MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Tungsten and copper (alloy) based divertor target plasma-facing components – state-of-the-art and developments towards the application of tungsten-copper composites

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EUROfusion

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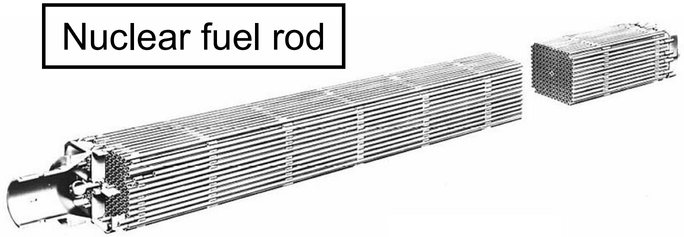
Nuclear fusion reactors – a highly demanding environment

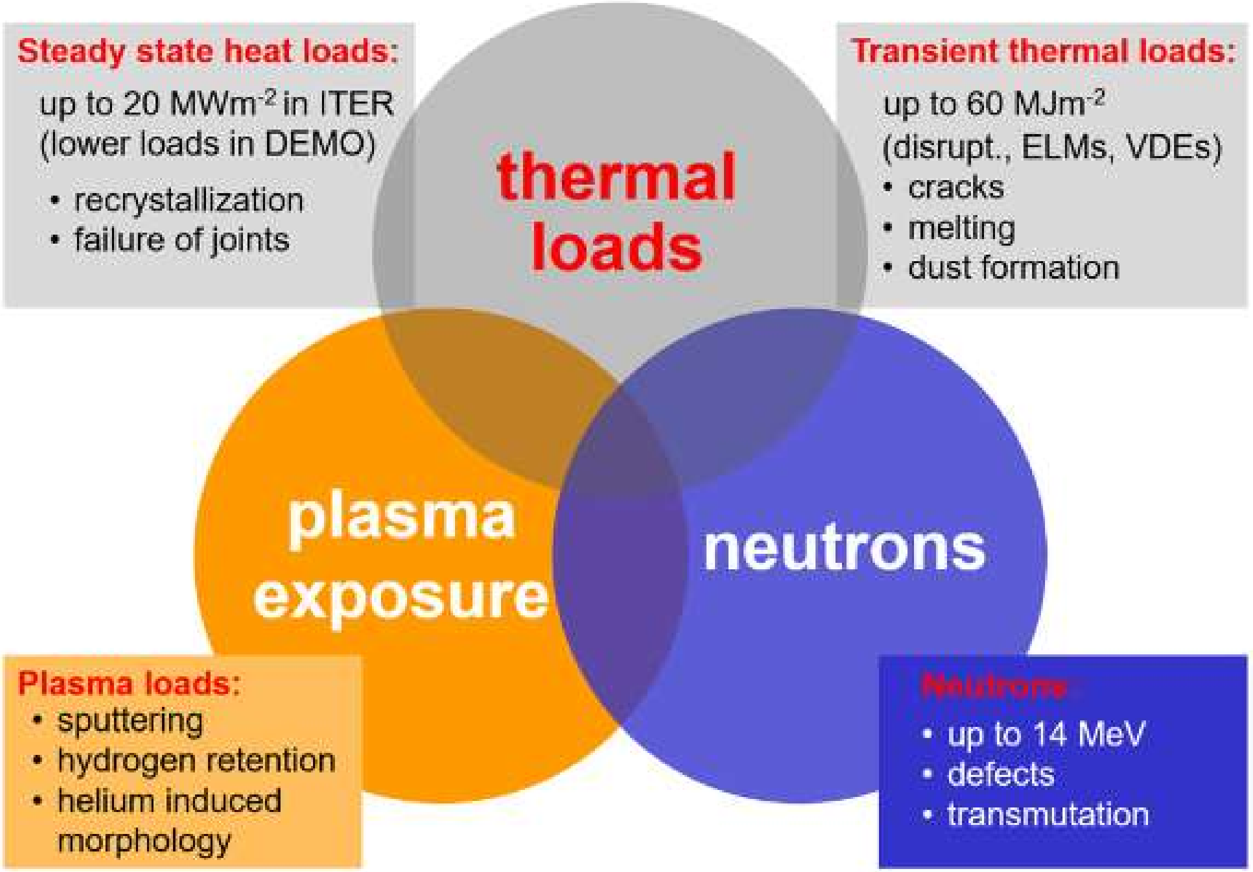
[https://de.wikipedia.org/wiki/Sonnenwärmekraftwerk#/media/Datei:PS20andPS10.jpg]

~ 1 MW/m²

Nuclear fuel rod



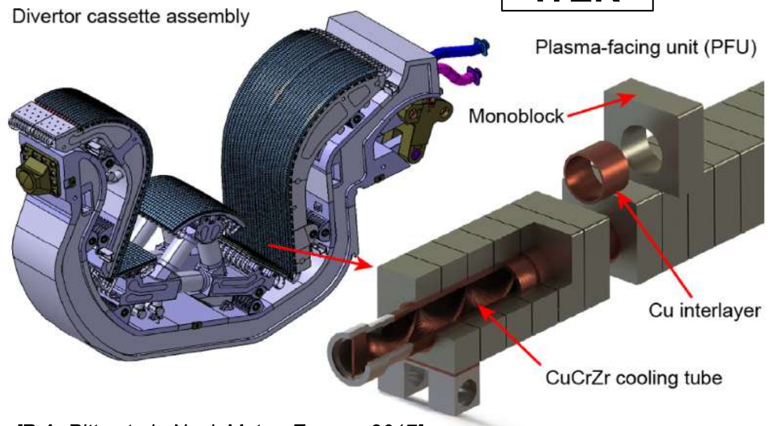
[https://de.m.wikipedia.org/wiki/Datei:Nuclear_fuel_element.jpg]



[J. Linke et al., Matter Radiat. Extremes, 2019]

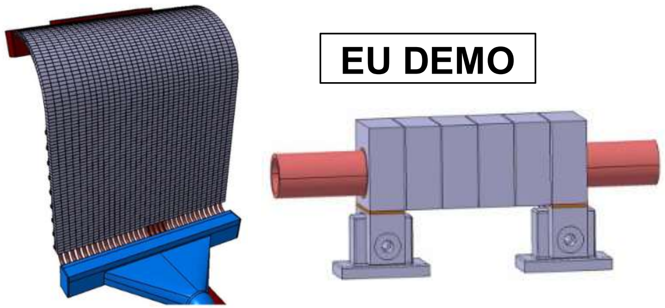
State of the art – Tungsten and copper based plasma-facing components (PFCs)

ITER



[R.A. Pitts et al., Nucl. Mater. Energy, 2017]

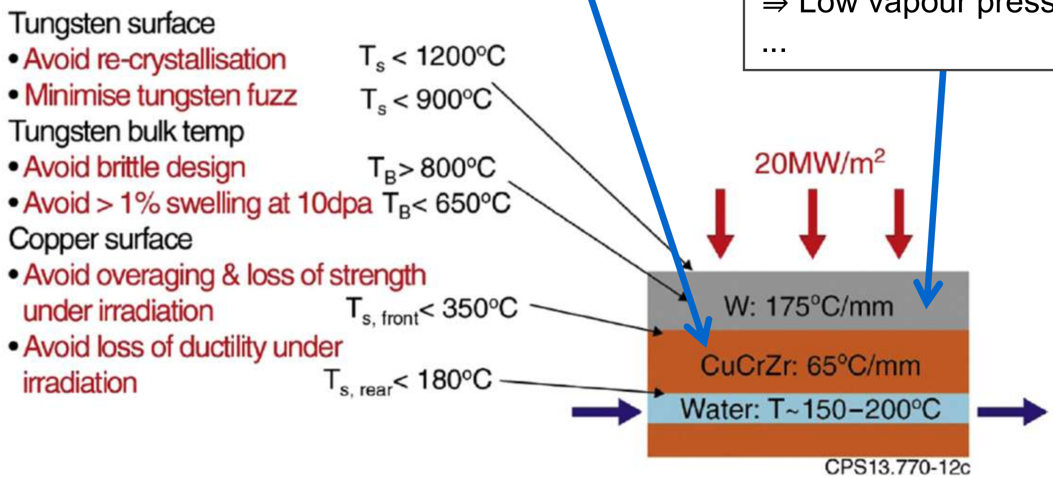
EU DEMO



[J.H. You et al., Fus. Eng. Des., 2022]

Cu (alloys) as heat sink materials
⇛ Excellent thermal conductivity

W as PFM
⇛ Low sputtering yield
⇛ Low tritium retention
⇛ High melting point
⇛ Low vapour pressure
...

