Recent Results of High Heat Flux Tests at GLADIS

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

High heat flux test facility GLADIS

Beam parameters:
- Hydrogen neutral beam,
- Heat flux: 2 – 45 (90) MW/m², 150 mm FWHM, Ø 50 mm (95% q'_{max})
- Pulse length: 1 ms – 45 s

Target cooling
- T_{in} 20 – 230 ± 0.5 °C, T_{out} max. 250 °C

Target diagnostics
- Water calorimetry, thermocouples
- Fast one- and two-colour pyrometers
- High-resolution CCD & IR cameras
- Visible Spectroscopy

Outline

Recent investigations

- **W Heavy Alloy as Armour Material**
- **W/Ta Cold Spray Coatings**
- **W_f/W armoured PFCs**
- **Additively Manufactured W-Cu PFCs**

New Spectroscopic Diagnostic

Further (planned) investigations

W Heavy Alloys as Armour Material

Areas with steady-state heat fluxes up to 10 MW/m² allow to consider W heavy alloys as PFM

- **reduced material and manufacturing costs**
- **improved mechanical properties** (higher fracture toughness, higher max. elongation)
- however: **Ni/Cu or Ni/Fe matrix limits the thermal performance**

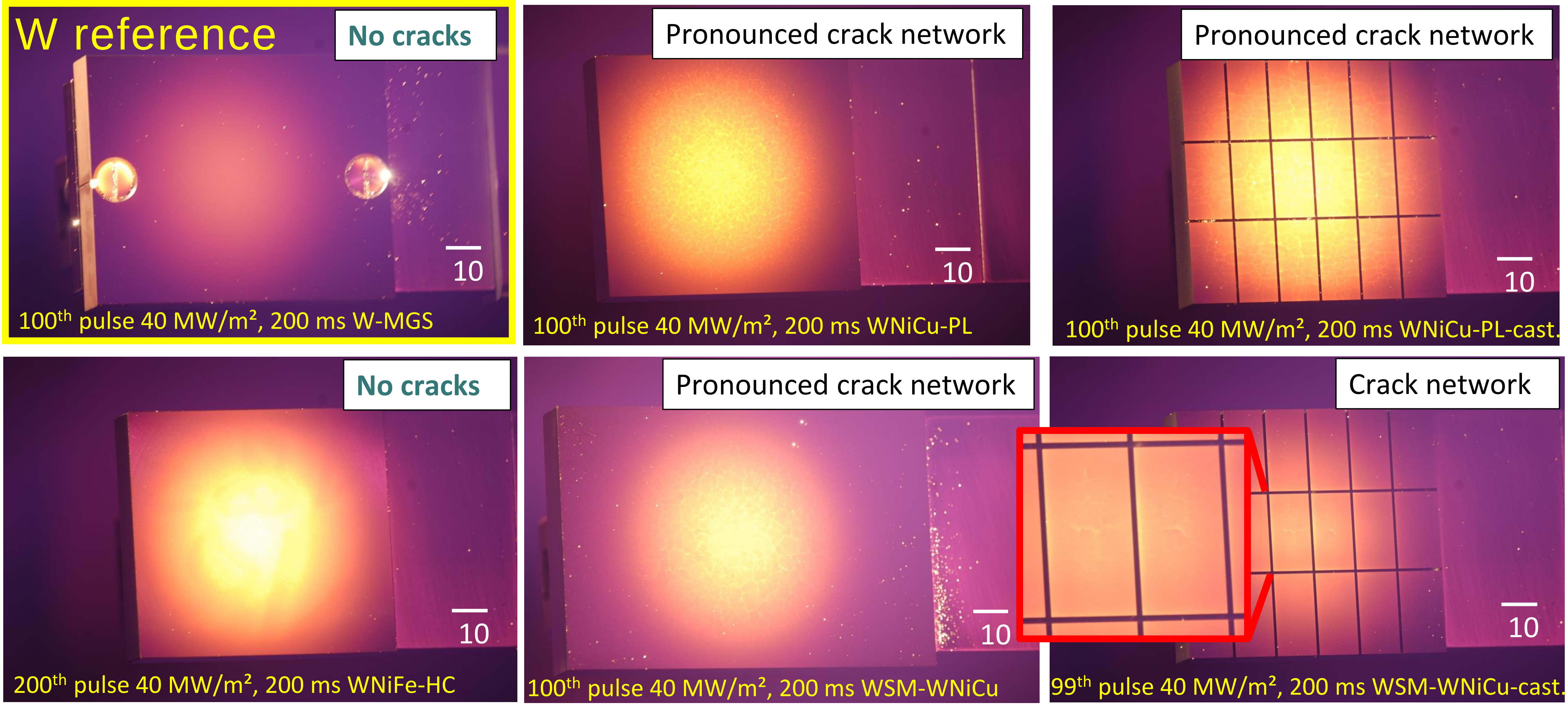
Material properties and suppliers of investigated W heavy alloy materials and bulk W

Material	Melt. Temp. [°C]	Therm. Cond.[W/(m·K)]	Supplier / Product name
W95Ni3.5Cu1.5	~1380 (Ni-Cu matrix)	≥ 85	HC Starck Hermsdorf / HPM 1801
		≥ 105	Plansee SE / Inermet® 180
		105	WHS Sondermetalle / WSM-W95NiCu
W97Ni2Fe1	~1440 (Ni-Fe matrix)	≥ 75	HC Starck Hermsdorf / HPM 1850
		≥ 85	Plansee SE / Densimet® 185
W	3420	164	MG Sanders
			Plansee SE

Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (1)

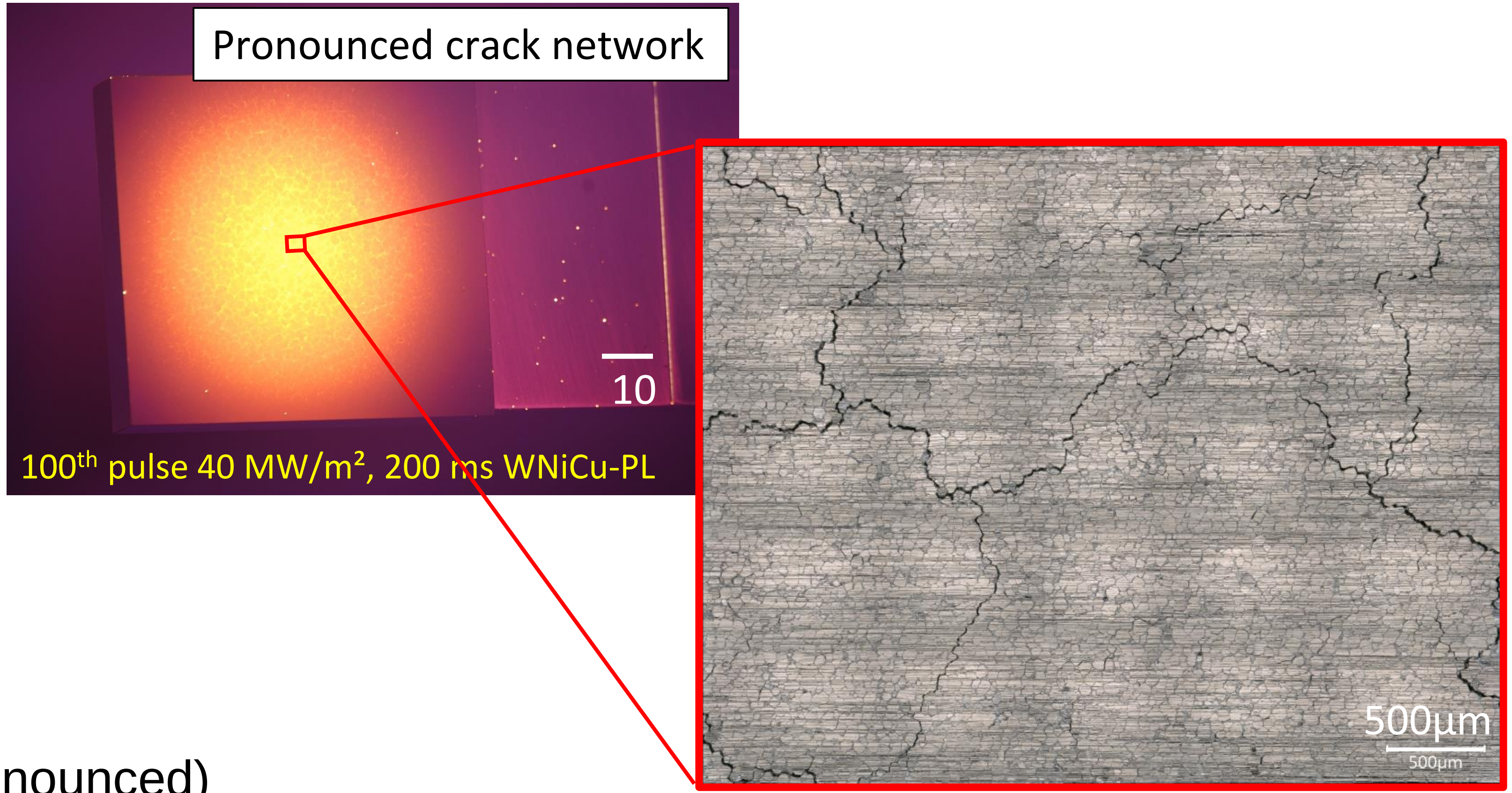
Sample/ Supplier material	**Geometry (length x width x height)**	**Loading / maximum surface temperature**	**Results**
W95NiCu WHS WSM-W95NiCu	115 x 79 x 17 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1180 °C	Pronounced crack network
W95NiCu WHS WSM-W95NiCu	80 x 74 x 15 [mm^3] castellated	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1130 °C	Crack network
W95NiCu Plansee INERMET® 180	80 x 74 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1270 °C	Pronounced crack network
W95NiCu Plansee INERMET® 180	80 x 74 x 17 [mm^3] castellated	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1250 °C	Pronounced crack network
W97NiFe Plansee DENSIMET® 185	80 x 74 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1280 °C	**Some cracks on different areas of the surface**
W97NiFe HC Starck HPM 1850	80 x 74 x 15 [mm^3]	200 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1300 °C	**No cracks, roughening of surface in the center**
W MG Sanders bulk W	95 x 75,8->77 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1130 °C	**No cracks**

Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (2)



CCD camera images for different samples of one of the last cycles at end of pulse.

Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (2)



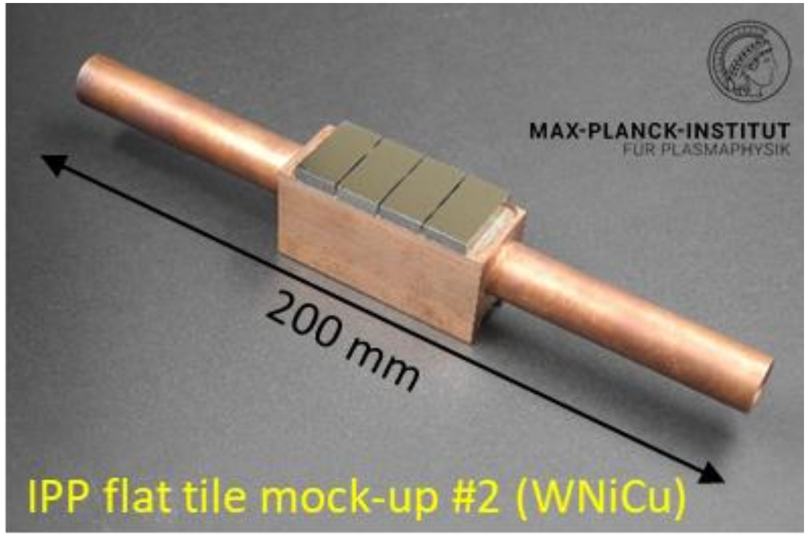
Microscopical image after GLADIS loading.

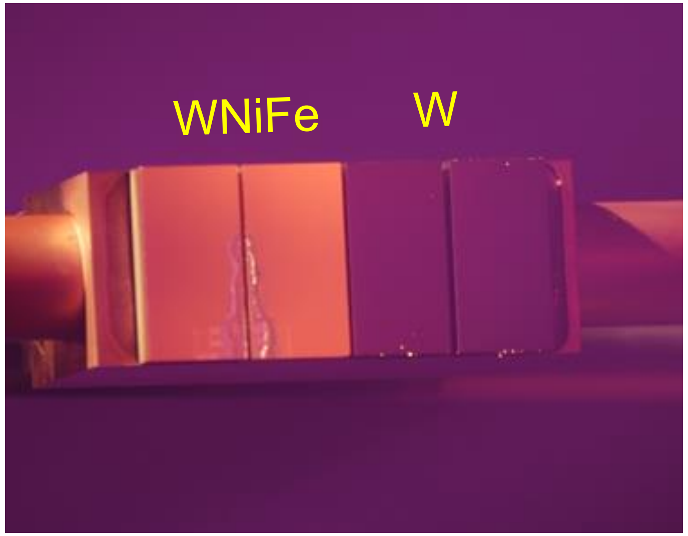
- all **W-Ni-Cu** alloys show (pronounced) **crack network** (even with castellated surface)
- all **W-Ni-Fe** alloys as well as **W** show **no surface damage** (up to T_{surf} = 1300°C)

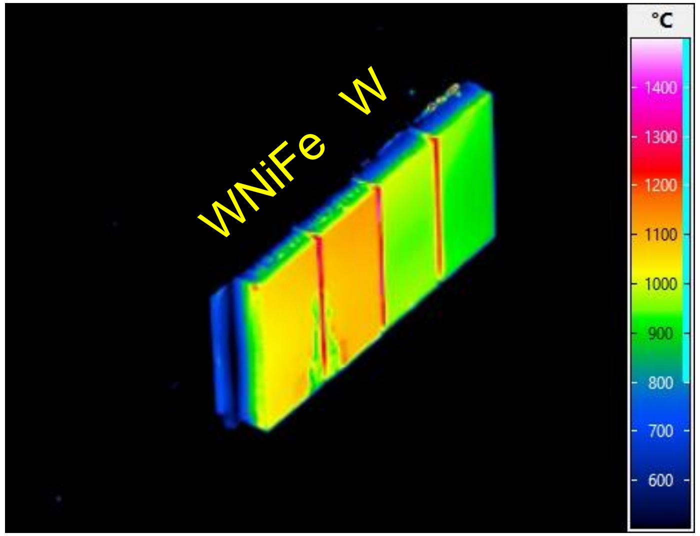
B. Böswirth et al. NME (2024)

Steady state loading of W heavy alloy flat tile mock-ups (1)

Mock-up	tile dimensions	Result screening	Result cycling
#1 W/WNiFe (4 tiles)	23 * 12 * 5 [mm³]	up to 12 MW/m² ok, ✓	100 x 10 MW/m², ok, ✓ 100 x 12 MW/m², ok, ✓
#2 WNiCu (4 tiles)	23 * 12 * 5 [mm³]	up to 12 MW/m² ok, ✓	100 x 10 MW/m², ok, ✓ 100 x 12 MW/m², ok, ✓ small bonding defects

