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FÜR PLASMAPHYSIK

Additive manufacturing techniques for the fabrication of tungsten based plasma-facing components

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EUROfusion

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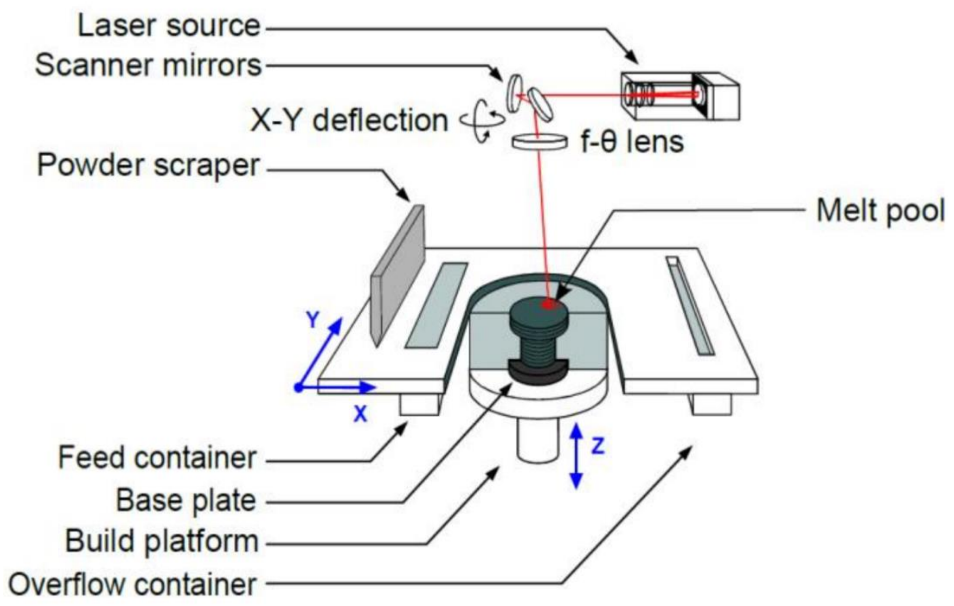
Introduction – Additive manufacturing processes

- **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]

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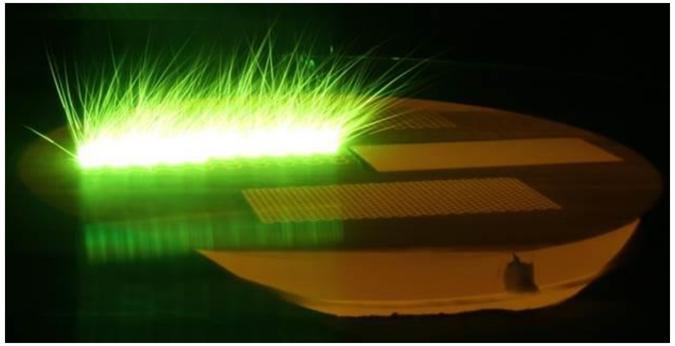
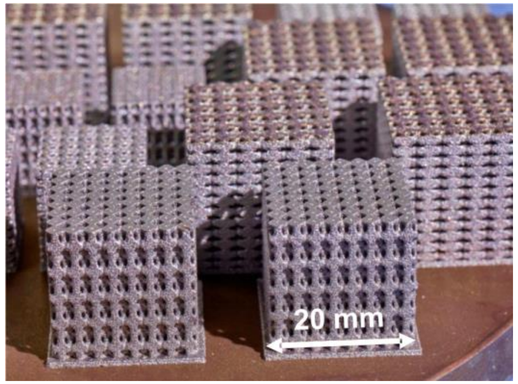
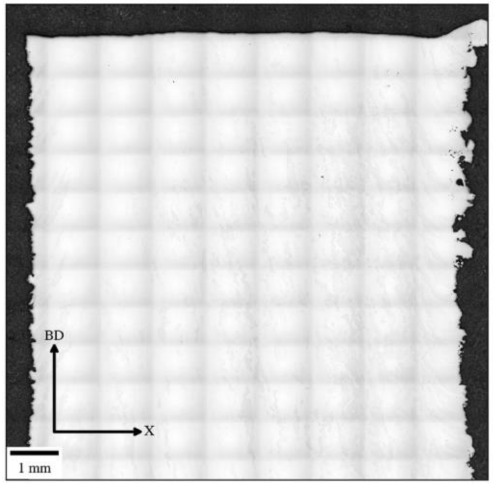
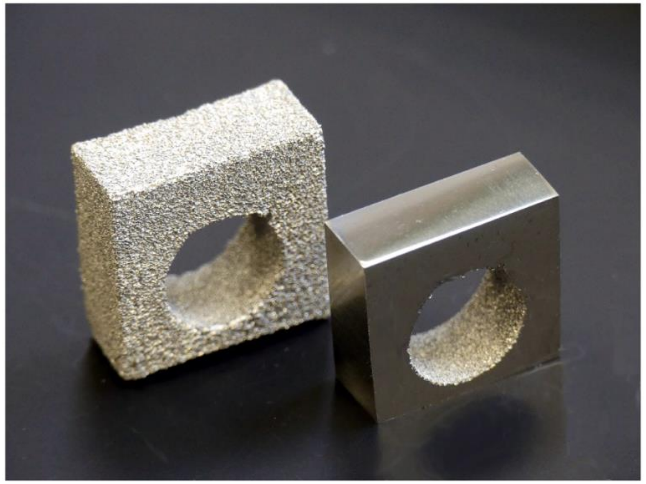






[C. Ledford et al., Int. J. Refract. Met. Hard Mater., 2023]



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

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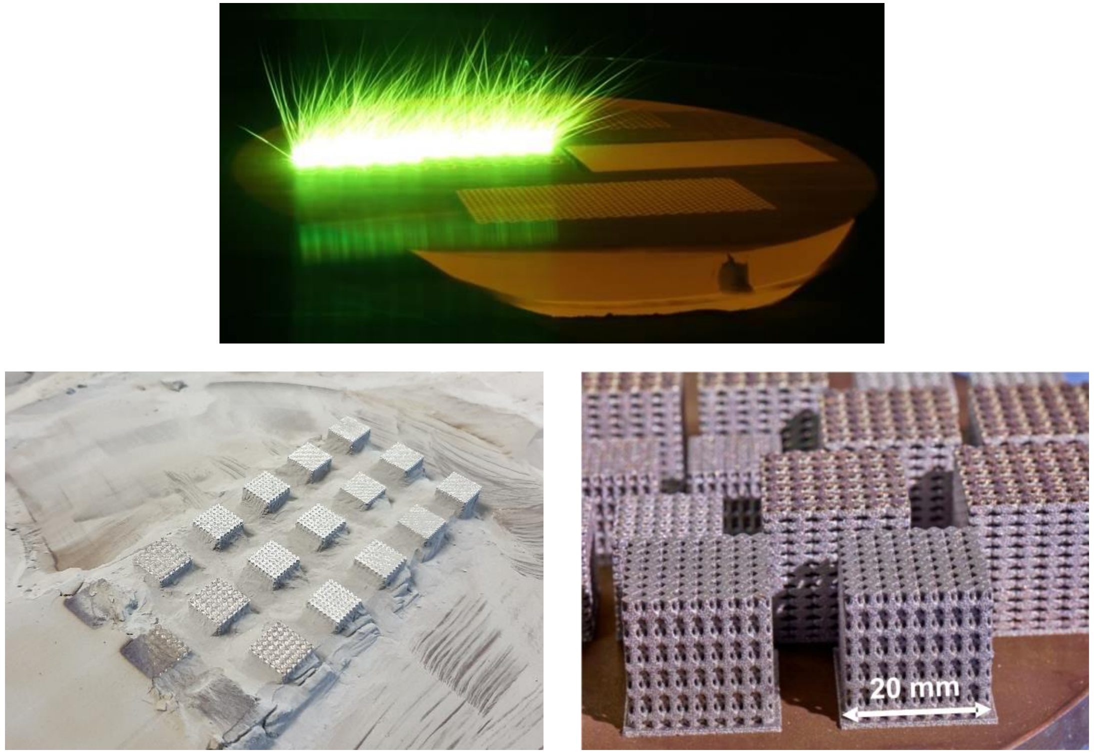
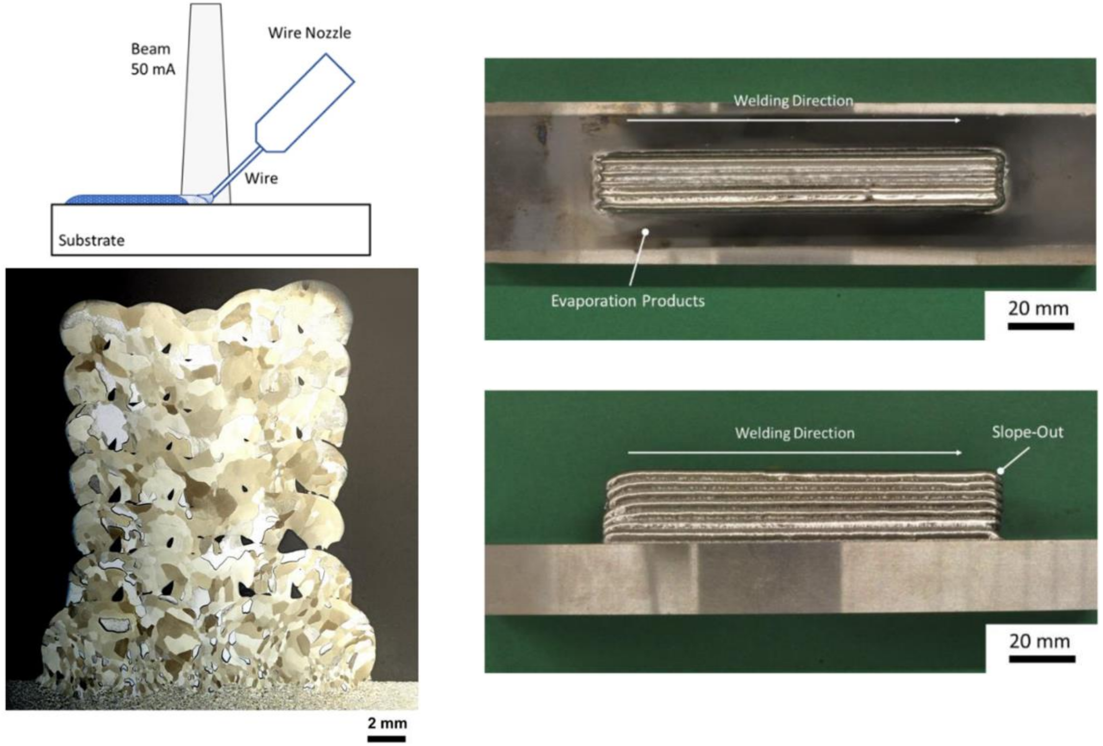
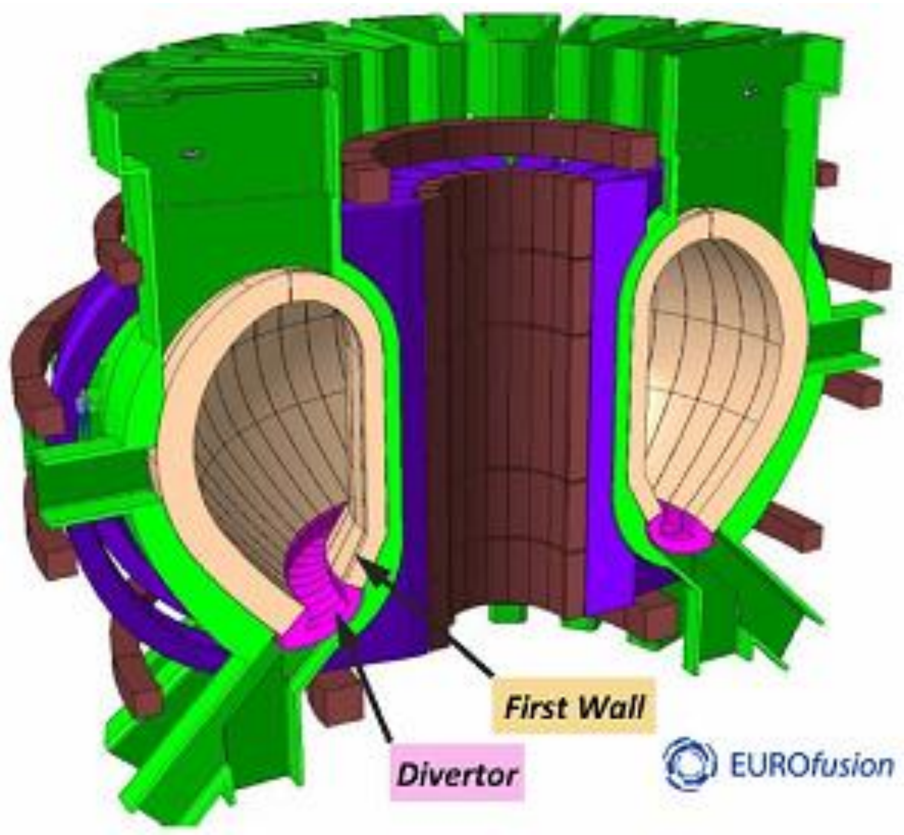