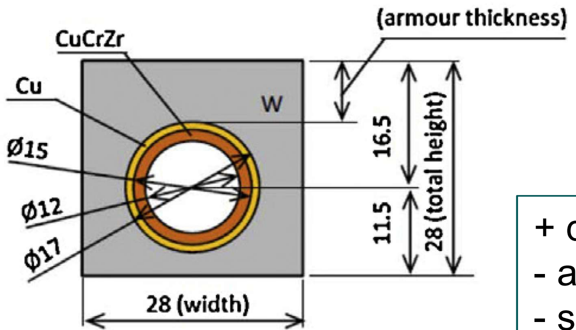


[D. Stork et al., J. Nucl. Mater., 2014]

- PFCs comprise differing materials → composite structure
- Decisive for PFC performance and integrity:
  - ➢ ~mm joining zone

Monoblock vs. flat-tile

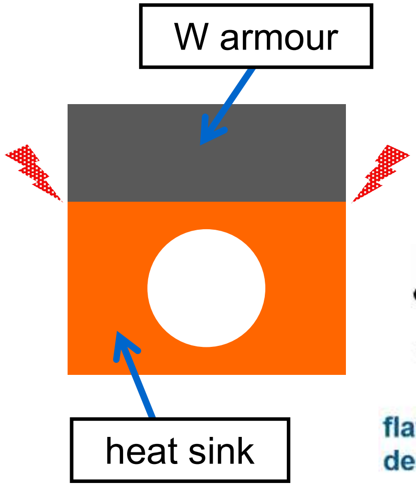
Tungsten monoblock design



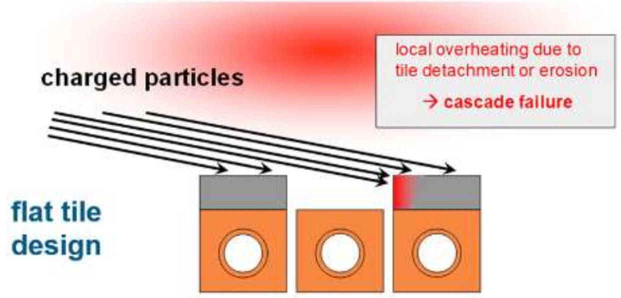
[T. Hirai et al., Phys. Scr., 2014]

+ damage tolerance
- amount of W
- scalability?

Tungsten flat-tile design



+ reasonable amount of W
+ bulky high conductivity heat sink
- high stresses at joint edges
- concern about cascade failure



[J. Linke et al., Matter Radiat. Extremes, 2019]

In future D-T fusion reactors

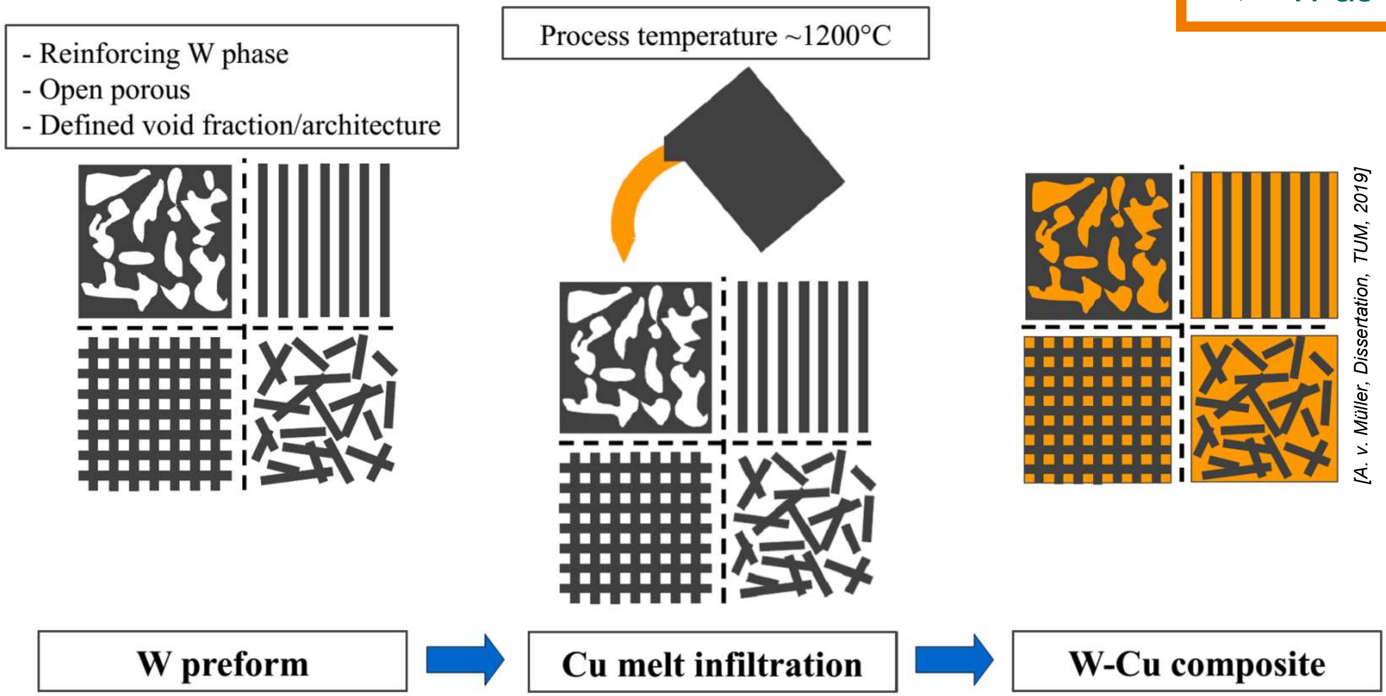
- High neutron dose → Uncertainties in material and component performance
- Higher demands on lifetime → less component replacements desired
- Larger elements → fewer edges and relaxed tolerances

Tungsten-copper (W-Cu) metal matrix composites (MMCs)

- Good-natured material system for metal matrix (MMC) composite fabrication
  - (nearly) no interfacial reaction or mutual solubility
  - fabrication through liquid melt infiltration possible
  - constituent materials readily available at moderate cost

W-Cu composite:
„mixture“ of W and Cu

- Cu matrix ensures high heat conduction
- W as reinforcing phase

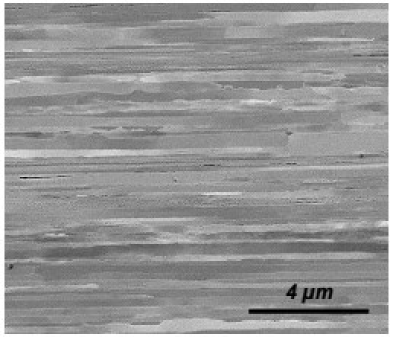


[A. v. Müller, Dissertation, TUM, 2019]

W fibre-reinforced composites

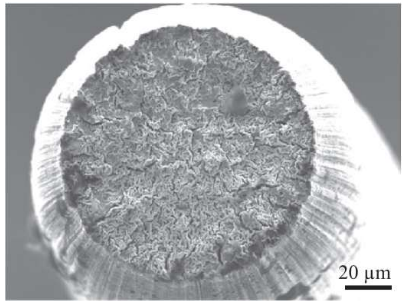
- Use of high-strength drawn W fibres
  - ⇛ *Texture/fine-grain strengthening effect*
  - ⇛ *High microstructural stability*
  - ⇛ *High strength at elevated temperature*

Longitudinal SEM cross section of a drawn W fibre



[A. v. Müller et al., Nucl. Mat. and Energy, 2018]

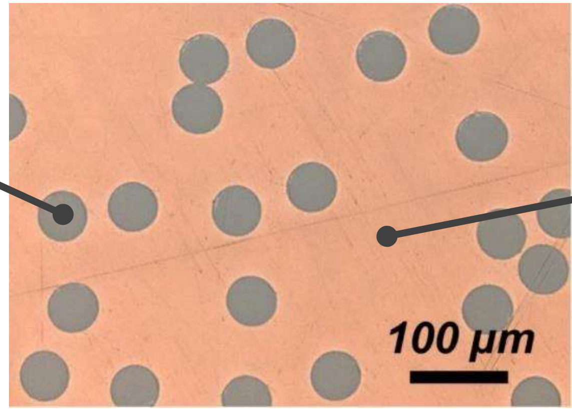
Ductile failure of a drawn K doped W fibre after annealing at 1900°C



[J. Riesch et al., Phys. Scr., 2016]

W matrix

W fibre



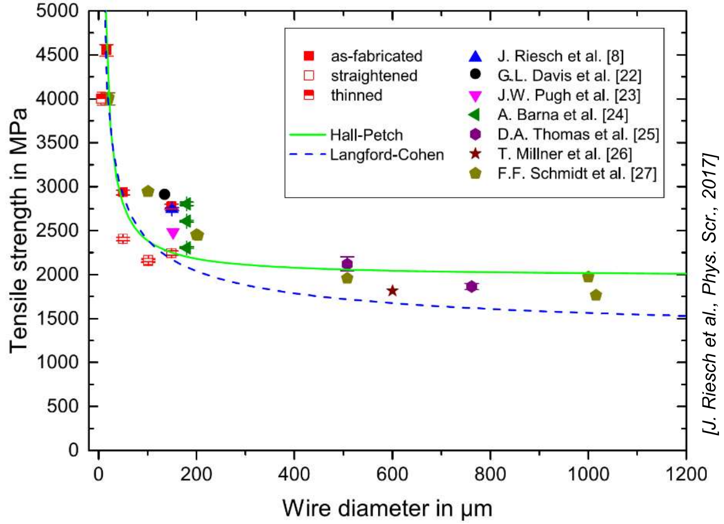
Cu matrix

W fibre-reinforced W

W fibre-reinforced Cu

Drawn W wire as reinforcement

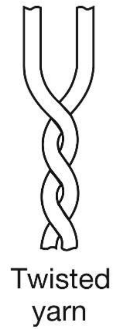
- Increasing fibre strength with decreasing fibre diameter