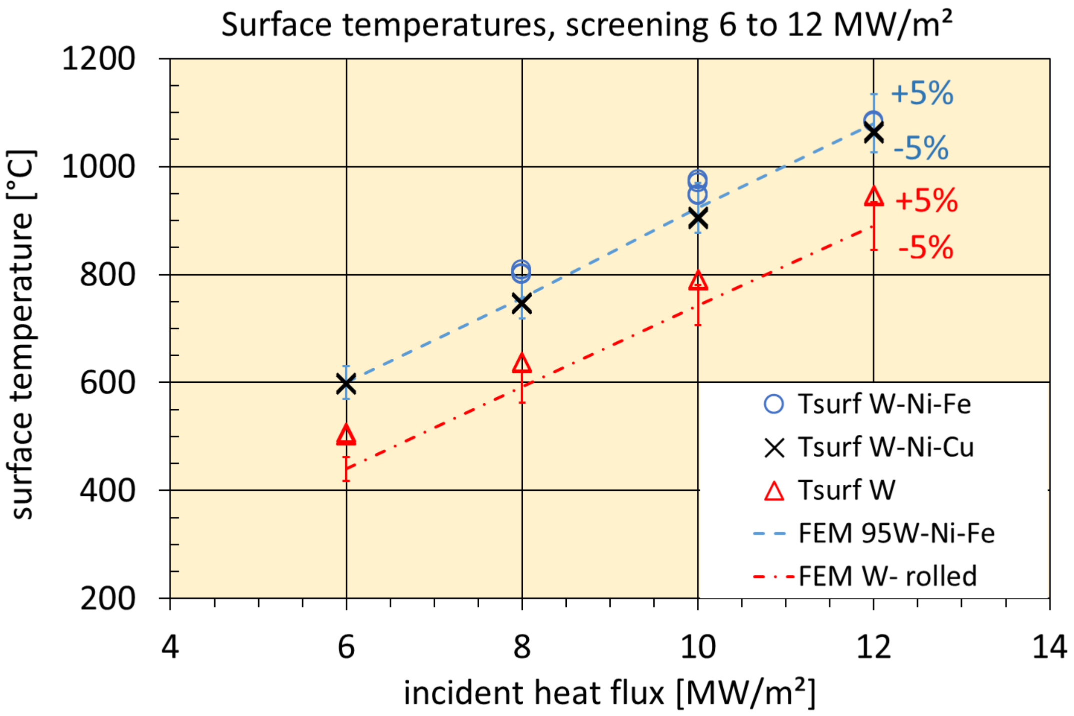


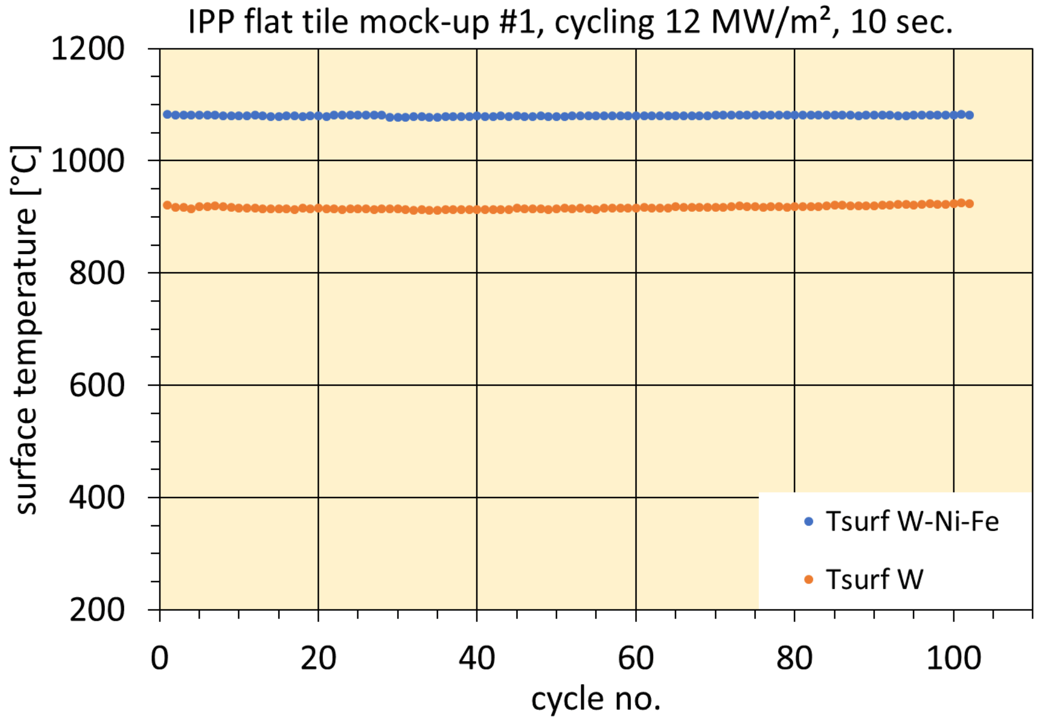




CCD image and infrared image of 100th pulse 12 MW/m² on flat tile mock-up #1.

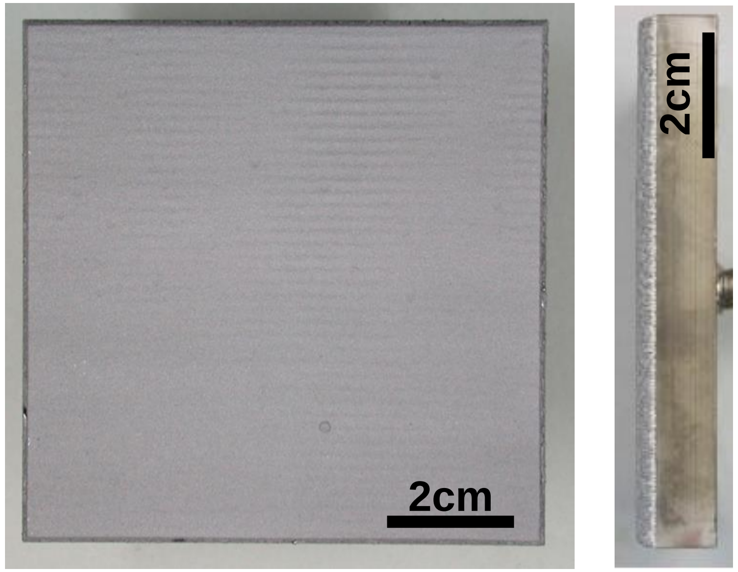
Steady state loading of W heavy alloy flat tile mock-ups (2)





- Thermal screening of both flat tile mock-ups (left): **good agreement of FEM calculations and experiments**
- **stable conditions in low cycle fatigue** loading at 12 MW/m² for 10 s (right) with W and W-Ni-Fe tiles

W/Ta cold spray coatings

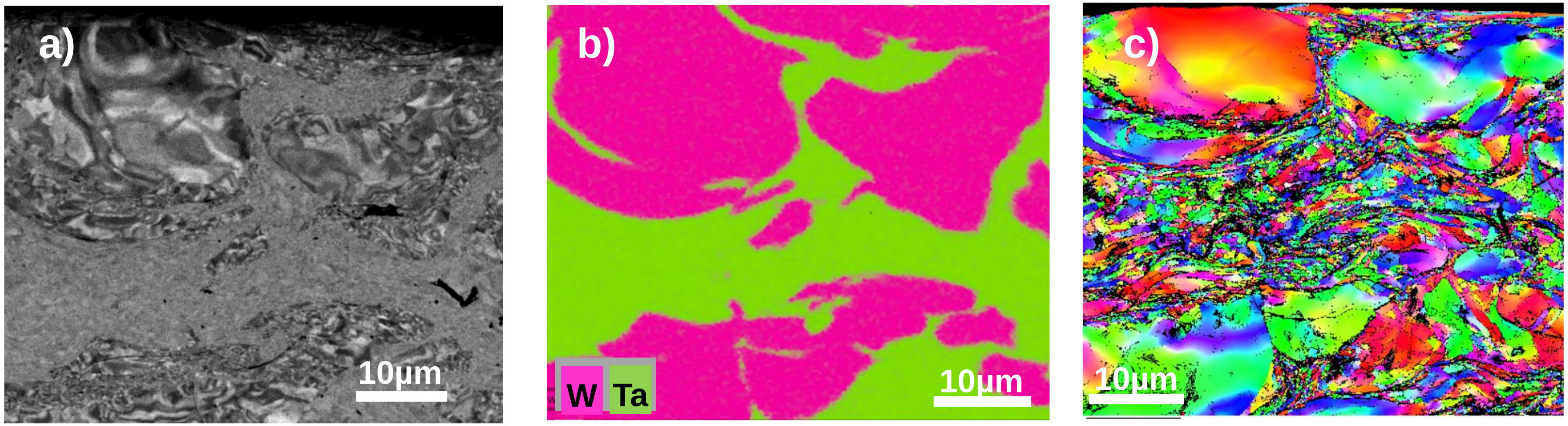


R. Neu et al. NME (2023)

W Coatings in Fusion Devices

- efficient method for W PFCs in areas with low/intermediate plasma fluence
- present day pulsed devices:
  W coatings sufficient even for highly loaded areas (divertor)
- DEMO first wall (W on EUROFER, $d_W \leq 2$mm):
  acceptable erosion lifetime