Electron beam - WEBAM



[F. Pixner et al., International Journal of Refractory Metals and Hard Materials, 2022]

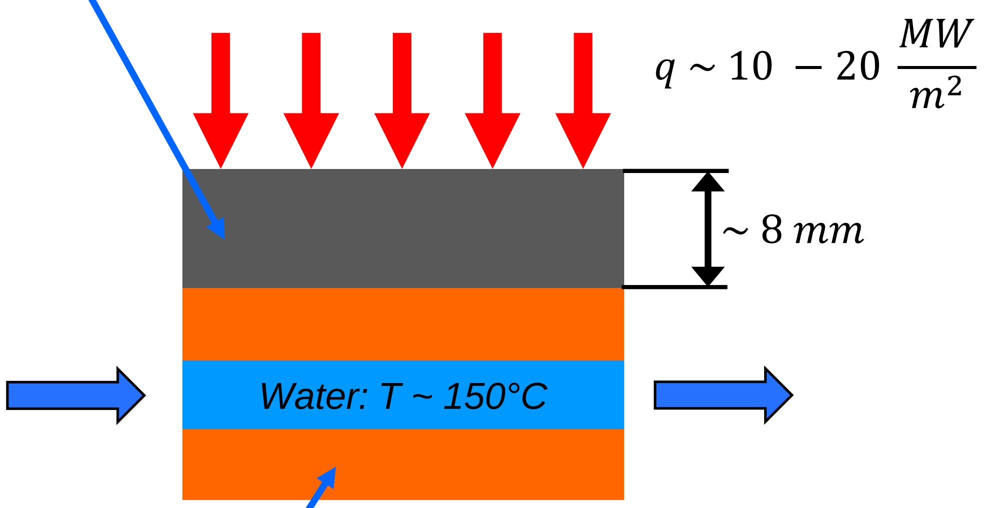
Introduction – Plasma-facing components



[T.R. Barrett et al., Fus. Eng. and Design, 2016]

Divertor target

PFM: Tungsten (W)
⇛ Low physical sputtering yield
⇛ Low retention of hydrogen isotopes
⇛ Low vapour pressure
⇛ High melting point
...

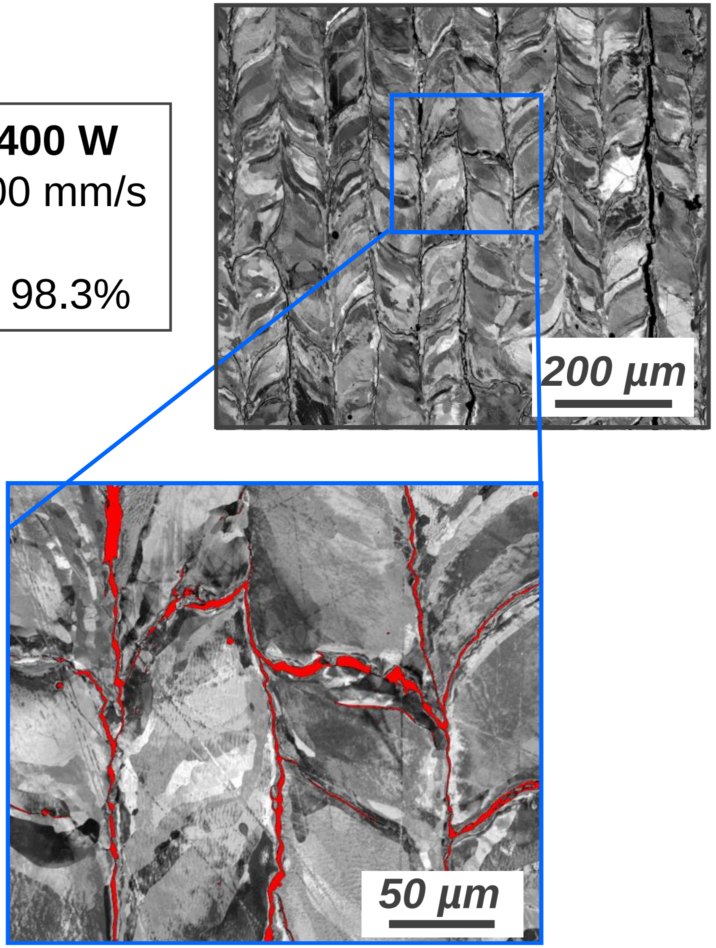


Heat sink: Copper (Cu) alloy or W-Cu composite materials
⇛ High thermal conductivity

PBF-LB/M of tungsten – Cracking

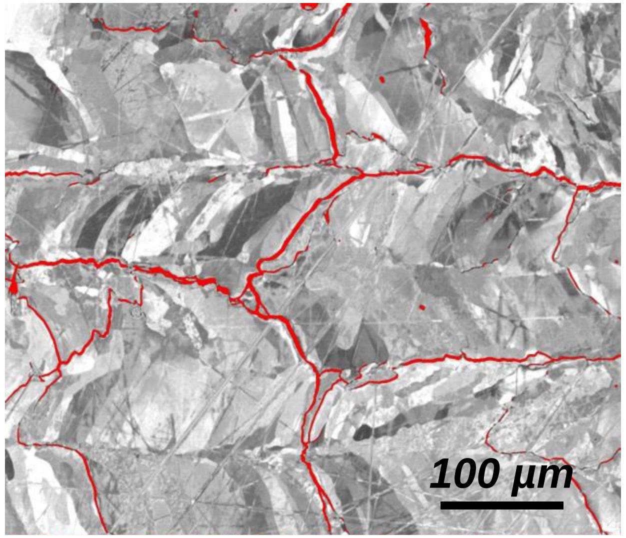
P = 400 W
v = 300 mm/s

ρ_{rel} = 98.3%



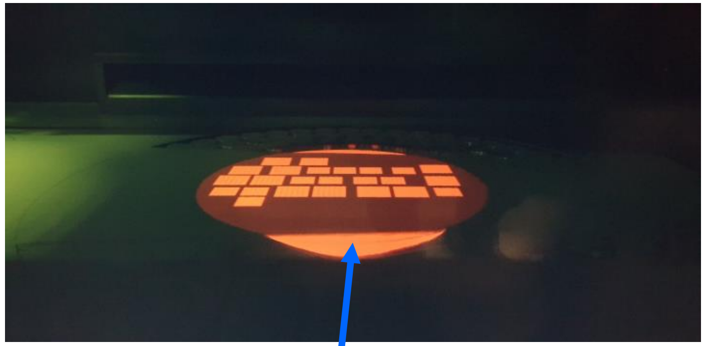
[A. v. Müller et al., Proceedings of the 6th International Conference on Additive Technologies (iCAT), 2016]

- PBF-LB/M of W with Substrate preheating up to 1000°C
  - Material can be consolidated with high density, but still shows microcrack defects