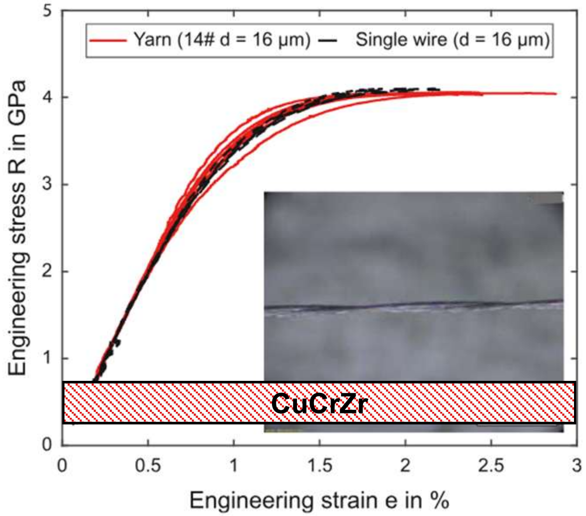


[J. Riesch et al., Phys. Scr., 2017]

- Twisted W yarn out of filaments with Ø = 16 µm
  - ➢ Tensile strength at room temperature ca. 4 GPa

[T. Gries et al., Textile Technology, 2015]



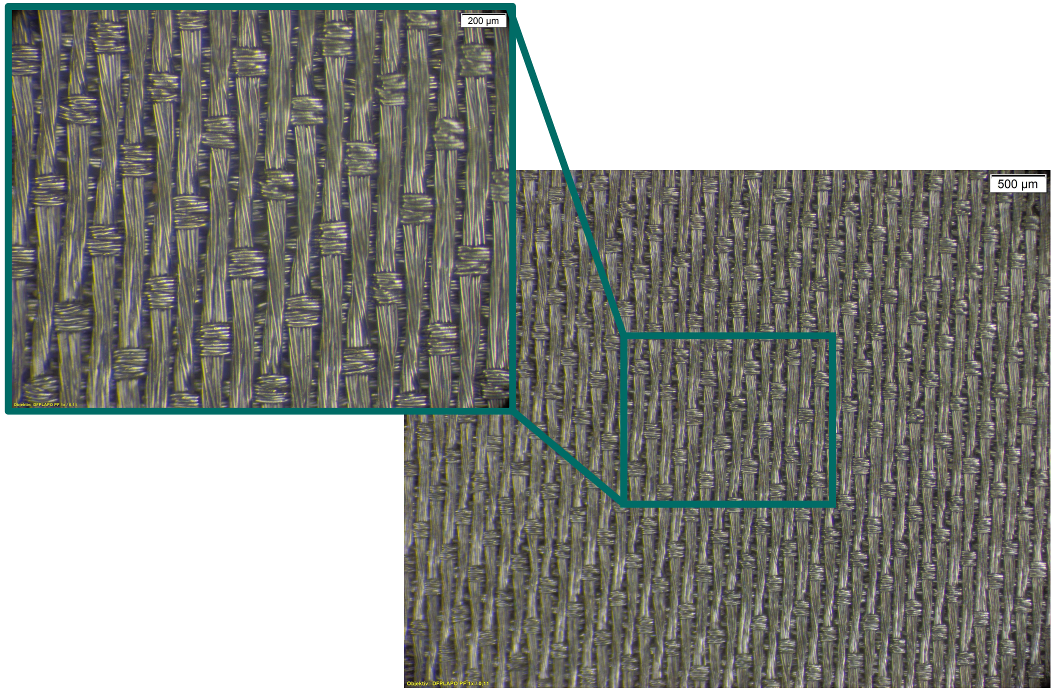


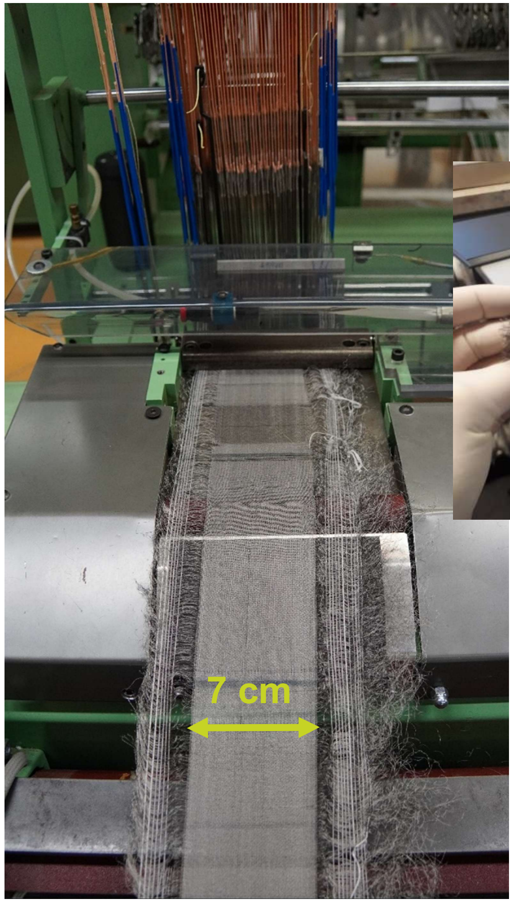
[J. Riesch, A. v. Müller et al., Nucl. Mater. Energy, 2024]

aerumtec
Copper Products and Solutions

Textile techniques for W preform fabrication – Weaving

- Flat weavings out of W yarn
  (14 x 16 µm) with different densities and patterns
  - High density: Atlas 1/7 with 84 warp yarns/cm

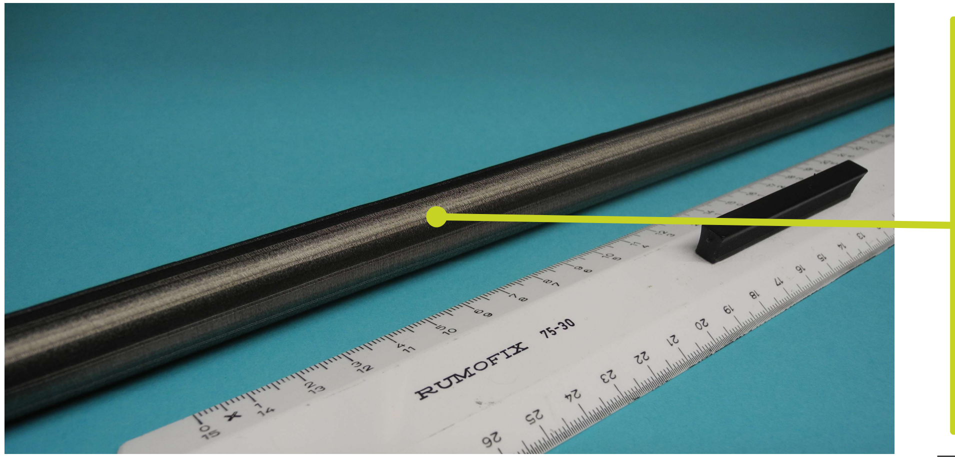


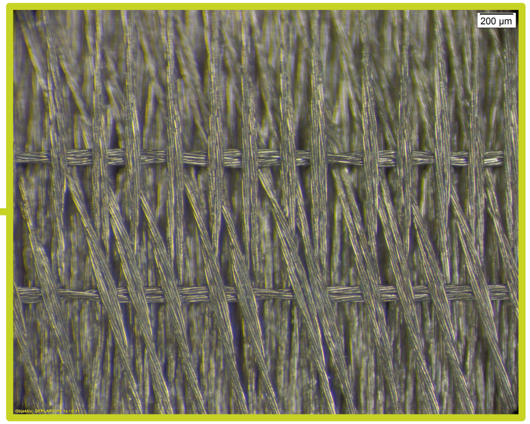


~10 m woven strand

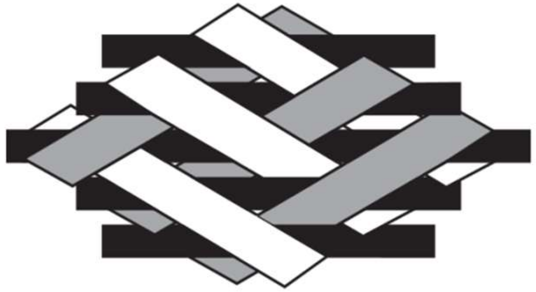
Textile techniques for W preform fabrication – Braiding

- Application to water-cooled PFCs ⇛ *W fibre-reinforced Cu heat sink pipe*
- Refined braiding technology:
  - fabrication of multilayered braids for medium scale W fibre-reinforced Cu heat sink pipes with a length ~400 mm





Triaxial braid
with axial reinforcement out of twisted W yarn (14 x 16 µm)



[P. Potluri and S. Nawaz, Developments in braided fabrics, in Specialist Yarn and Fabric Structures, R.H. Gong, Ed. Elsevier, 2011]

PFC mock-ups – HHF testing

- High heat flux (HHF) qualification testing of **monoblock type mock-ups** with **tungsten fibre-reinforced copper heat sink pipe**