⇒ **Cold Spray:** thick (mm) coatings with limited power load during application process (full W not successful yet)



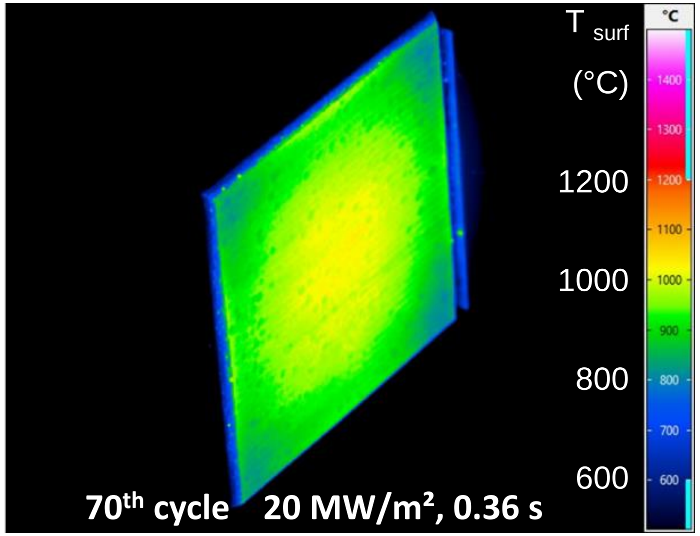
Structure of coating (d=2 mm)

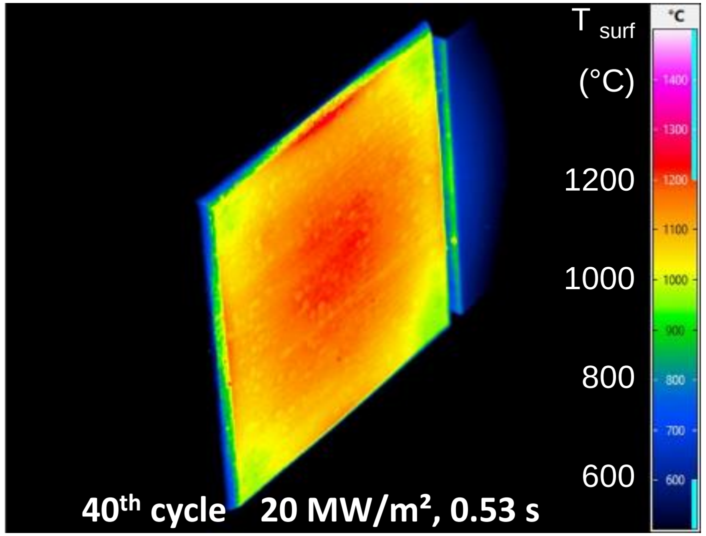
a) cross section (BSE)

b) elemental composition (EDX)

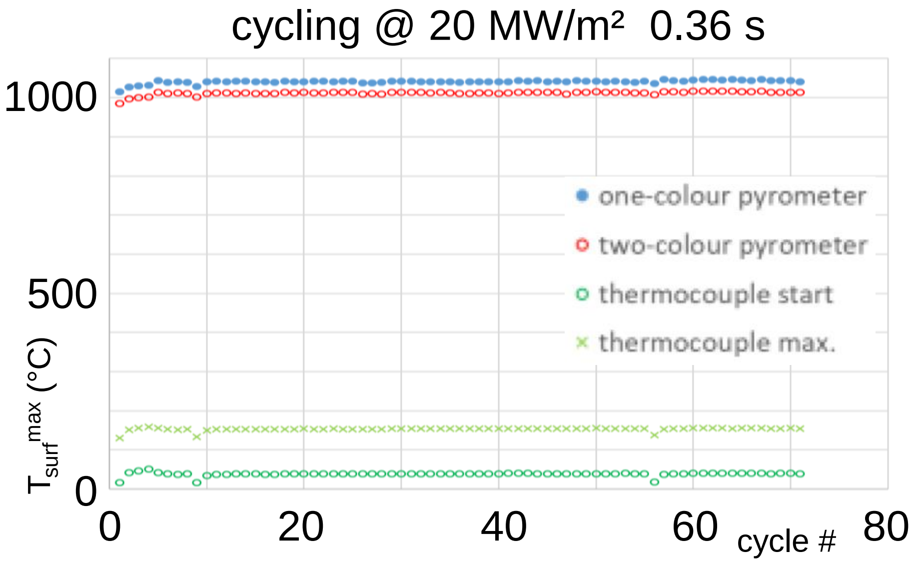
c) crystal orientation (EBSD)

W/Ta cold spray coatings





Step	Power Density (MW/m²)	T_{surf}^{max} (°C)	Pulse Length (s)	# of Pulses
1	2-4	<800	≤ 4	several
2	6	800	1.6	70
3	8	800	1	70
4	10	800	0.7	70
5	10	1000	1.15	70
6	12	1000	0.9	70
7	15	1000	0.58	70
8	20	1000	0.36	70
9	20	1200	0.53	27/40



W/Ta cold spray coatings:

- successful deposition of 2 mm coatings with 70% W on P92 steel
- very low porosity and good thermal conductivity

R. Neu et al. NME (2023)

Results of HHF tests under adiabatic loading conditions:

- no deterioration/damage at power loads up to 20 MW/m² (for T_{surf}^{max} =1000 °C)
- delamination starts at edges (in the coating) @ T_{surf}^{max} = 1200 °C (but no catastrophic failure)

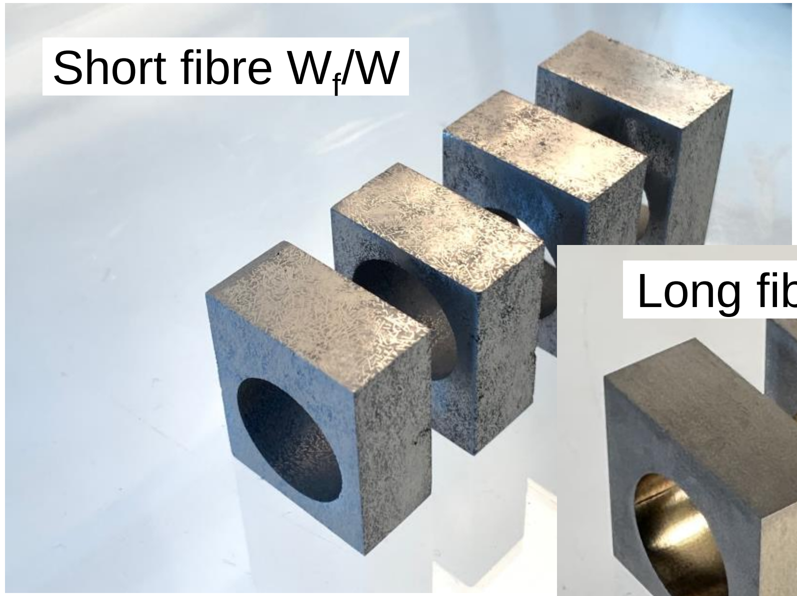
K. Hunger et al. (2023) 19th PFMC
R. Neu et al. (2024) 33rd SOFT