P = 400 W, v = 510 mm/s,
T = 1000°C

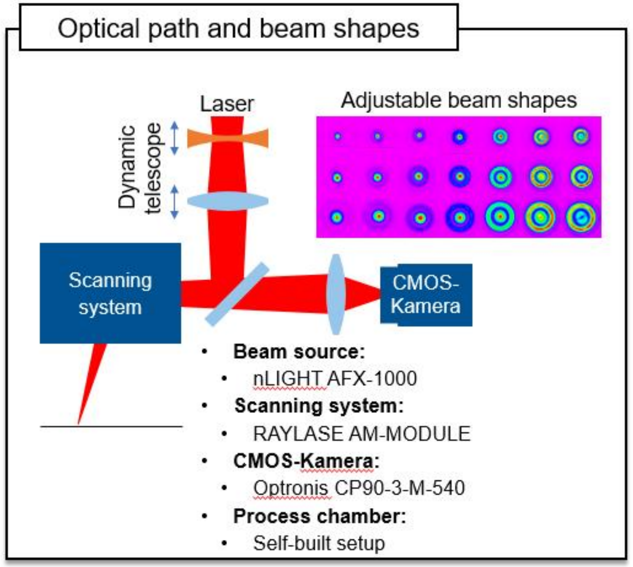
[A. v. Müller et al., Nuclear Materials and Energy, 2019]

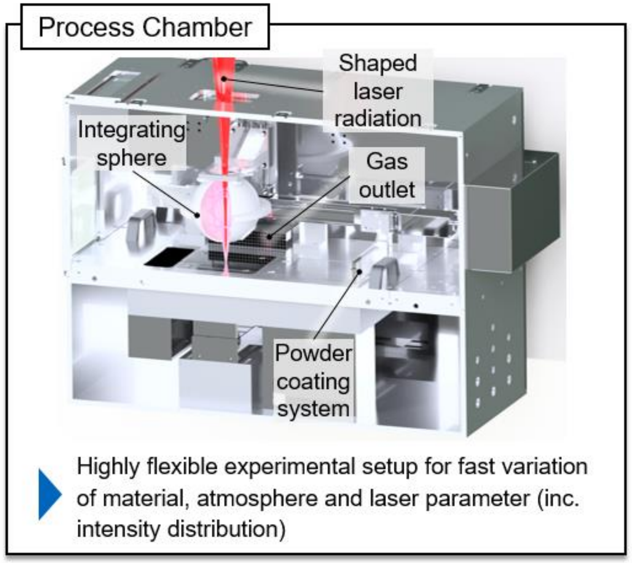


W substrate plate

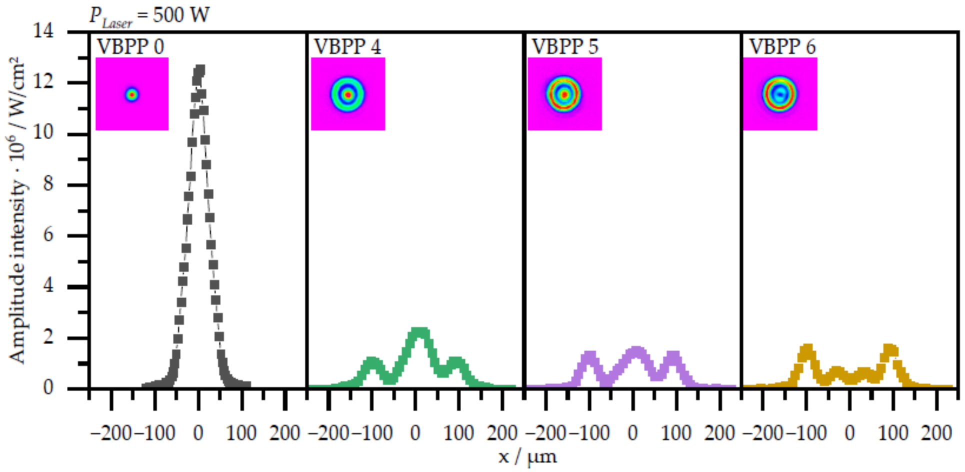
PBF-LB/M of tungsten – Laser beam shaping

- Laser beam shaping can be used to infuence the melt pool characteristics
  - e.g. welding depth, cooling rates
    - Enlargement of process window
    - Less processing defects



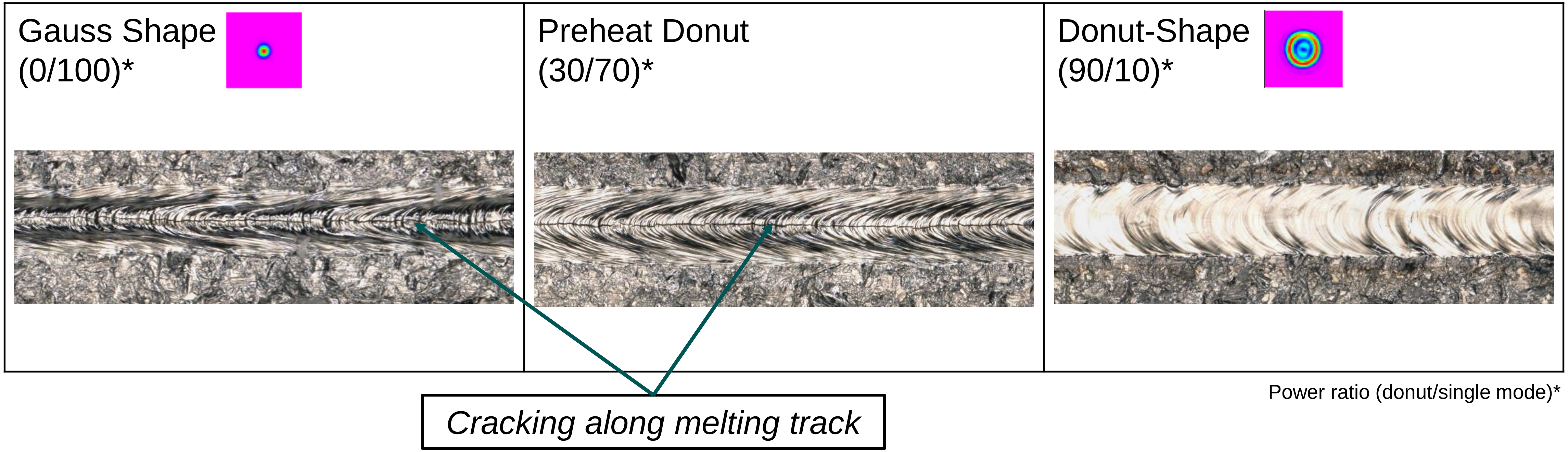


- Investigation of processing by using different ring-shaped laser beam profiles (nLight AFX 1000 laser source)



PBF-LB/M of tungsten – Laser beam shaping

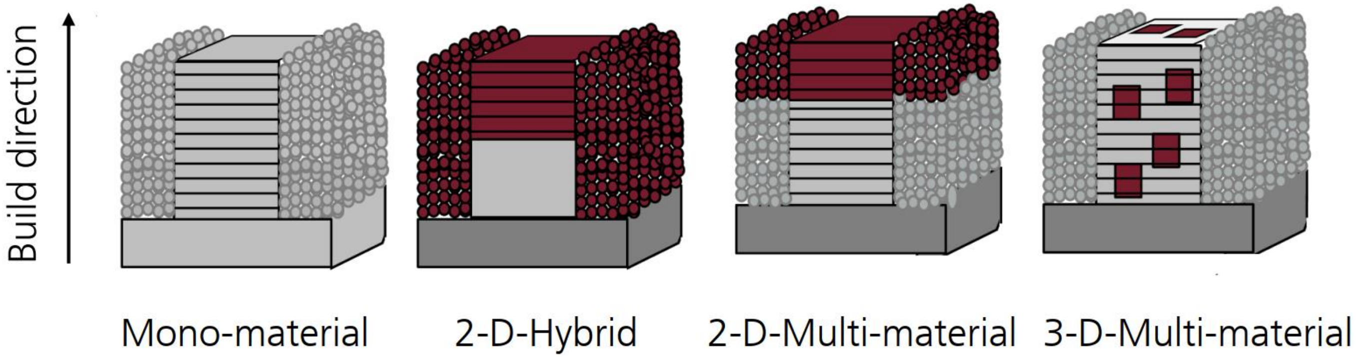
- First experiments with different ring-core distributions conducted
  - Melting tracks on W substrate with 800 W and 600 mm/s

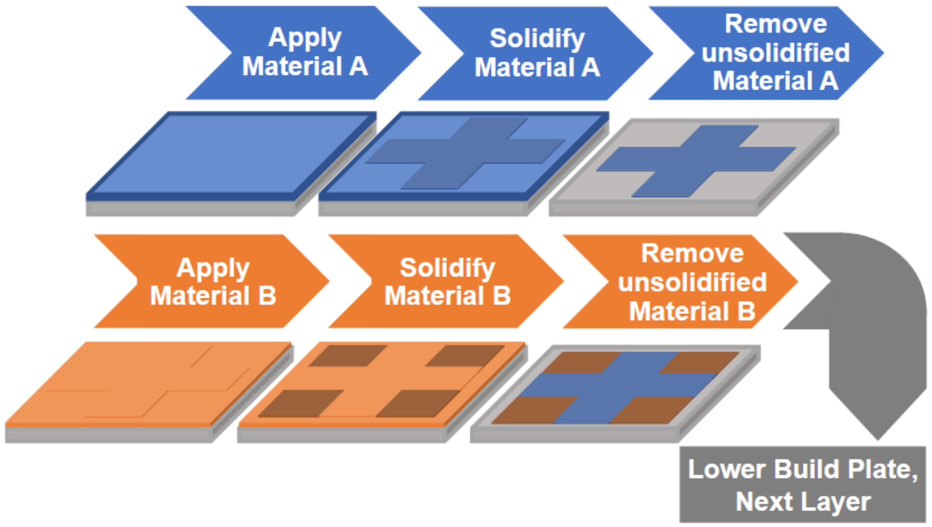


Power ratio (donut/single mode)*

- Comparative work with simulations of the laser beam melting behaviour in the context of EUROfusion WPMAT ongoing