  ⇛ Brazed joint (AuCu alloy, ultrasonic NDE) between W monoblocks and W fibre-reinforced Cu heat sink pipe

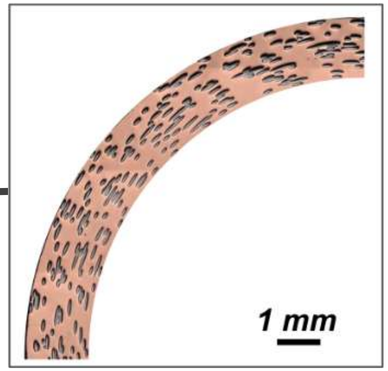
  ⇛ DEMO relevant hot water cooling conditions
    - T = 130°C, p = 40 bar, v = 16 m/s

  ⇛ Successful HHF testing
    - up to **1000 load cycles at 20 MW/m²**

HHF test facility GLADIS @ IPP Garching

200 mm

[A. v. Müller et al., Phys. Scr., 2020]

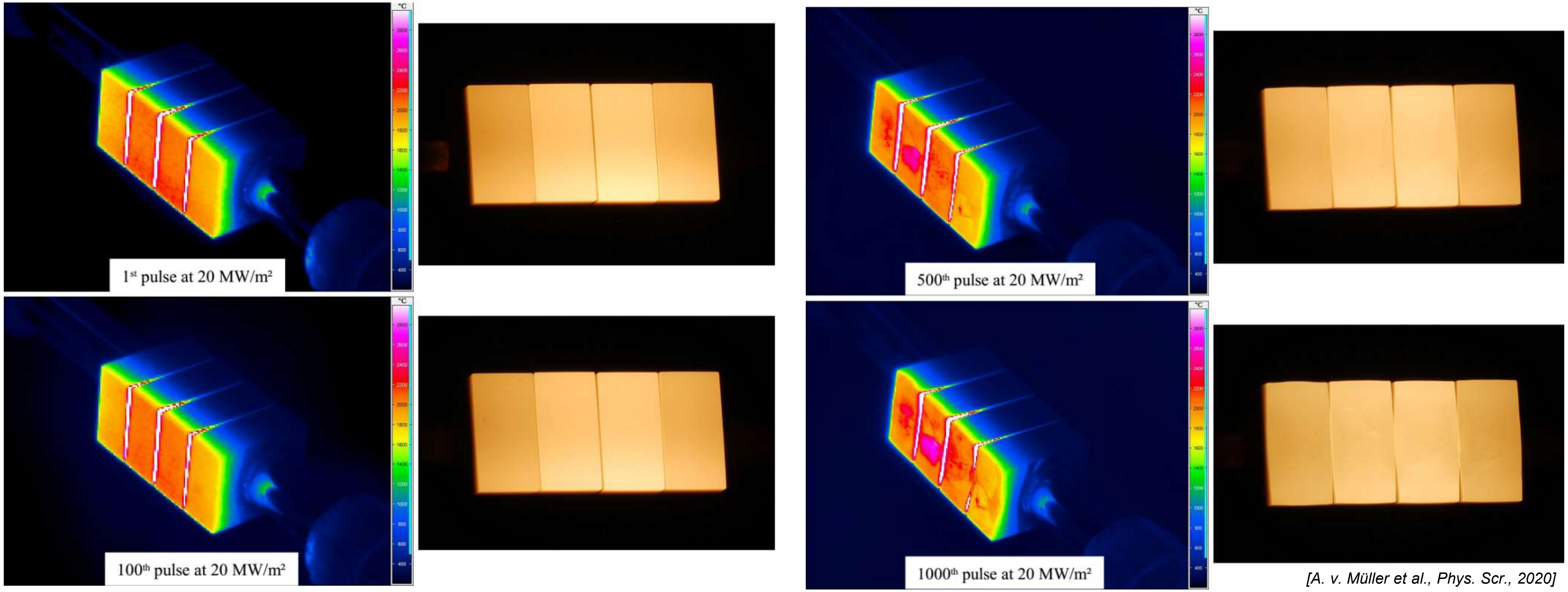


[A. v. Müller et al., Fusion Eng. Des., 2017]

W fibre-reinforced Cu pipe

PFC mock-ups – HHF testing

- Infrared and optical images of PFC mock-up during HHF testing for 1000 cycles at 20 MW/m^2
  (FEA: $T_{surface,max}$ = 2272°C, W armour thickness: 8 mm)



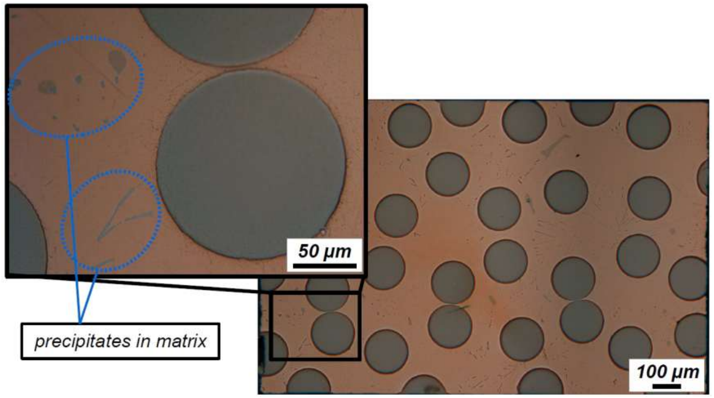
[A. v. Müller et al., Phys. Scr., 2020]

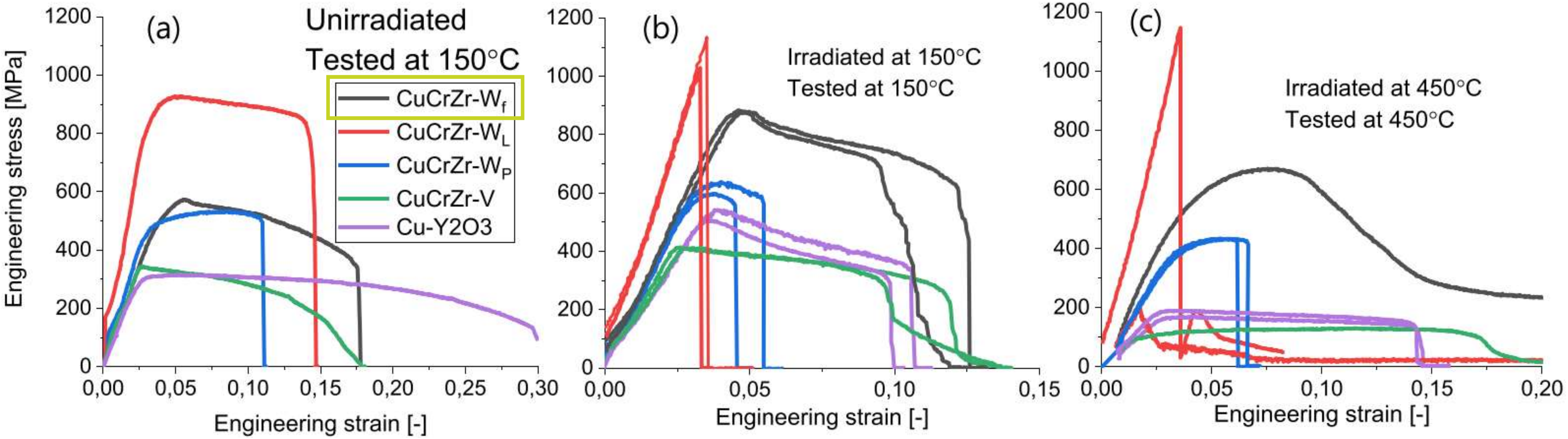
- Maximum temperature of the tungsten fibre-reinforced copper heat sink at 20 MW/m^2 according to *FEA: $T_{pipe,max}$ = 430°C*

Neutron irradiation of W fibre-reinforced CuCrZr

- EU irradiation campaign for screening mechanical properties of advanced Cu-based materials for PFC applications (water-cooled divertor)
    - assessment of strength properties by tensile testing
    - irradiation/test temperatures 150°C to 450°C

- Neutron exposure was performed in Belgian material test reactor BR2
    - target irradiation fluence defined as 1 dpa (in W)



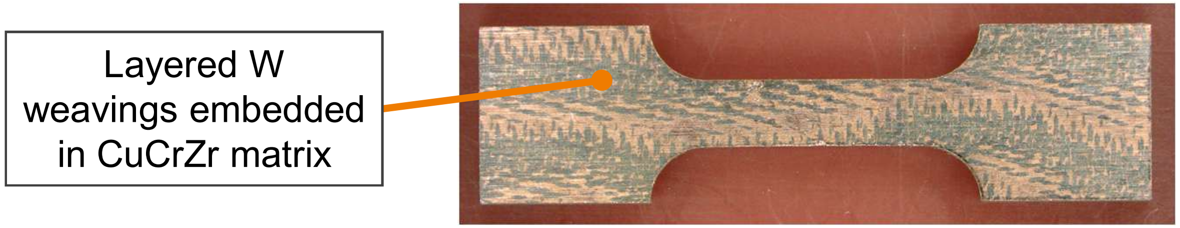


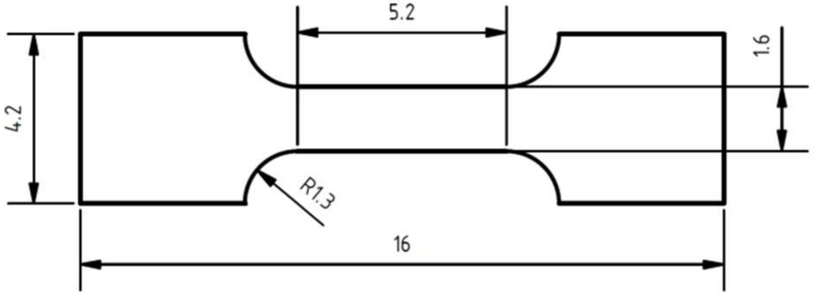
[D. Terentyev et al., Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys, Nucl. Fusion, 2021]