Short Fibre Powder Metallurgic - W_f/W PFCs

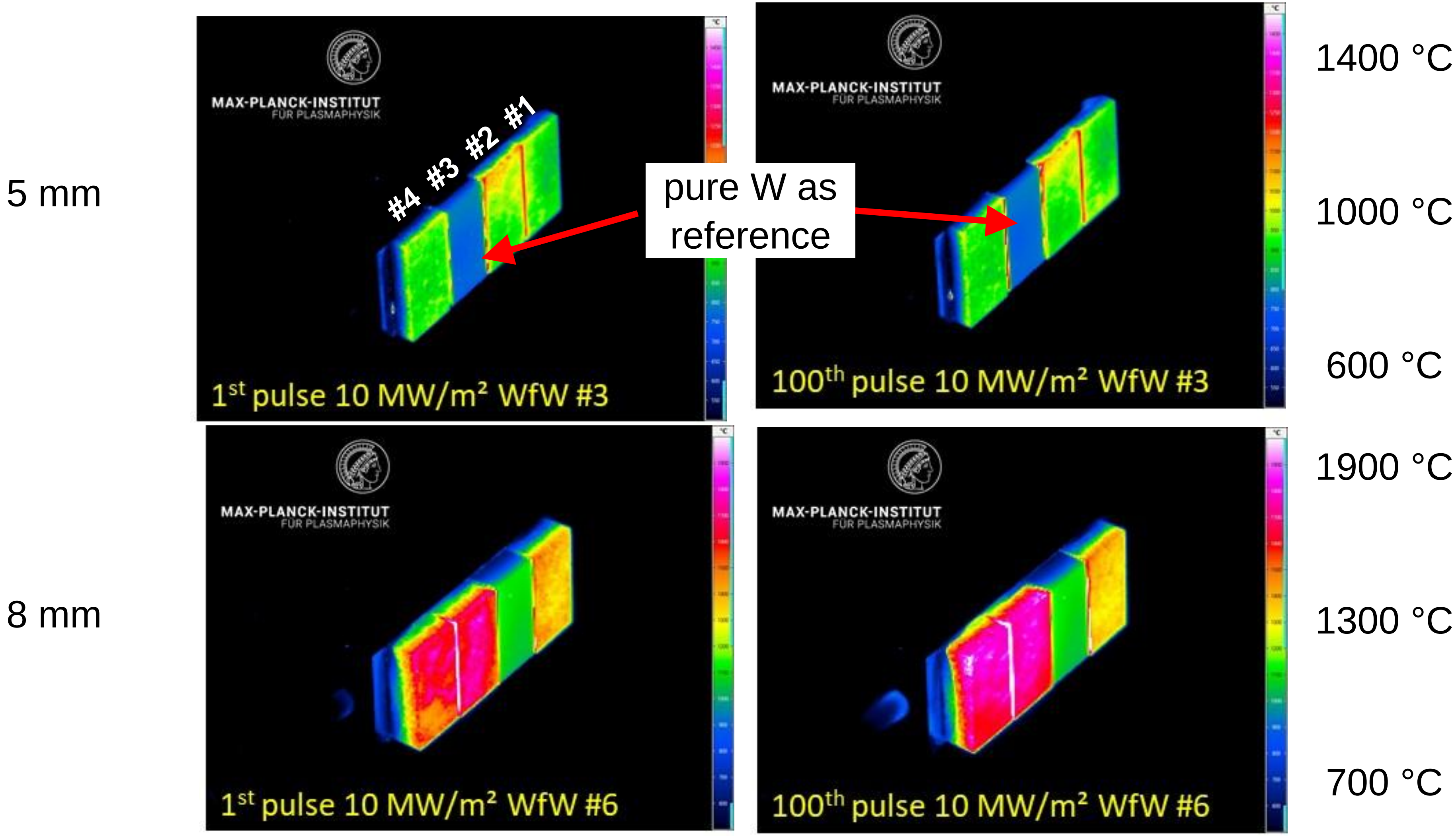
Flat tile: joining completed;
initial high heat flux tests performed

J. Riesch et al. (2021) 18th PFMC

Mono block: pre-characterisation ongoing;
joining to cooling structure pending



HHF Test Results – Comparison of Thin & Thick SF W_f/W Flat Tiles



HHF Test Results – Comparison of Thin & Thick SF W_f/W Flat Tiles

Tile sizes and thicknesses of mock-ups.

No.	*Tile thickness* [mm]	*Tile surface area* [mm] × [mm]	*Number of tiles*
3	5	23 × 12	4
4	5	23 × 24.5	2
5	8	23 × 24.5	2
6	8	23 × 12	4

Hot spot on this edge
(after third loading)

Hot spot on this edge
(after second loading)

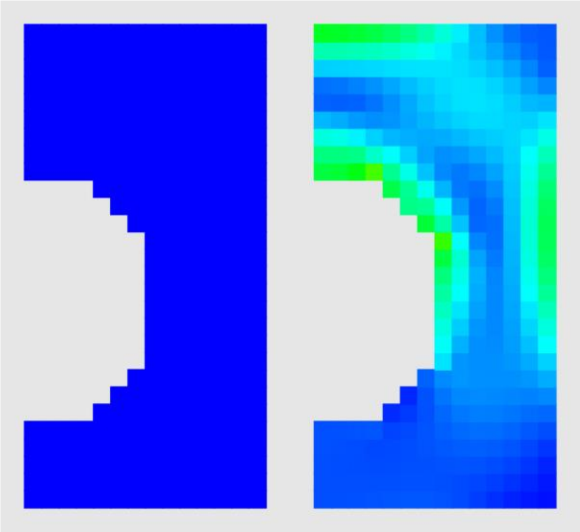
- substantial number of defects in short fibre composite leads to reduced thermal conductance
- first long fibre PM W_f/W samples show better internal structure

No.	T_{max} 10 MW m^{-2} *1st cycle* [°C]	T_{max} 10 MW m^{-2} *100th cycle* [°C]	T_{max} 12 MW m^{-2} *1st cycle* [°C]	T_{max} 12 MW m^{-2} *100th cycle* [°C]	T_{max} 15 MW m^{-2} *1st cycle* [°C]	T_{max} 15 MW m^{-2} *100th cycle* [°C]
3	1140	1090	1780	1700	1970	2220
4	1180	1250				
5	no cycling — surface temperature at screening already 2580 °C					
6	1890	1950	1867	1960		