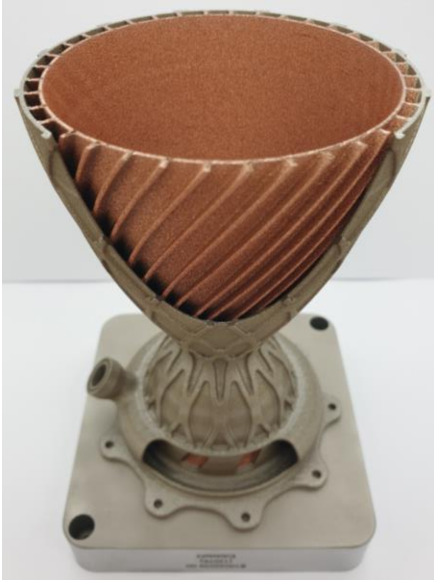
PBF-LB/M multi-material fabrication





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

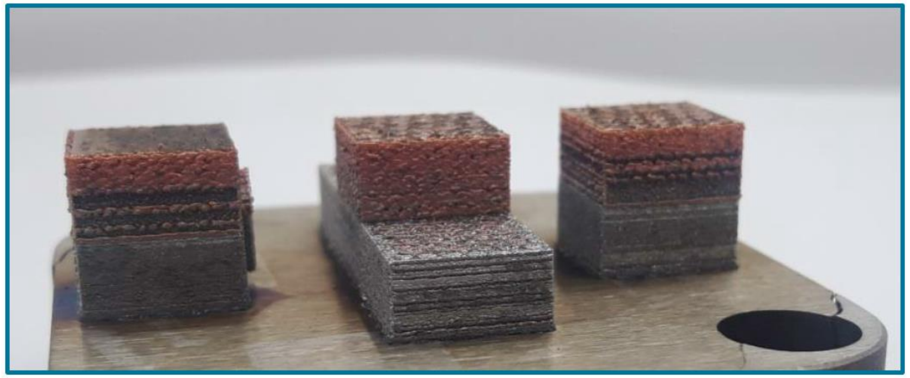
- Significant progress during recent years regarding multi-material PBF-LB/M processing

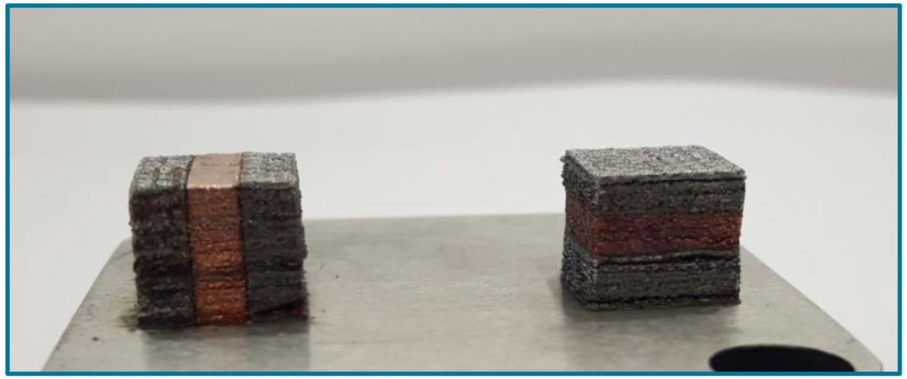


Fraunhofer IGCV

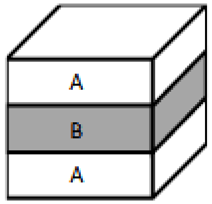
PBF-LB/M multi-material fabrication – W/CuCrZr

- Investigation about basic processability of W and CuCrZr in one process

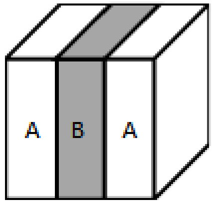




0° transition



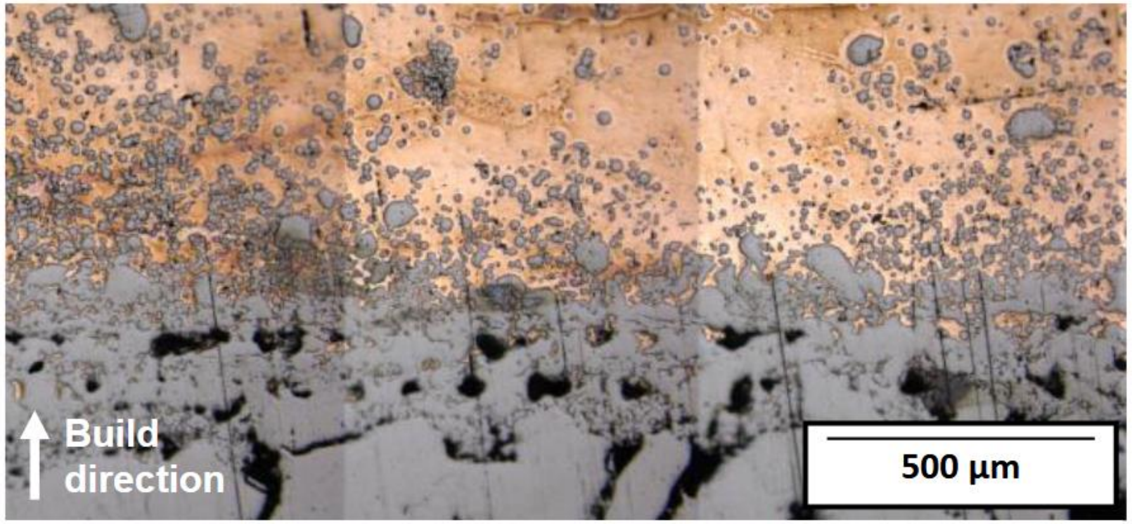
90° transition



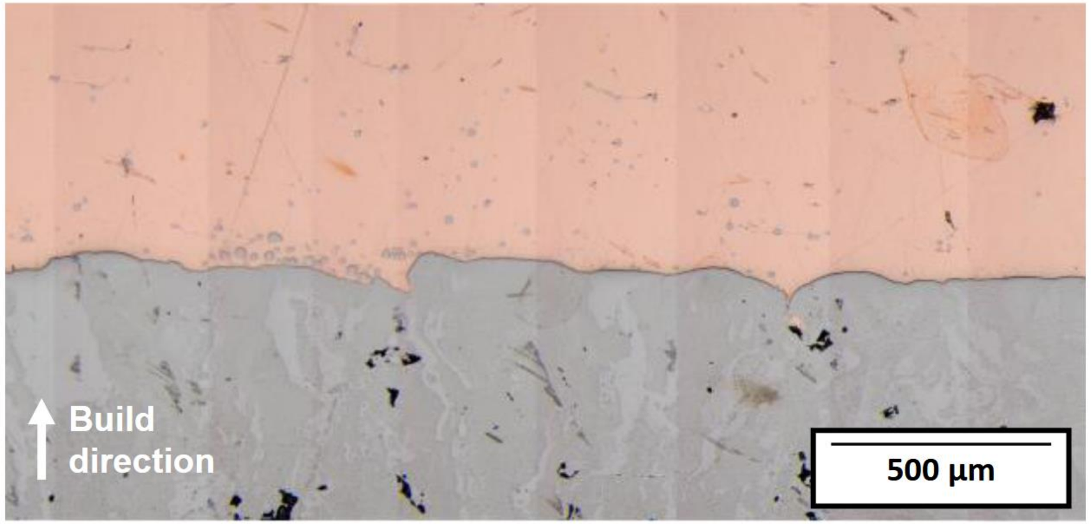
- 2-D multi-material AM
  - Manufactured on an SLM 250 with manual material change
  - Build-up of W/CuCrZr with reduced cross-contamination
- 3-D multi-material AM
  - Manufactured on an SLM 250 with automatic material suction device
  - Investigation of the cross-contamination and material quality for 0° and 90° transition

PBF-LB/M multi-material fabrication – W/CuCrZr

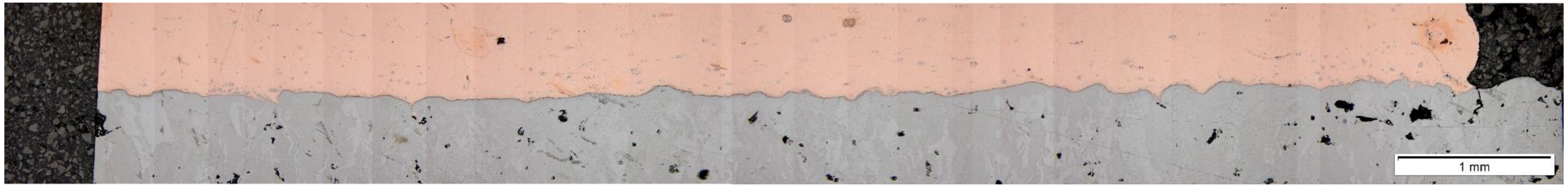
3-D multi-material AM
with recoater-mounted suction unit to remove unsolidified powder



2-D multi-material AM
with manual powder application through glovebox

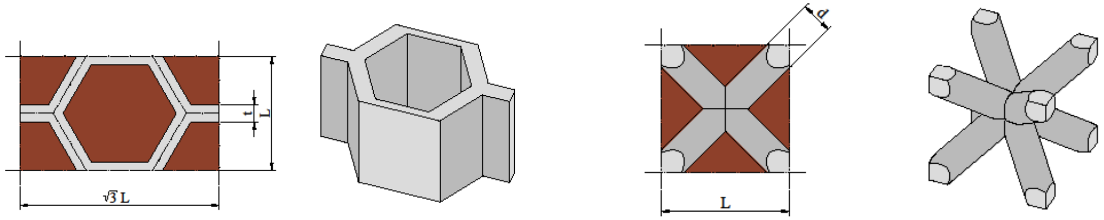


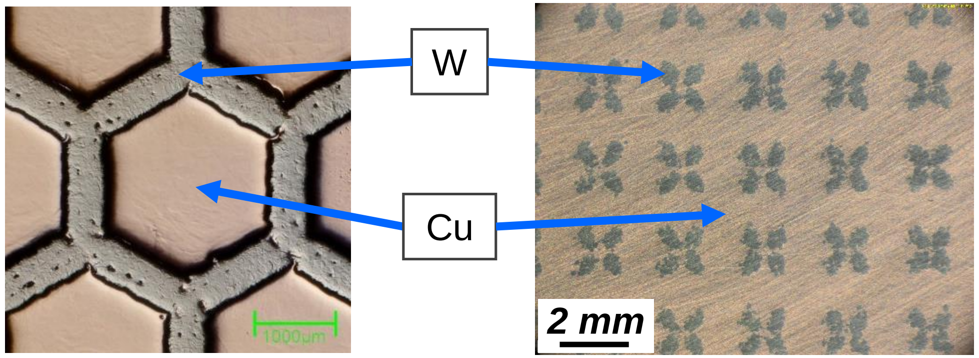
W/CuCrZr joint fabricated via 2-D multi-material AM