W fibre-reinforced Cu – Outlook

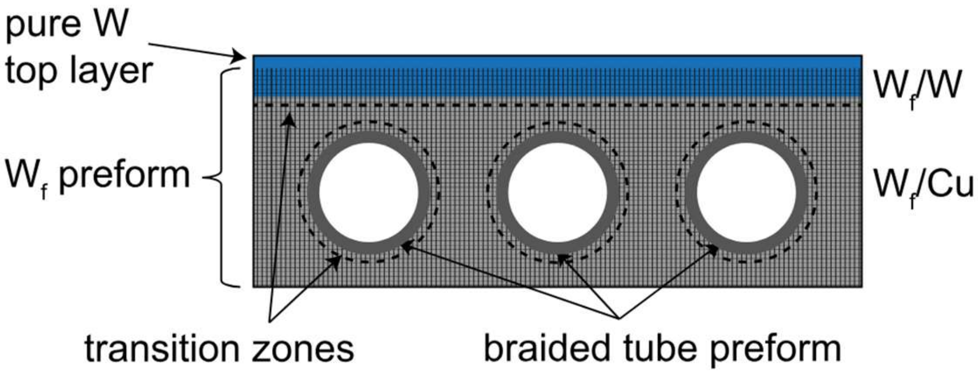
- Work towards the use of Cu alloy (CuCr, CuCrZr) as matrix material and upscaling of fabrication technology

- Tensile specimens for upcoming neutron irradiation experiments (BR2) fabricated





- Combination of W fibre-reinforced Cu and W fibre-reinforced W in one composite structure
  - Exploit extraordinary properties of W fibres also for armour-heat sink joint enhancement
  - Work towards 3D fibrous W preforms

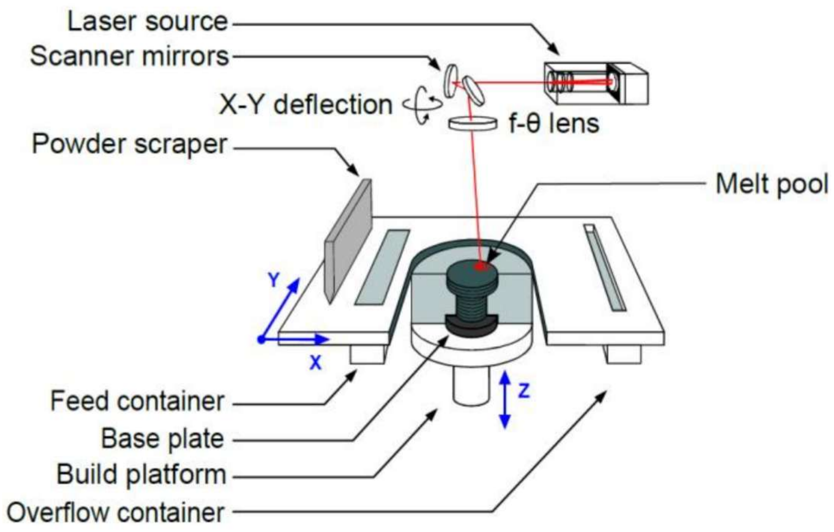


[J. Riesch, A. v. Müller et al., Nucl. Mater. Energy, 2024]

Additive Manufacturing of W

- **Additive manufacturing (AM)**:
  - three-dimensional objects are created by sequential layerwise deposition of material under computer control
  - objects with more or less arbitrary shape can be produced

Laser - PBF-LB/M

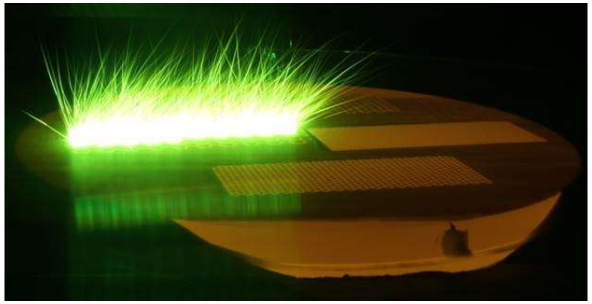


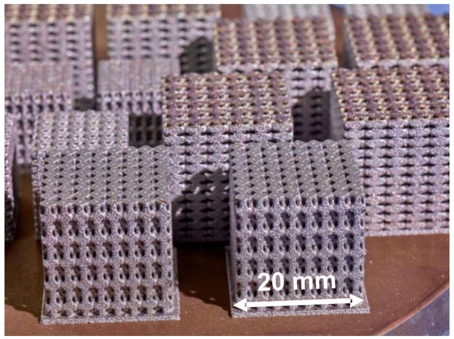
[K. Kempen et al., Solid Freeform Fabrication Symposium, 2011]

Additive Manufacturing of W

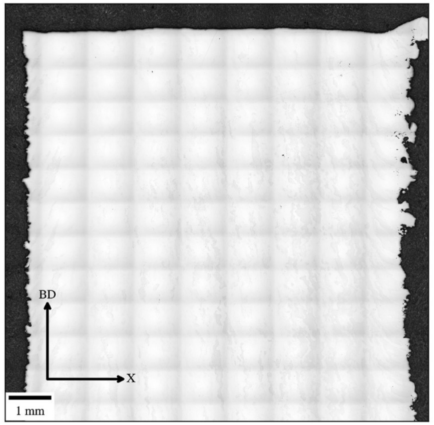
- **Additive manufacturing (AM)**:
  - three-dimensional objects are created by sequential layerwise deposition of material under computer control
  - objects with more or less arbitrary shape can be produced

Laser - PBF-LB/M	Electron beam - PBF-EB/M

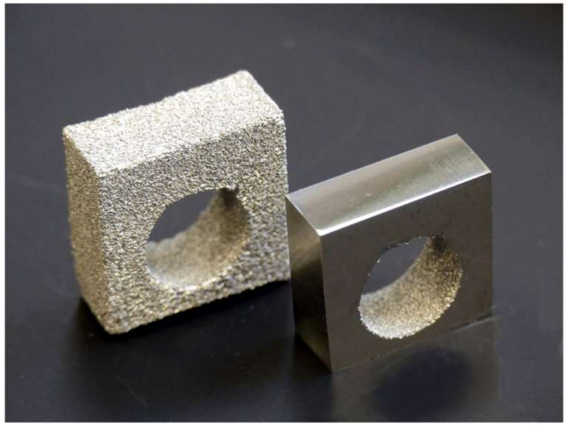




[A. v. Müller, D. Dorow-Gerspach et al., Journal of Nuclear Materials, 2022]



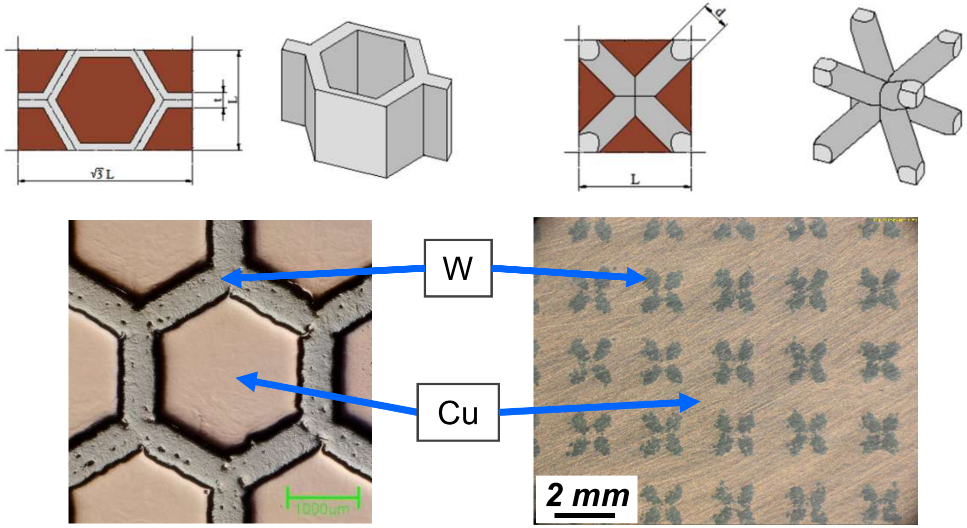
[C. Ledford et al., Int. J. Refract. Met. Hard Mater., 2023]



