “Determine S/XB for W in GyM”	+ 2,0 PM	+6,250 k€
SP7.10 Role of energetic neutrals in Ion Cyclotron Wall Conditioning	2020	LPP-ERM-KMS	Removed costs for Antenna	-5,000 k€	-2,500 k€
	2019	LPP-ERM-KMS	Removed costs for Antenna	-10,000 k€	-5,000 k€
Mission budget	**2020**	Not allocated	Increase of mission budget	+23,636 k€	+23,636 k€