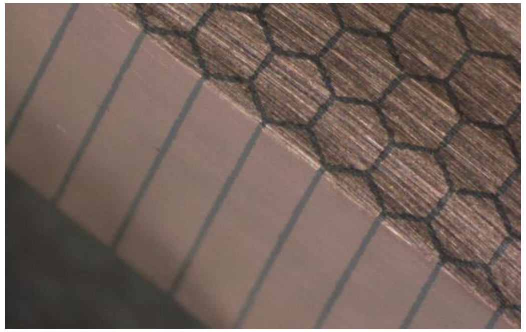
W-Cu composite structures based on AM preforms

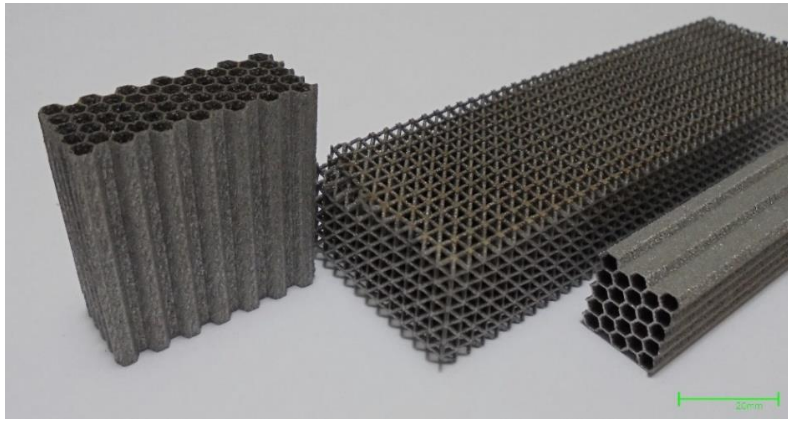
- Influence of microstructure and volume fraction on thermomechanical properties



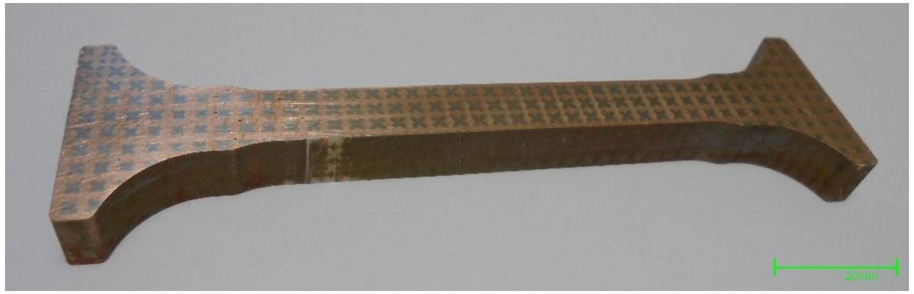


Additively manufactured and Cu melt infiltrated W structures





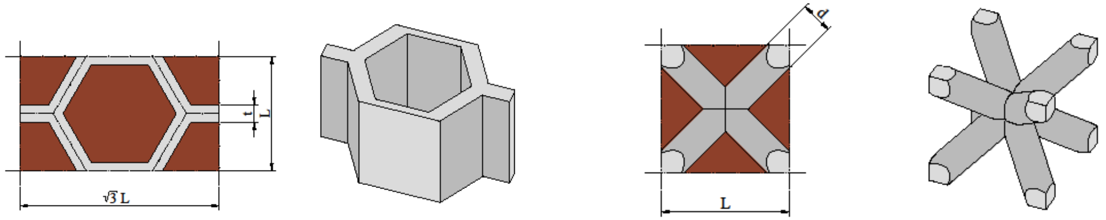
W structures (unit cell size 2.5 mm) fabricated by means of PBF-LB/M: honeycomb structures and lattices

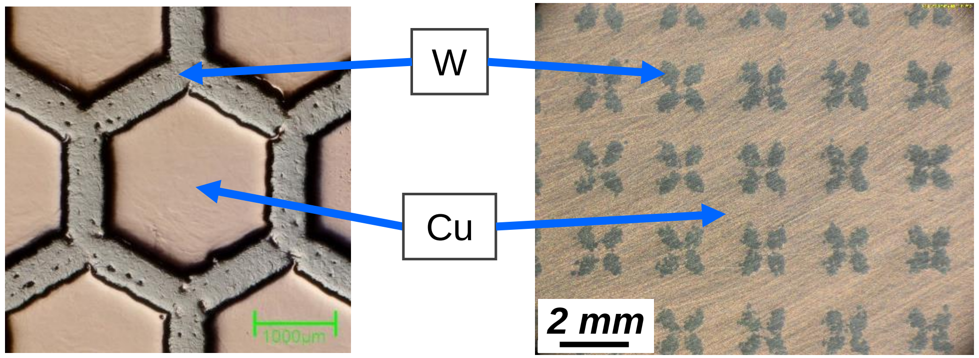


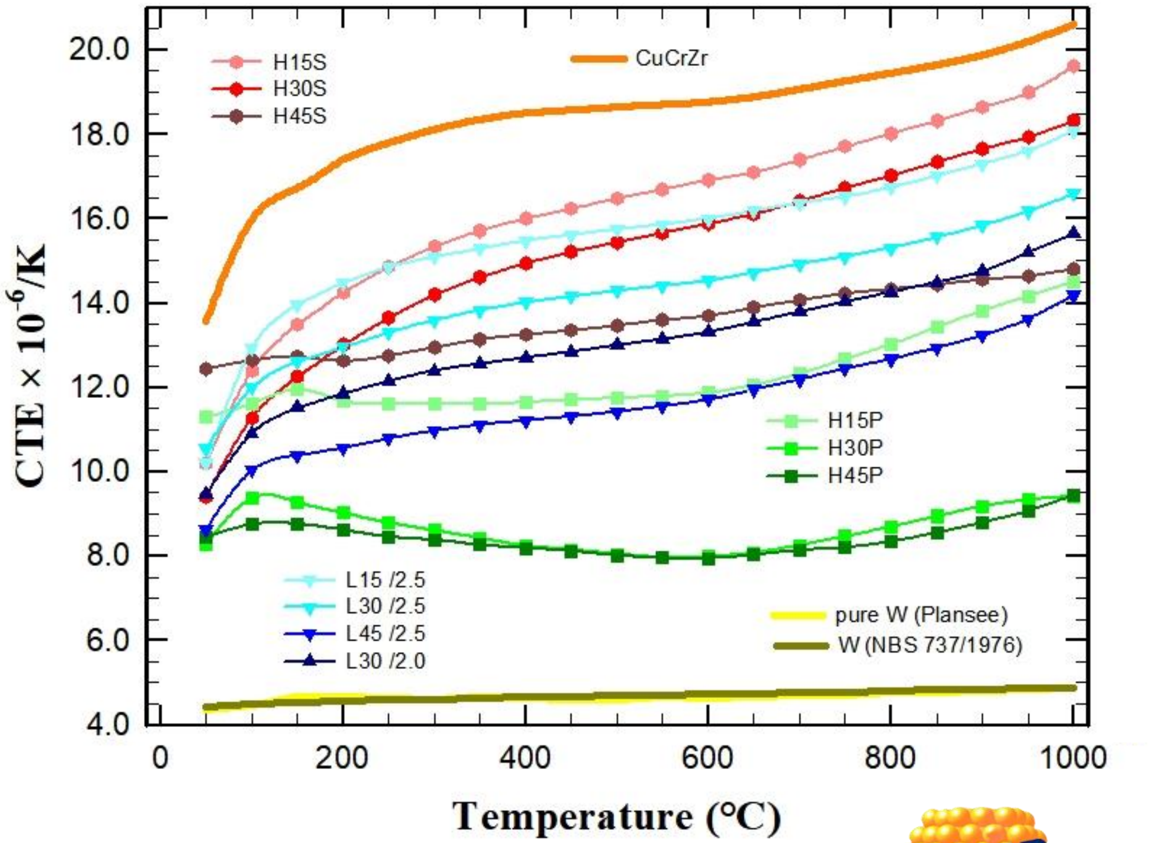
W-Cu tensile specimen based on W lattice (unit cell size 2.5 mm, W volume fraction 0.3)