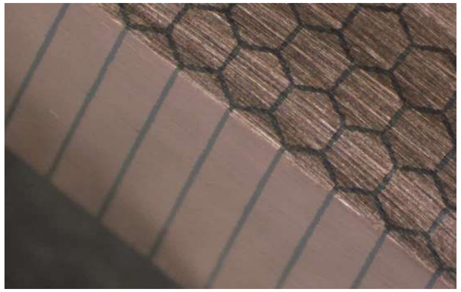
[D. Dorow-Gerspach, et al., Nuclear Materials and Energy, 2021]

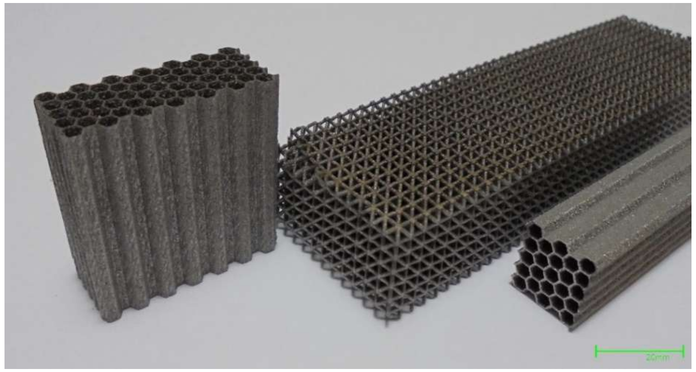
Tailored W-Cu composite structures

- Influencing macroscopic thermomechanical properties through tailored microstructure

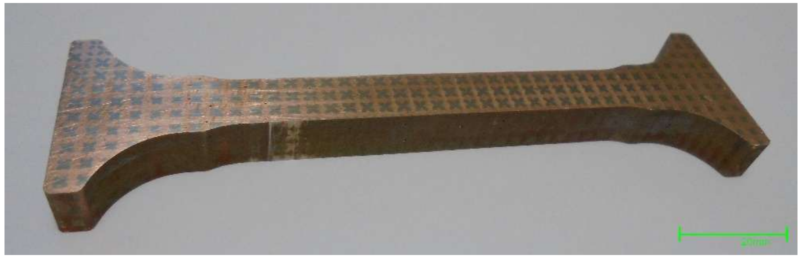


Additively manufactured and Cu melt infiltrated W structures





W structures (unit cell size 2.5 mm) fabricated by means of PBF-LB/M: honeycomb structures and lattices

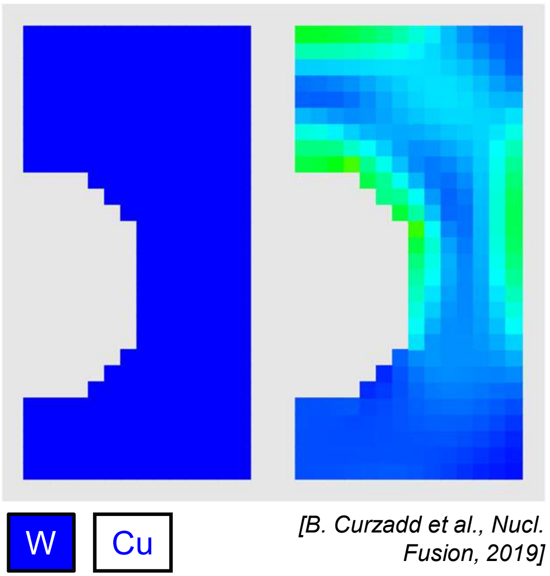


W-Cu tensile specimen based on W lattice (unit cell size 2.5 mm, W volume fraction 0.3)

Tailored W-Cu composite structures

- Influencing macroscopic thermomechanical properties through tailored microstructure
  - » Optimisation of W-Cu material distribution for PFC performance enhancement

Material distribution **Stress field**

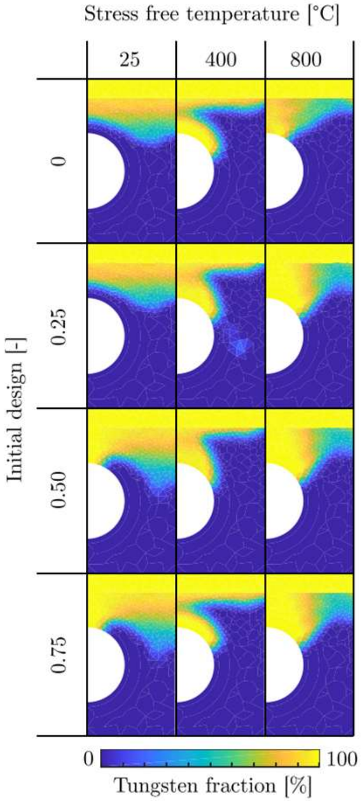


[B. Curzadd et al., Nucl. Fusion, 2019]

576.1 MPa

-85.7%

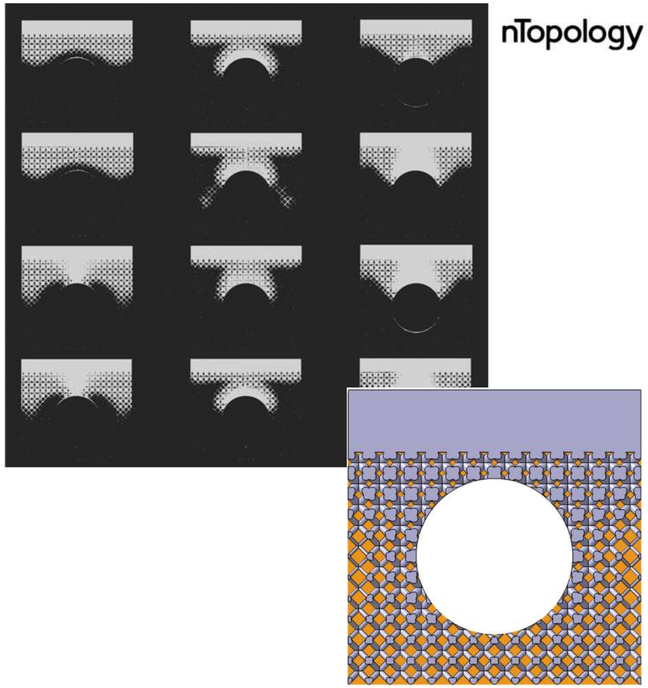
82.2 MPa



(a) von Mises cost function, with temperature constraints

[S. Van den Kerkhof et al, Nucl. Fusion, 2021]

Translation to CAD designs



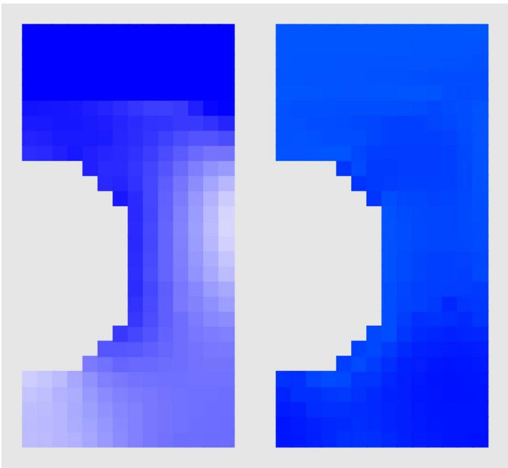
Tailored W-Cu composite structures

W

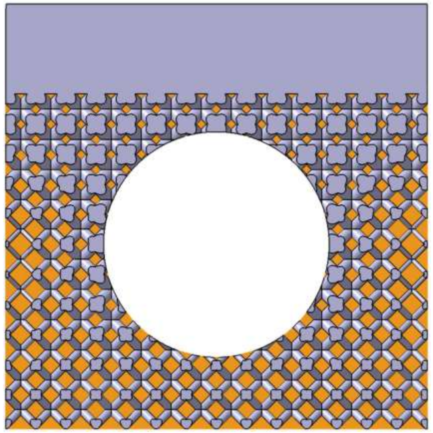
Cu

Q_N = 10 MW/m^2
T_0 = 650 °C

Material distribution **Stress field**

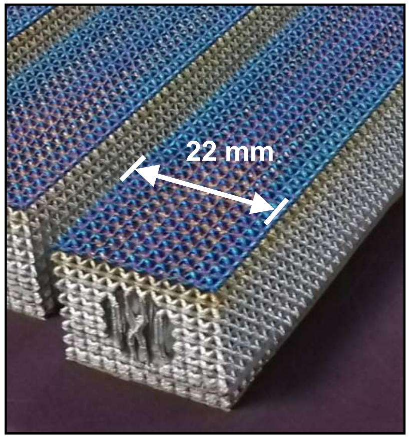


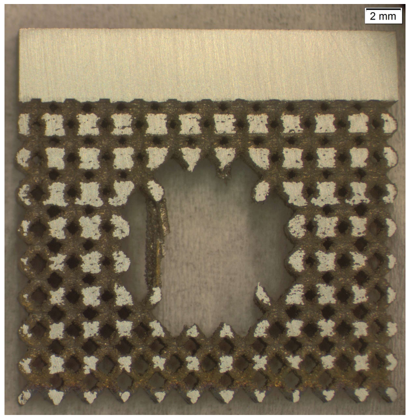
[B. Curzadd et al., Nuclear Fusion, 2019]