J. Riesch et al. NME (2024)

Optimised W-Cu Composite Structures

Material distribution **Stress field**



W Cu

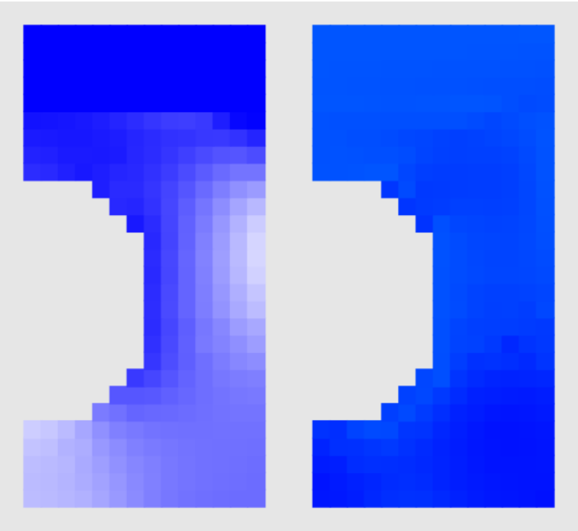
580 MPa

-86%

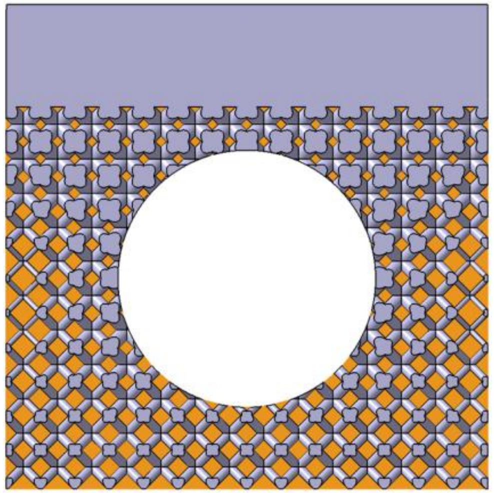
82 MPa

B. Curzadd et al., Nuclear Fusion, 2019

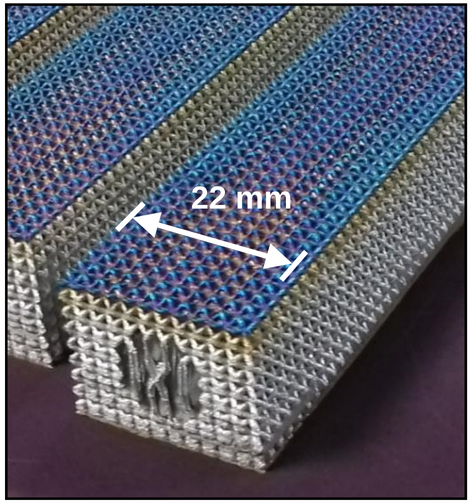
Material distribution **Stress field**

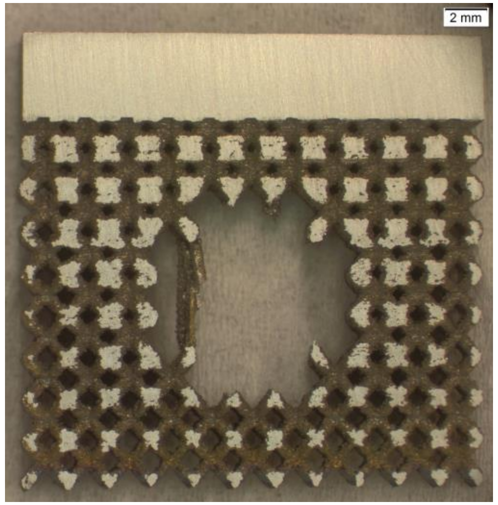


CAD model of tailored W lattice



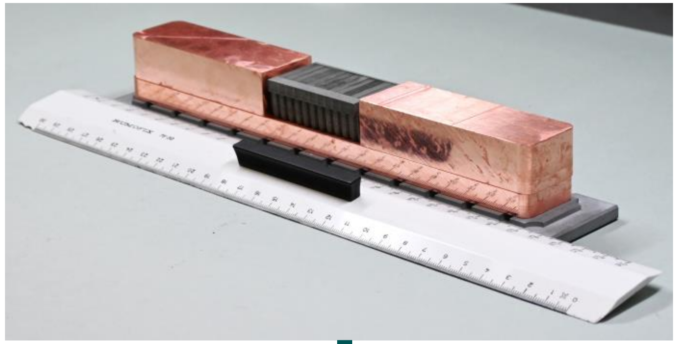
W lattice preforms fabricated by means of PBF-LB/M