W-Cu composite structures based on AM preforms

- Influence of microstructure and volume fraction on thermomechanical properties







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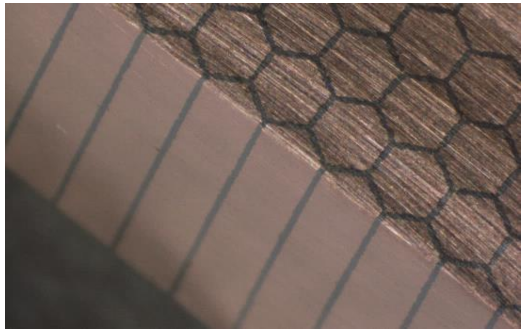
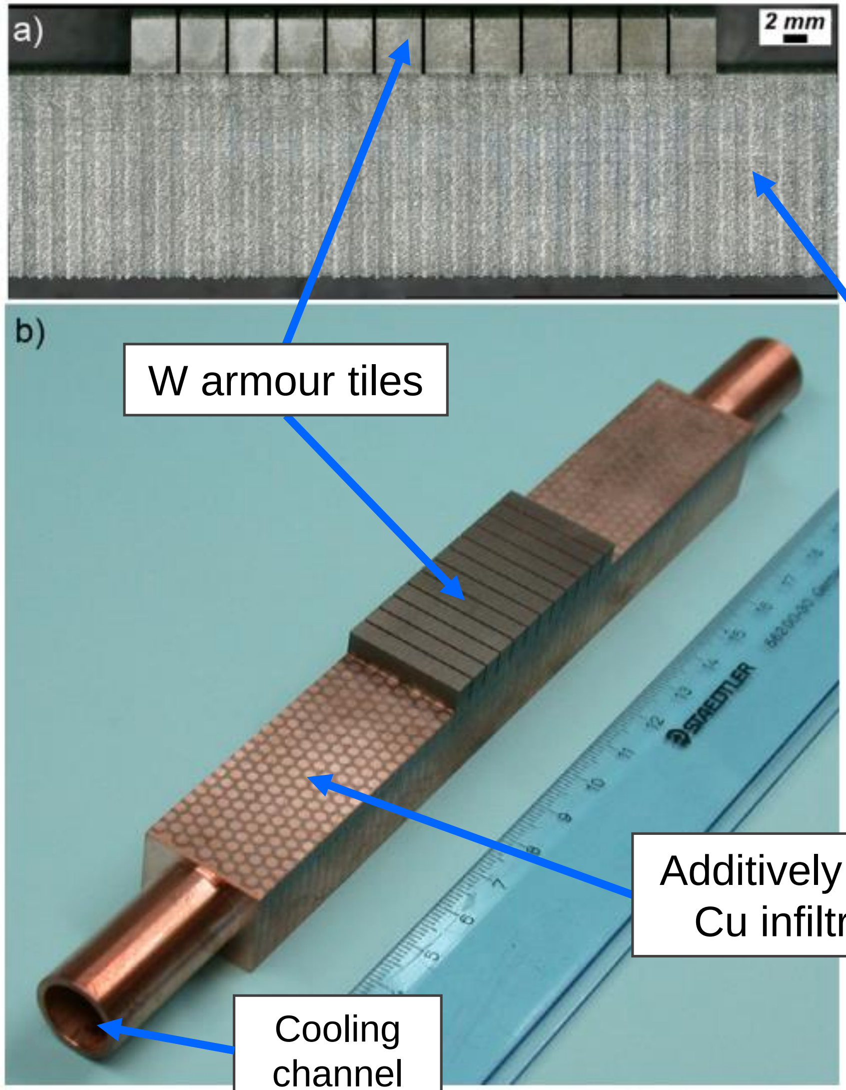
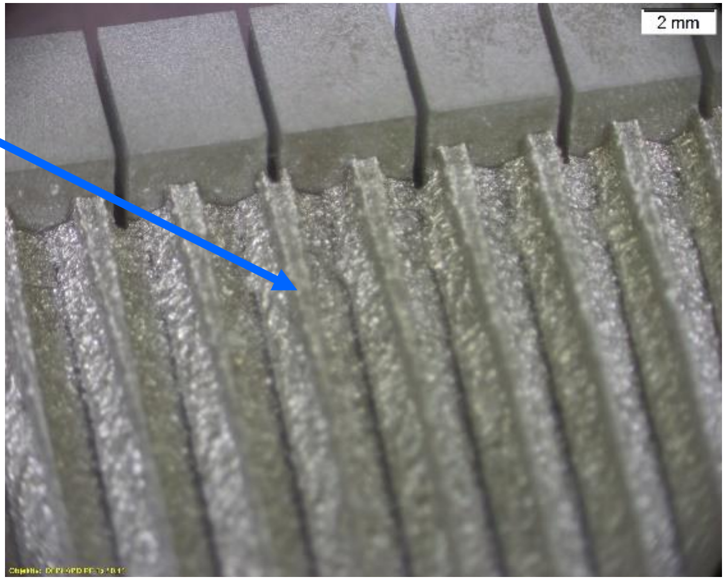


Divertor application – W-Cu composite structures based on AM



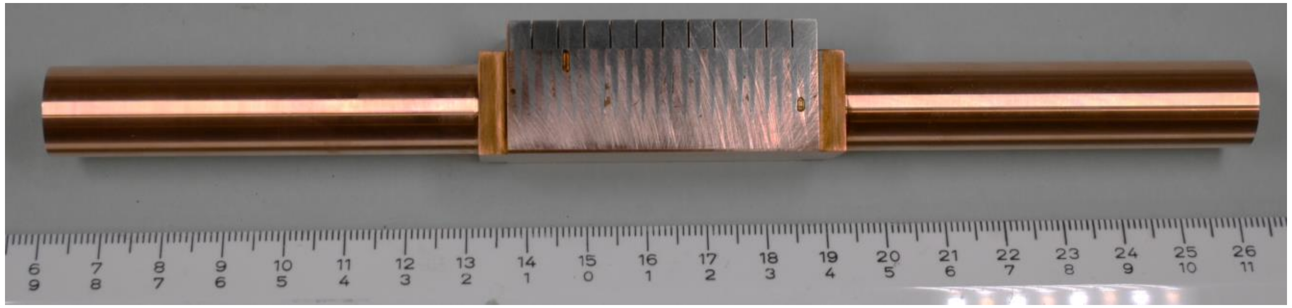
- Graded honeycomb structure with attached W tiles as preform for small scale PFC mock-up
  - Functionally graded properties of composite structure
  - Intimate bonding between W armour and heat sink

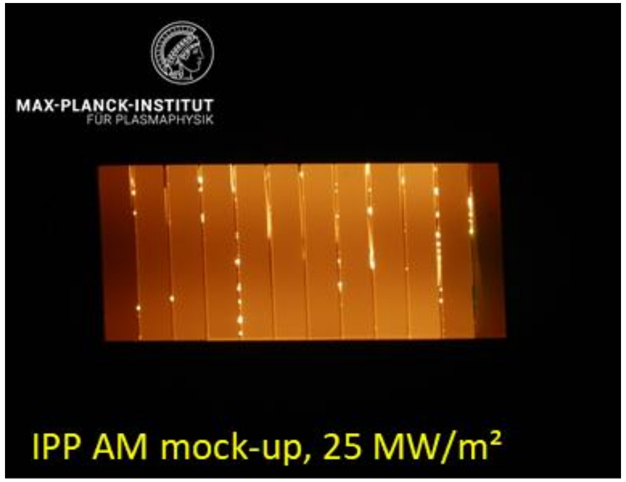


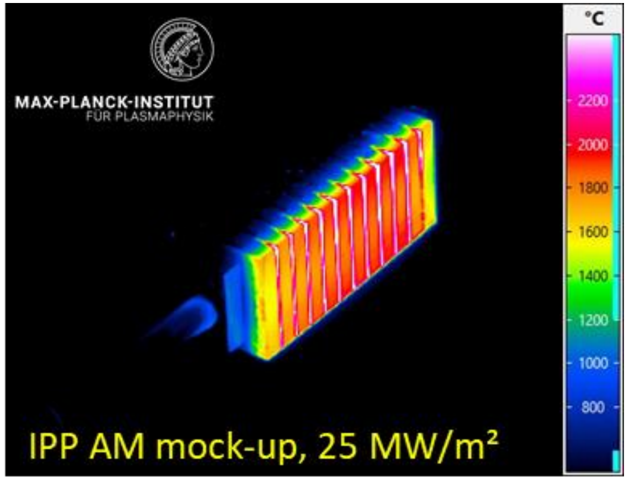
[A. v. Müller, D. Dorow-Gerspach et al., Journal of Nuclear Materials, 2022]

Divertor application – W-Cu composite structures based on AM

- High heat flux testing with the GLADIS facility at IPP Garching
    - Screening up to 25 MW/m² (maximum surface temperature ≈ 1800°C)
    - Cyclic loading: 90 pulses @ 10 MW/m² → small leak detected → repair/-testing ongoing