CAD model of a lattice structure based on an optimised W-Cu material distribution

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





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

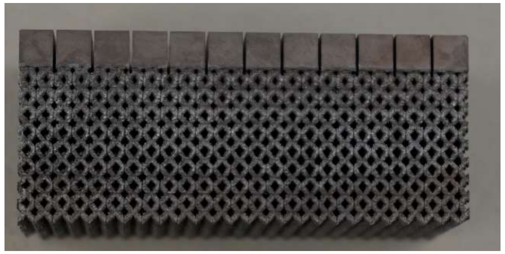
PFC mock-up fabrication and testing

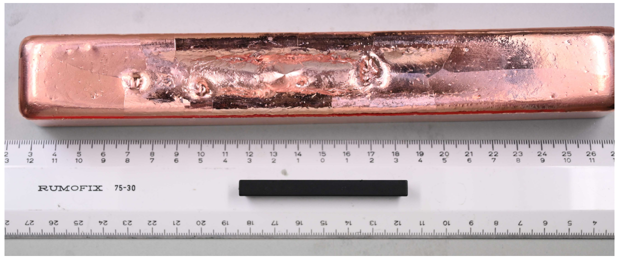
AM preform fabrication

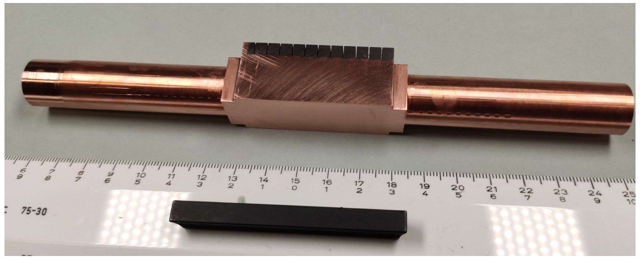
Cleaning

Cu(CrZr) Infiltration

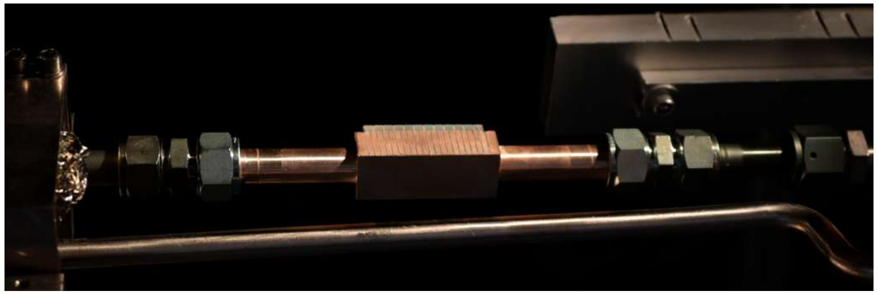
Machining





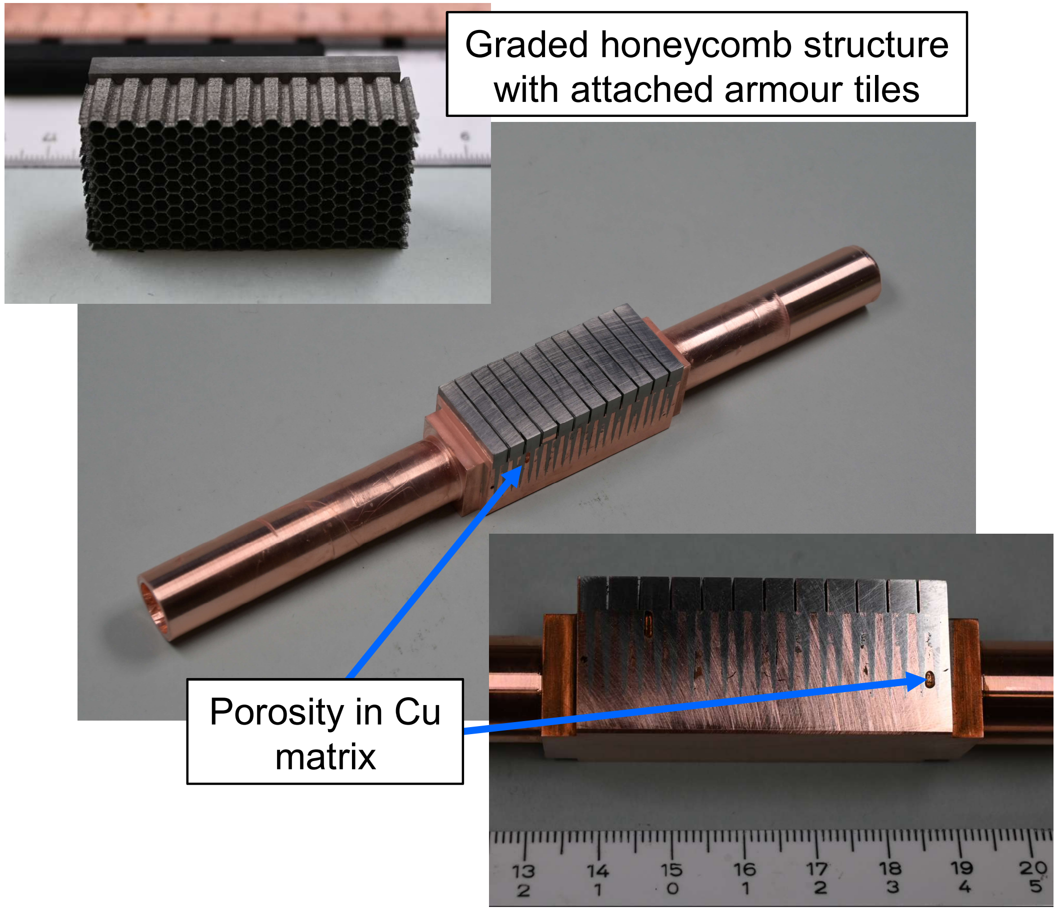


HHF testing in GLADIS facility
@ IPP Garching

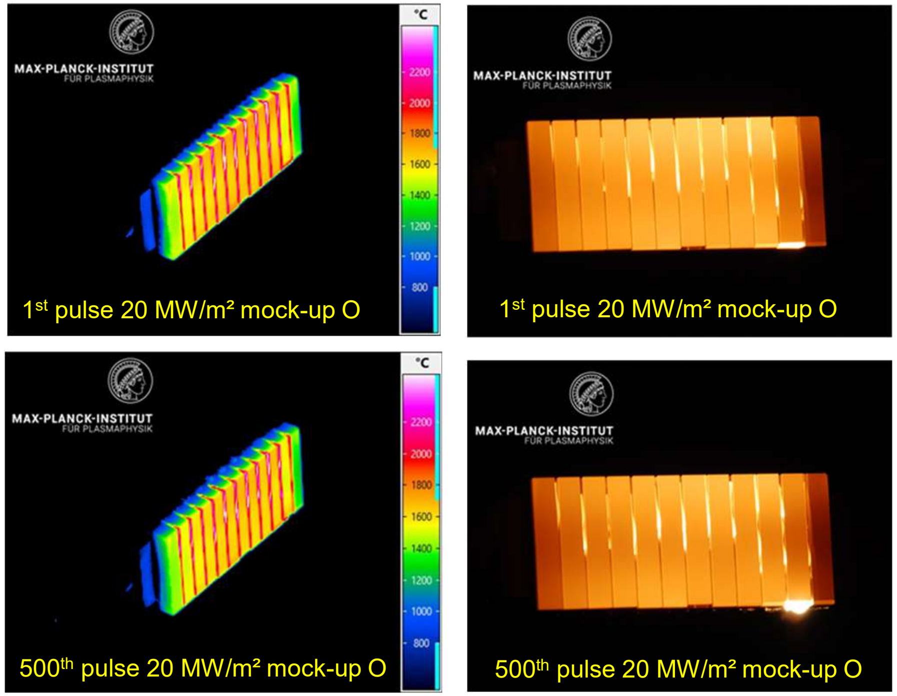


PFC mock-up HHF testing – FGM-like honeycomb

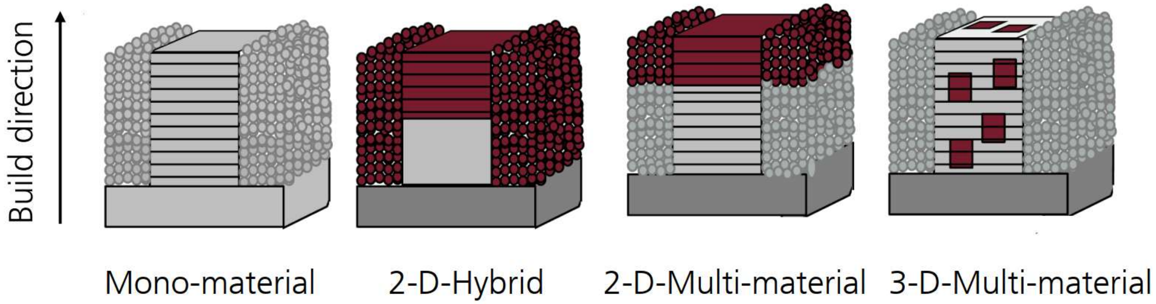
Poster No. 12, R. Lürbke et al.