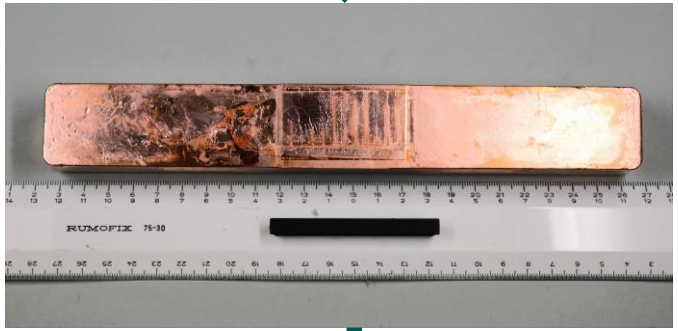


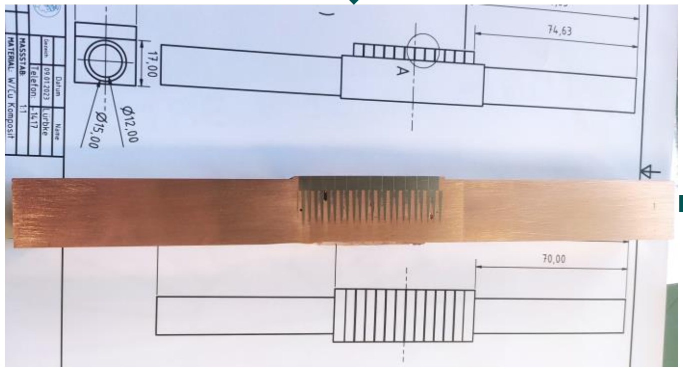


Cross section of tailored W lattice preform fabricated by means of PBF-LB/M

Additively Manufactured / Infiltrated W-Cu PFCs

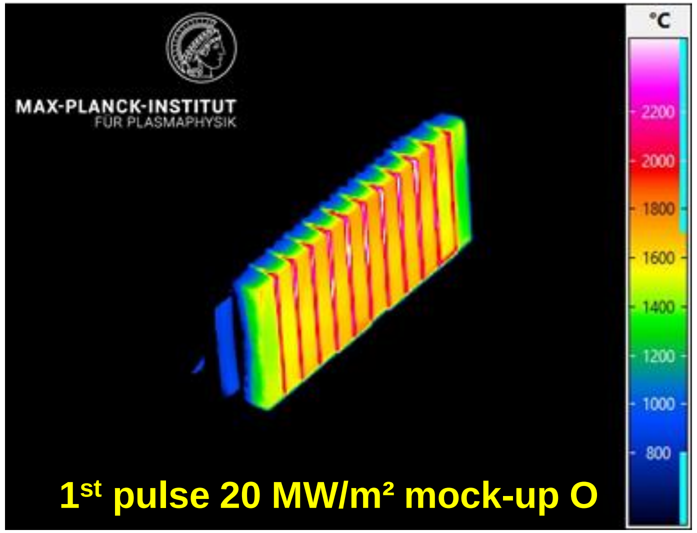




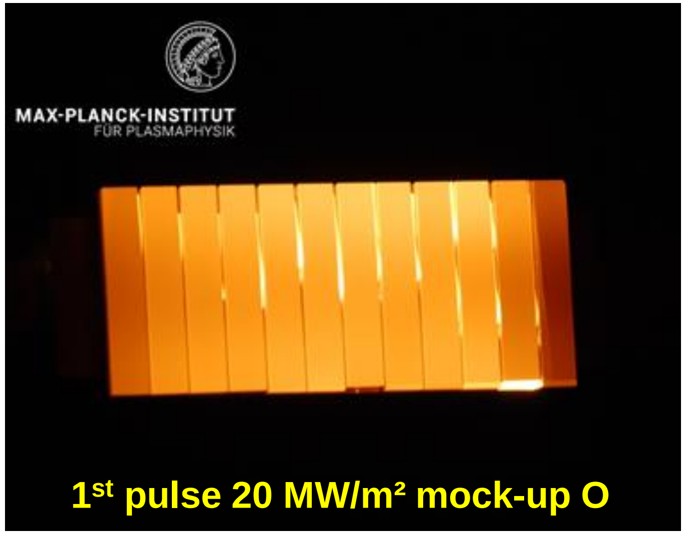


Preparation of a W-Cu composite heat sink from an AM W preform

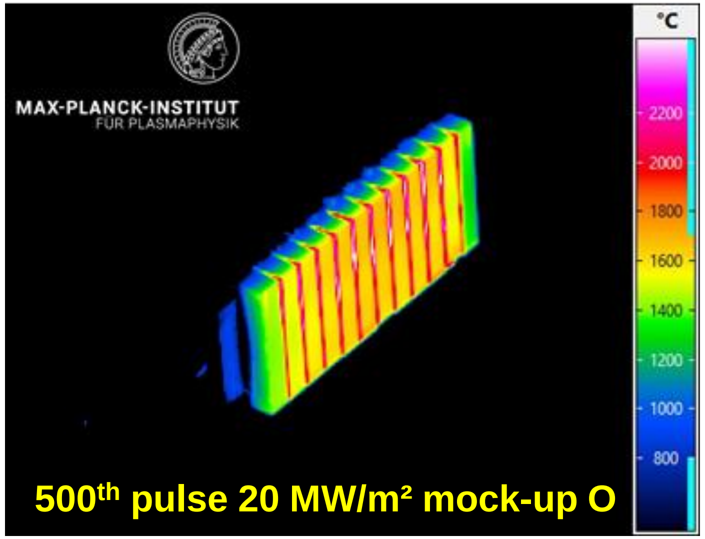
High Heat Flux Tests of AM W-Cu PFCs



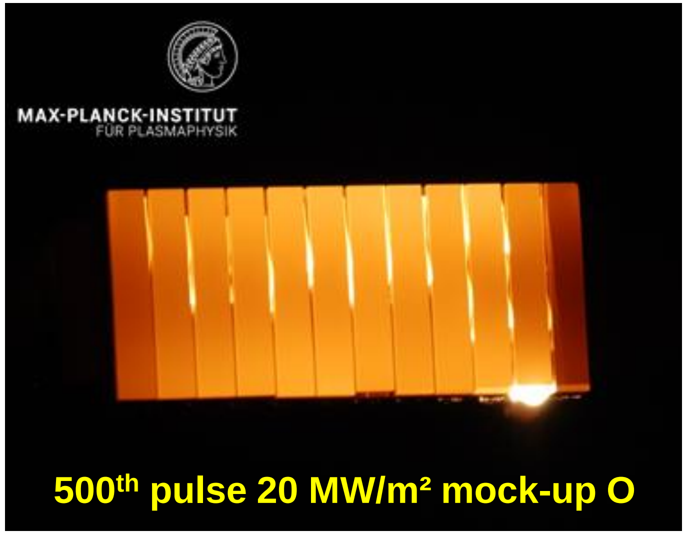
1st pulse 20 MW/m² mock-up O



1st pulse 20 MW/m² mock-up O



500th pulse 20 MW/m² mock-up O



500th pulse 20 MW/m² mock-up O

- cold water cooling conditions (T_{in}=27 °C, p_{in}=16.7 bar, v=12 m/s):
  - screening up to 25 MW/m²,
  - **100 x 10 MW/m²**
- hot water cooling conditions (T_{in}=130 °C, p_{in}=40.3 bar, v=16 m/s):
  - screening up to 20 MW/m²,
  - **500 x 20 MW/m²**

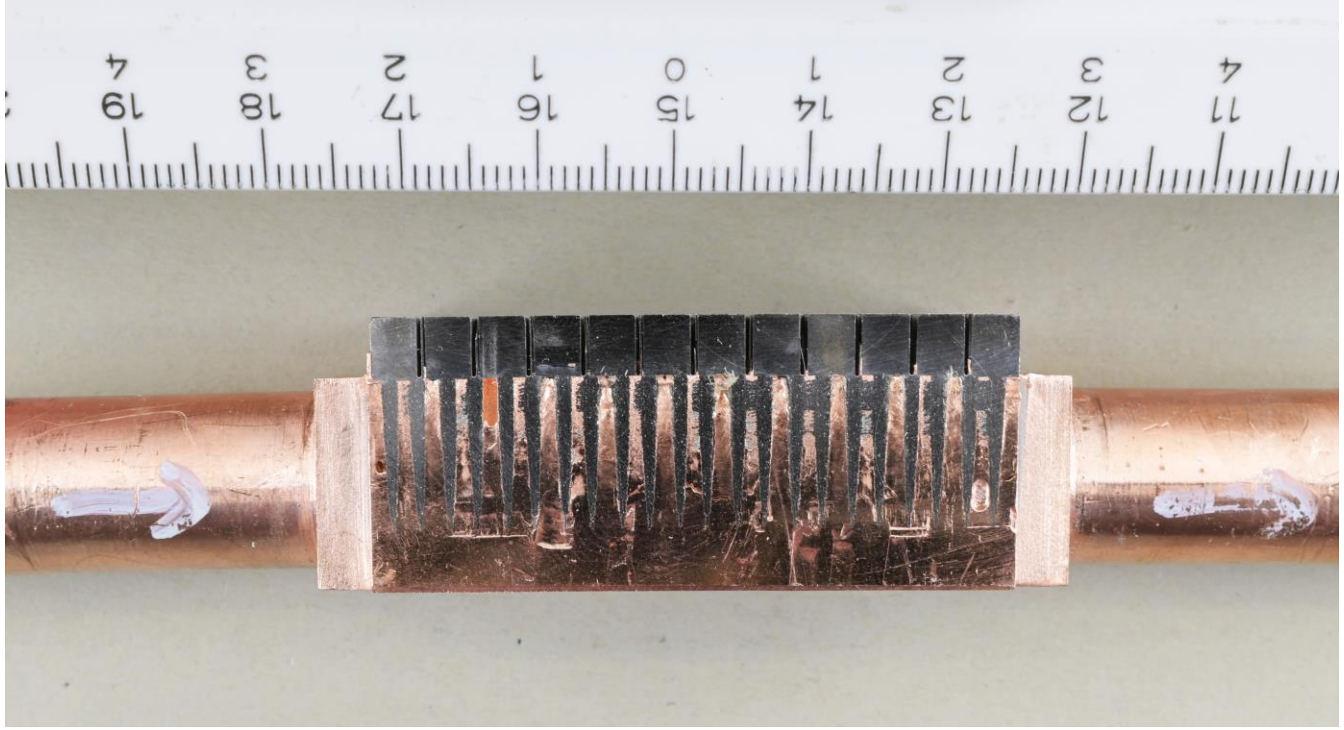
Very good behaviour in HHF tests:

Rather homogeneous (and low) surface temperatures

No obvious defects or changes

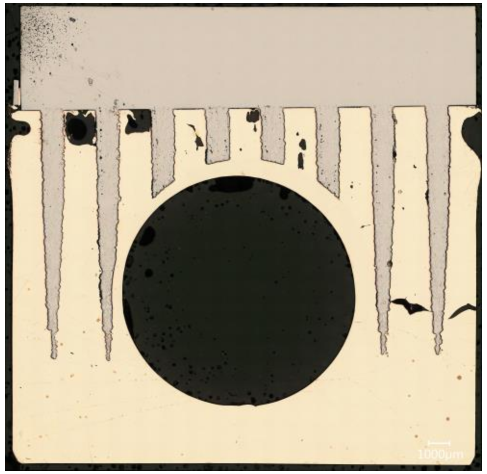
Post Exposure Examination of AM W-Cu PFCs

„Optimized“ AM mock-up after HHF testing



- very good HHF test performance of first AM mock-up despite obvious cavities
- no delamination / deformation of armour tiles
- improved infiltration process identified
- new (improved) mock-up almost ready

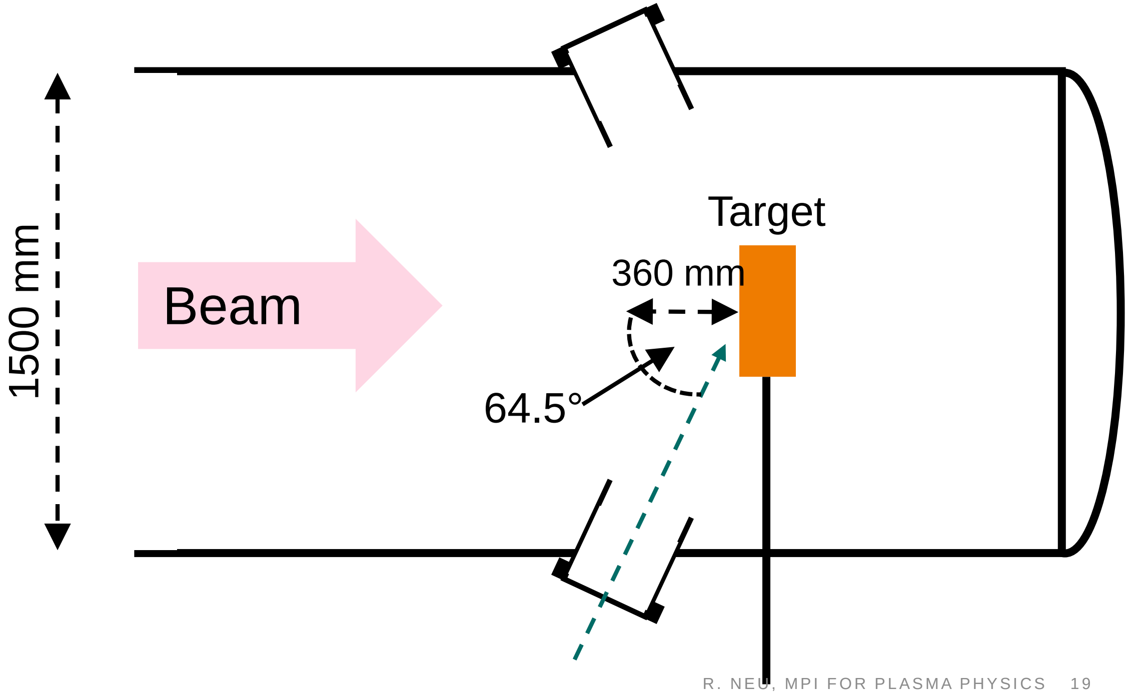
metallographic cross section



A.v.Müller et al. JNM (2022)
R. Lürbke et al (2024) NuMat

New Spectroscopic Diagnostic at GLADIS

- Avantes fibre-optical spectrometer **AvaSpec-ULS4096CL-EVO**
- Grating: 600 lines/mm, blaze 300 nm
- Wavelength range 270 nm to 785 nm calibration certificate: 270 nm to 806 nm
- Detector: CMOS 4096 pixels (7 × 200 µm)
- Resolution (with 10 µm slit): ca 0.4 nm FWHM