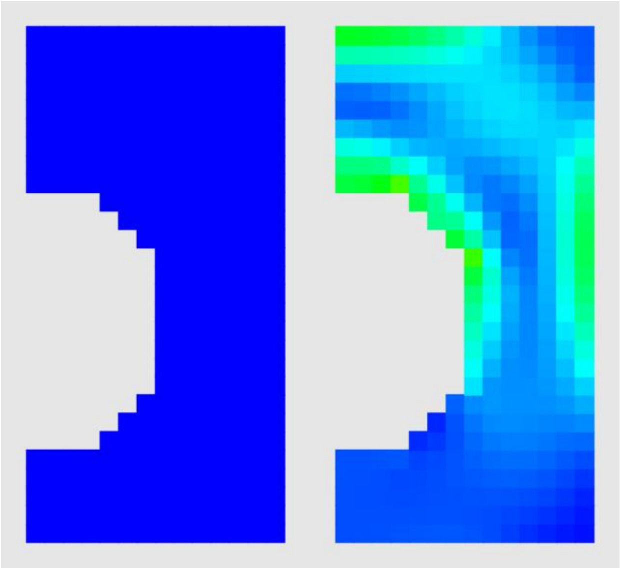


HHF test facility GLADIS @ IPP Garching

Optimised W-Cu composite structures

- Optimisation of W-Cu material distribution for PFC performance enhancement

Material distribution **Stress field**

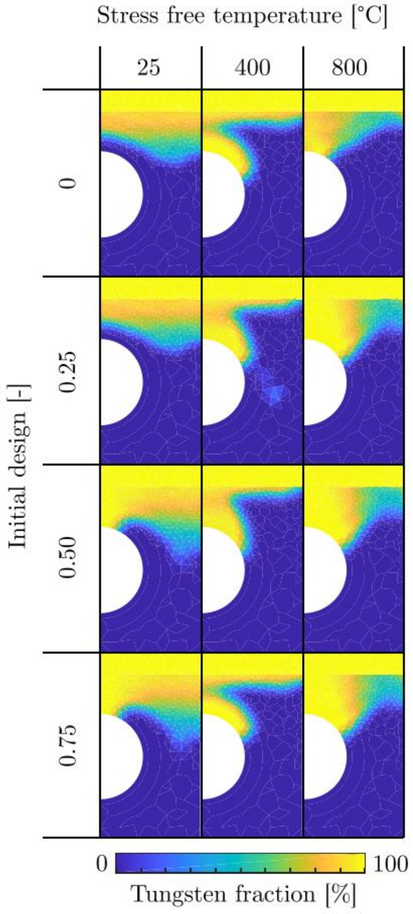


576.1 MPa

-85.7%

82.2 MPa

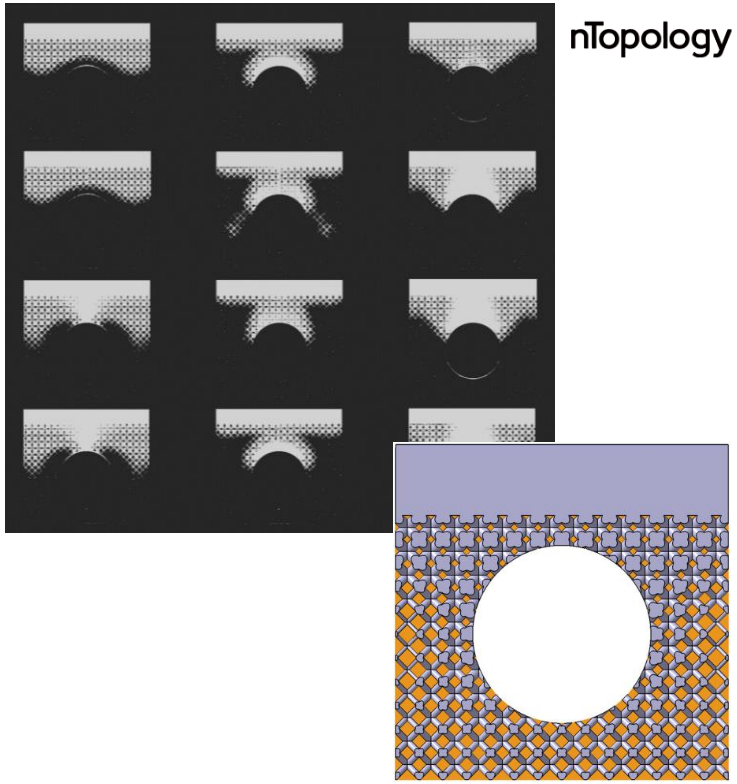
[B. Curzadd et al., Nucl. Fusion, 2019]



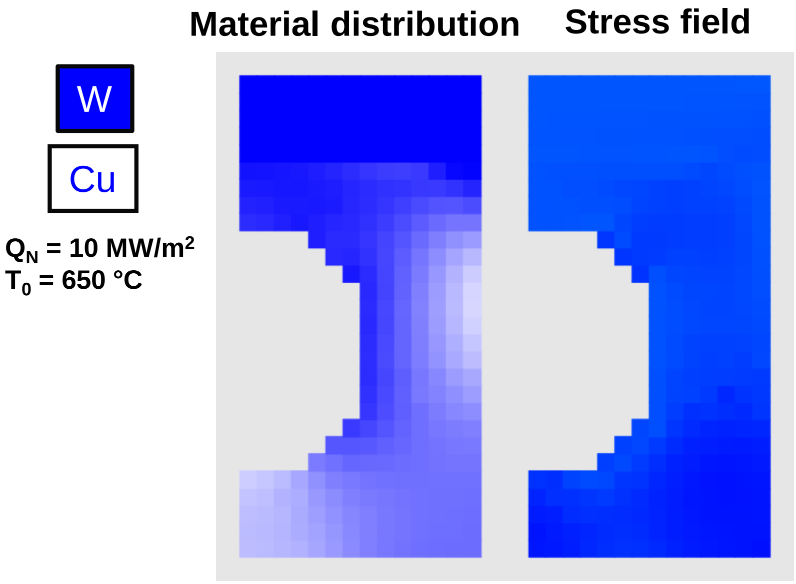
(a) von Mises cost function, with temperature constraints

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

Translation to CAD designs



Optimised W-Cu composite structures



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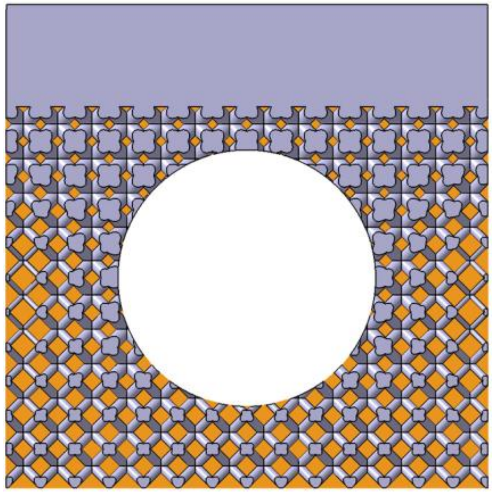
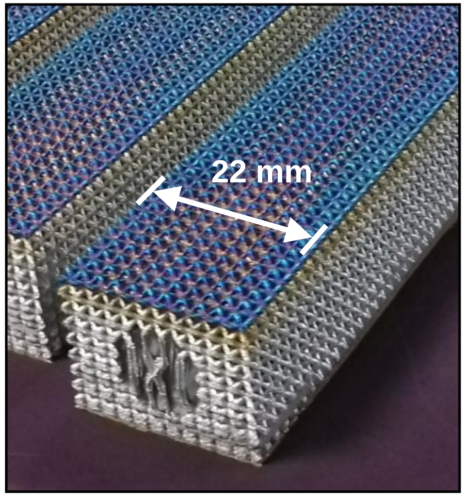
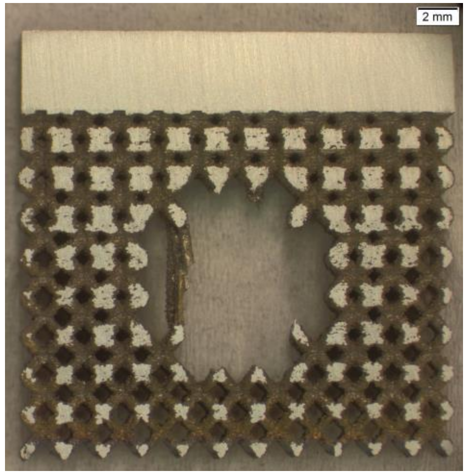


CAD model of a lattice structure based on an optimised W-Cu material distribution

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

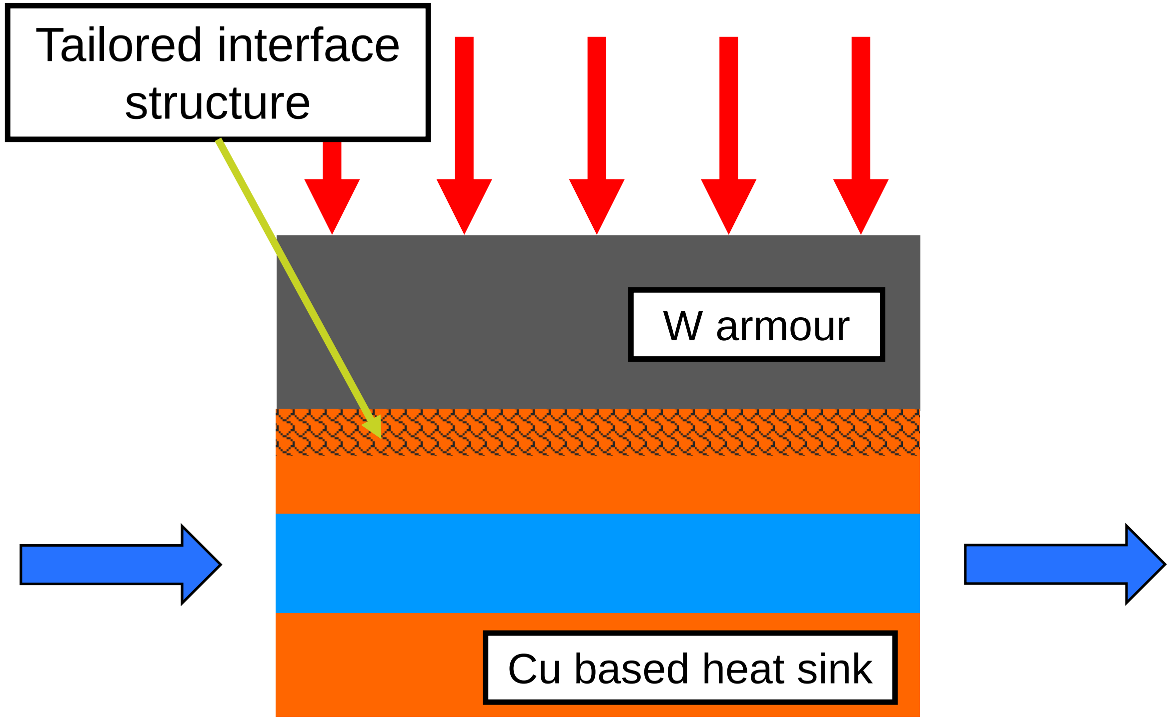




Cross section of tailored W lattice preform fabricated by means of PBF-LB/M

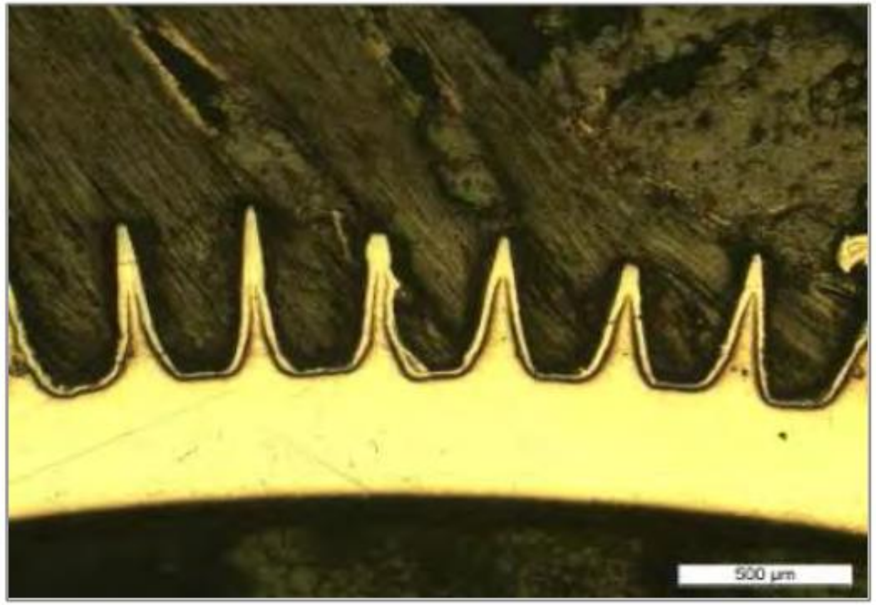
W-Cu interface structures for joint enhancement