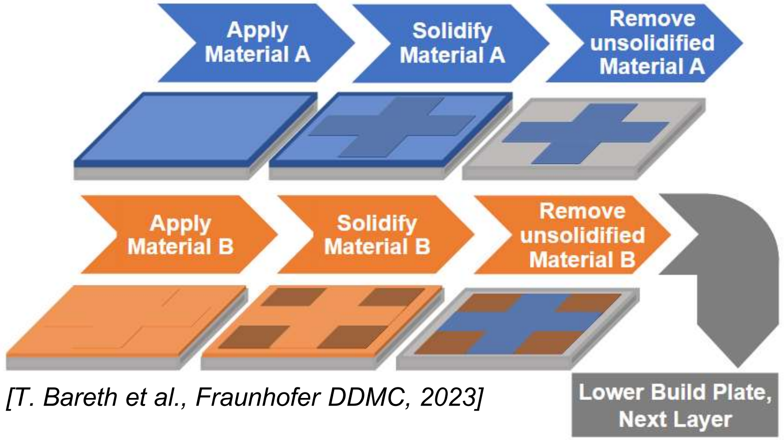


- 500 cycles at 20 MW/m^2 surface heat load
  - » Stable surface temperature (≈1650°C) during cycling
  - » No indication of performance hampering damage



Multimaterial PBF-LB/M

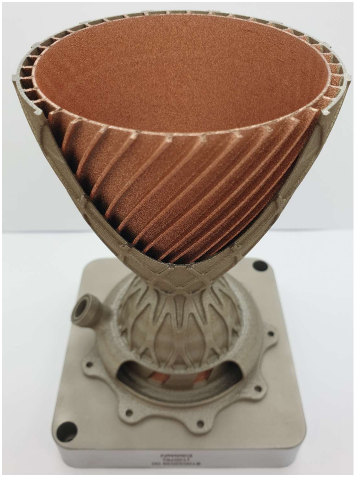




[T. Bareth et al., Fraunhofer DDMC, 2023]

- Multi-material AM enables high design freedom
  - Combination of different materials (properties) in one process
  - Objective: 3-D arbitrary material distribution

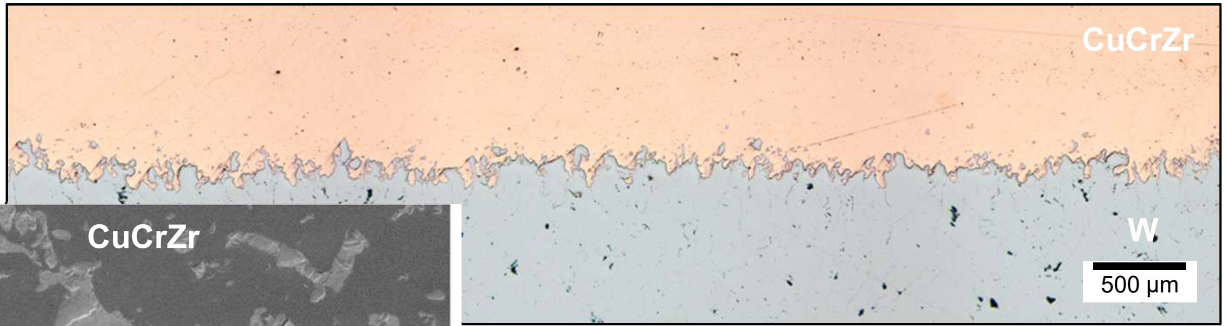
- Significant progress during recent years regarding multi-material PBF-LB/M processing

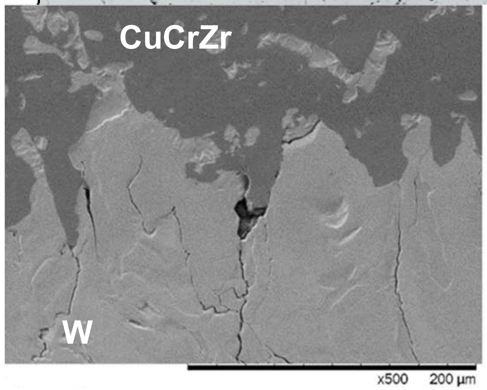


Steel/CuCrZr multi-material PBF-LB/M part

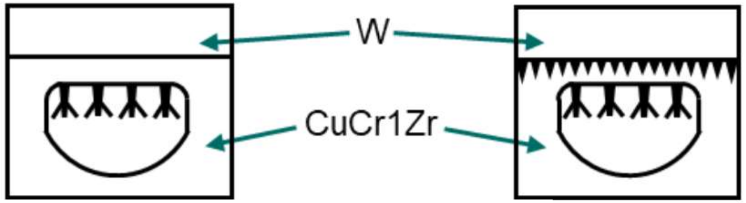
Multimaterial PBF-LB/M – W/CuCrZr

- Good W/CuCrZr interface quality through 2-D multi-material AM build of CuCrZr on W
  - » „undulating“ transition

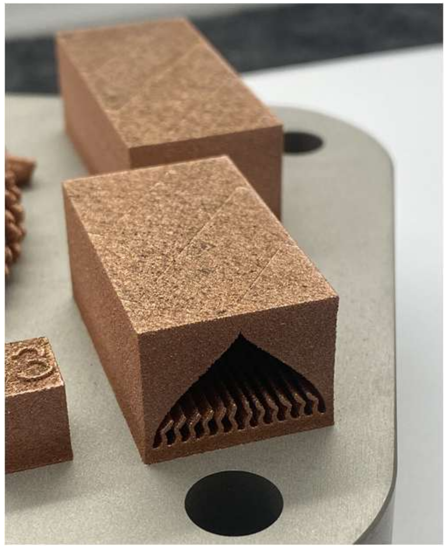




- Small-scale PFC mock-up multi-material W/CuCrZr fabrication activities ongoing

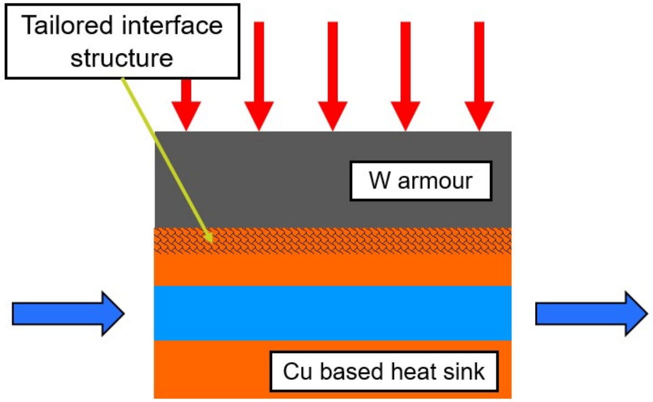


[R. Lürbke et al., Advances in Additive Manufacturing with Powder Metallurgy, 2023]

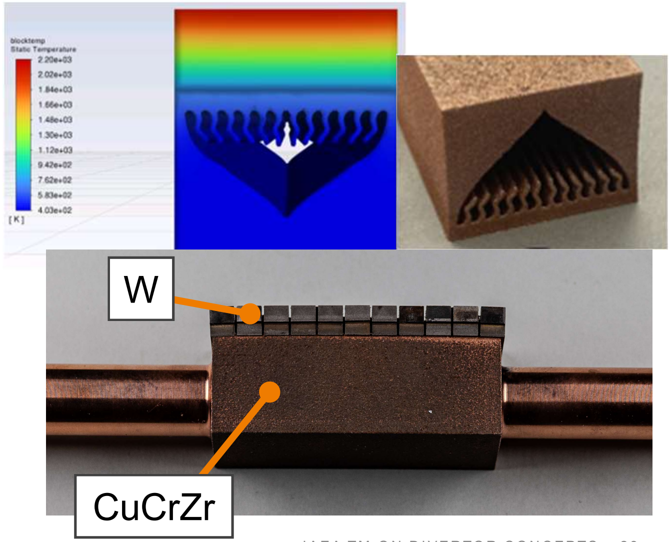


Additive manufacturing for W-Cu PFCs – Outlook

- Exploit AM towards structured interfaces for resilient W-Cu divertor PFC joints



- Exploit cutting-edge AM processes/fabrication methods for PFC applications/design
  - ➢ Electron beam-based AM of W
  - ➢ Adapted laser beam-based methods, e.g. beam shaping
  - ➢ W-CuCrZr hybrid/multi-material AM
    - o HHF testing of first specimen ongoing



Summary

- Tungsten and copper (alloy) based divertor target plasma-facing components (PFCs)
  - ➢ Implementation in existing and planned fusion experiments/devices

- Work on tungsten-copper composites for PFC performance and damage resilience enhancement

  - ➢ Tungsten fibre-reinforced composites based on preforms out of drawn tungsten fibres, incuding upscaling of industrial fabrication technology and neutron irradiation experiments

  - ➢ Progress in additive manufacturing (AM) technologies relevant for divertor PFCs
    - Exploitation of design freedom given by AM → tailored tungsten-copper composite structures
    - Fabrication and high heat flux testing of small-scale PFC mock-ups based on AM

Many thanks for your attention!
Questions?

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Federal Ministry of Research, Technology and Space

Innovative composite structures for highly loaded plasma-facing components in fusion devices (ICoStruc), FKZ 13F1021