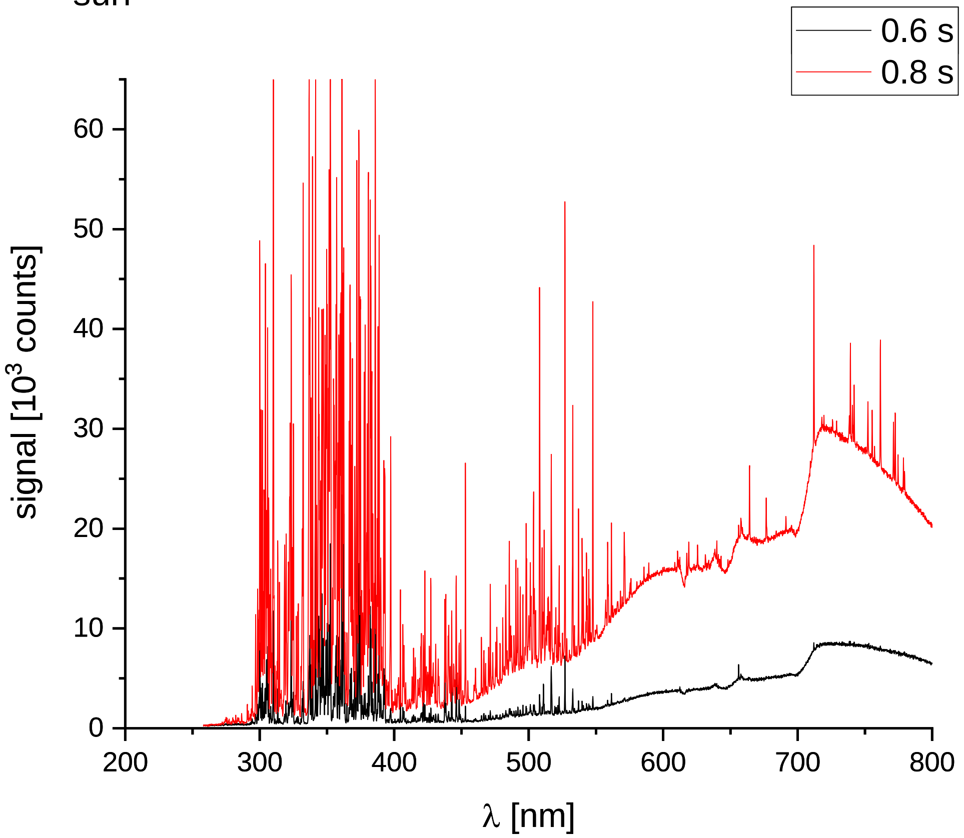


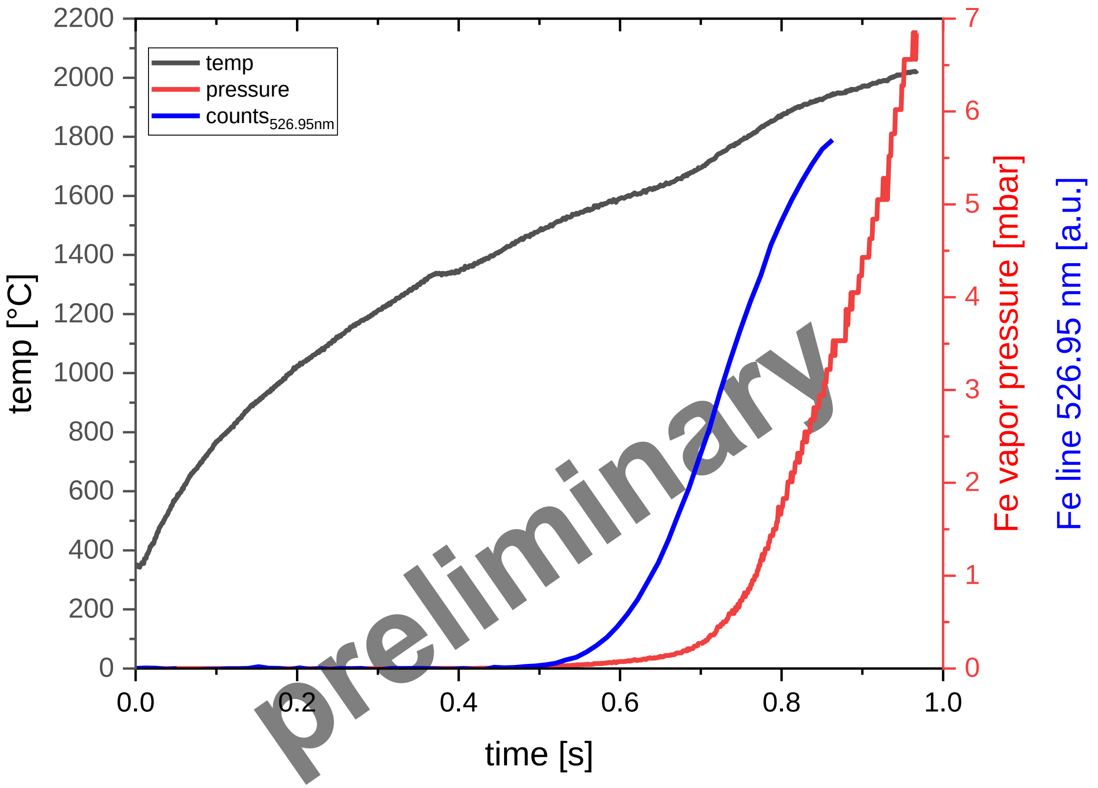
- Distance to target: 1 m
- Viewing angle to surface normal: 64.5°

New Spectroscopic Diagnostic at GLADIS

Melt experiment on WNi2Fe1 target

- adiabatic loading 30 MW/m², 2.5 s
- $T_{surf}^{max} > 3000$ °C





- strong increase of thermal background (in line with T_{surf} measurements)
- rise of of Fe I line similar to vapour pressure (T_{surf} offset)

Further (planned) HHF testing

- Liquid Sn mock-up with W capillary porous system for WPPRD-LMD *J. Scholte et al. NME (2024)*
- C actively cooled flat-tile PFCs with TZM heat sink for WPDIV-JT60SA
- W actively cooled mono-block mock-ups for WPDIV-IDTT *S. Roccella et al. (2023) 30th SOFE*
- W actively cooled mono-block mock-ups for WPDIV-DEMO *J.-H. You et al. NME (2022)*
- W / W alloy / W-laminate actively cooled mono-block mock-ups for WPDIV-MAT *F. Crea et al. FED (2024)*
- W actively mono-block mock-ups for KSTAR
- W and W heavy alloy inertially cooled mock-ups for CFS *J. Riesch et al. (2024) 33rd SOFT*
- W and W heavy alloy actively cooled PFCs for WPDIV-W7X *J. Fellinger et al. NME (2023)*
- W actively cooled flat-tile PFCs with TZM/CuCrZr heat sink for WPDIV-JT60SA