- Narrow joining zone between armour and heat sink decisive for PFC integrity and performance
  - W-Cu interface structuring based on AM for enhanced bonding of W armour and heat sink



„Heuristic“ approach

Example: AMC for CFC/CuCrZr joints



[T. Huber et al., Plansee Seminar, 2009]

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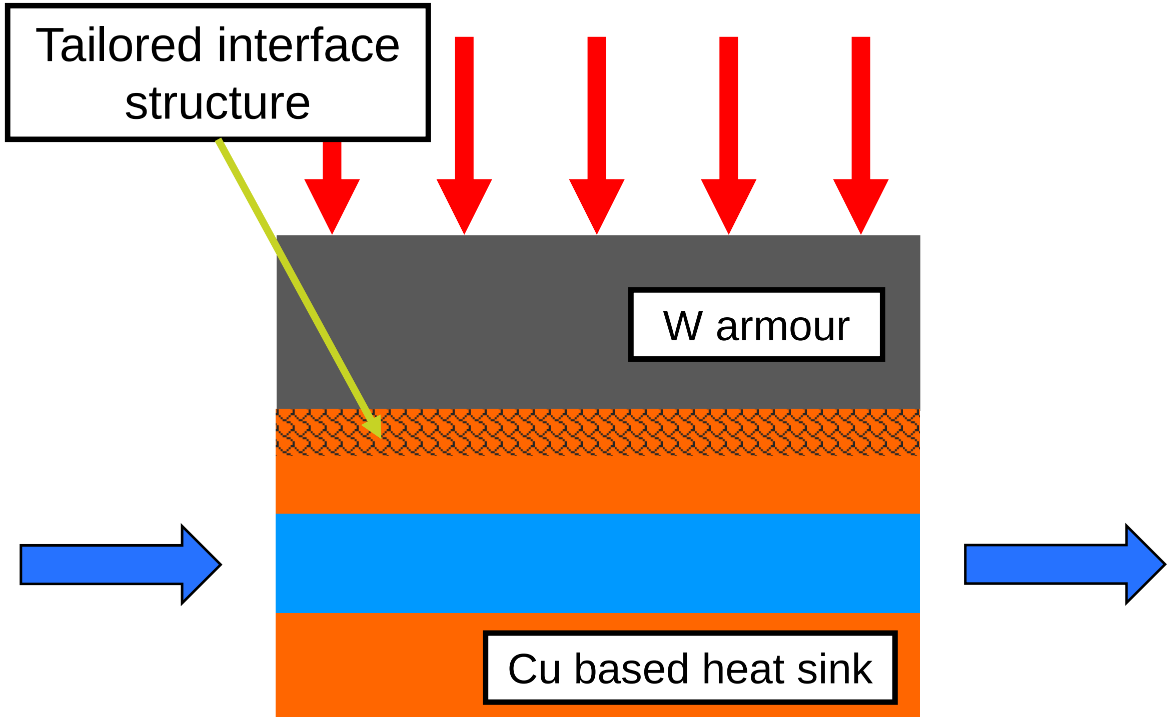
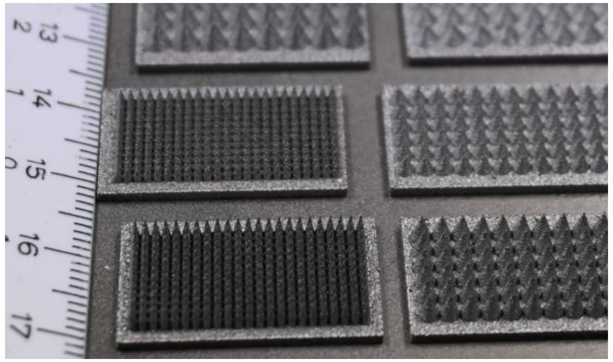
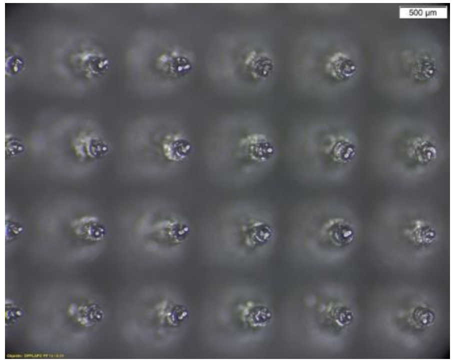
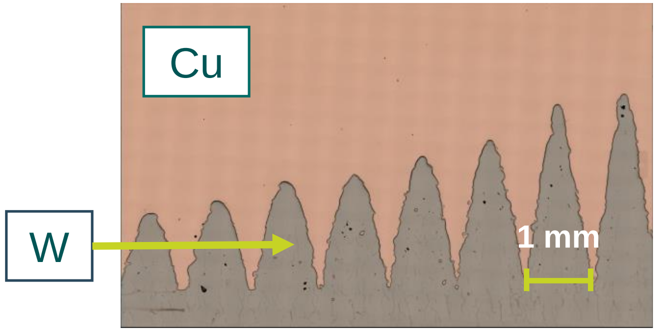


„Heuristic“ approach

W cones fabricated by means of PBF-LB/M





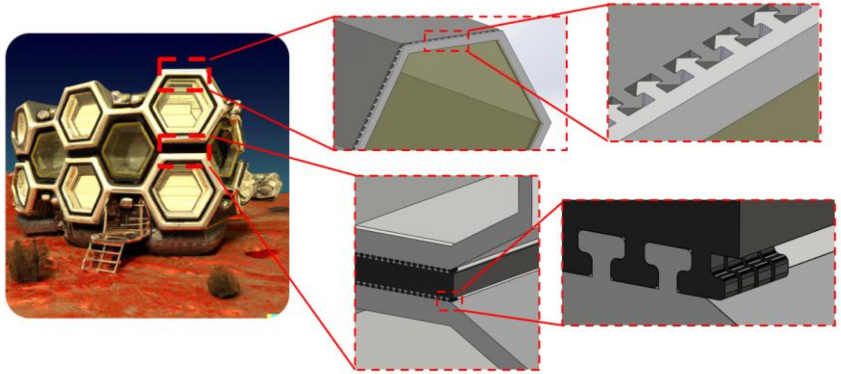


Cross section of W cones with Cu casting

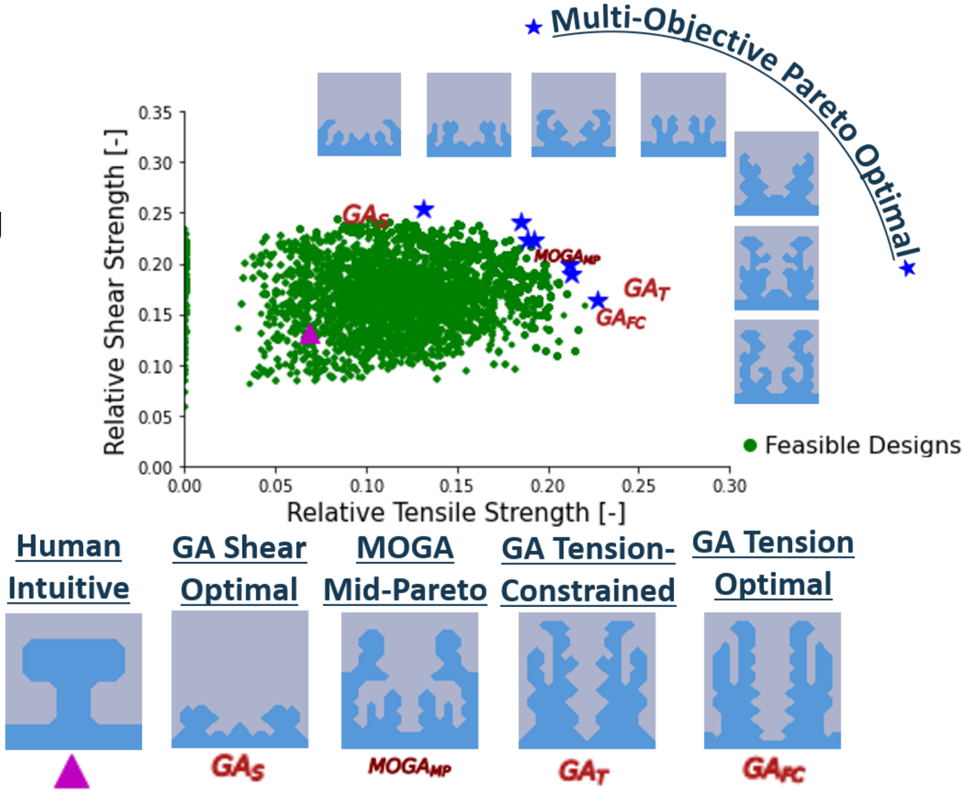
W-Cu interface structures for joint enhancement

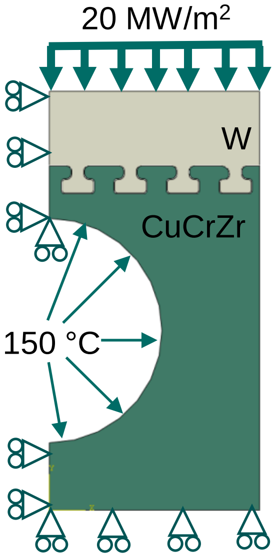
- Interlocking metasurfaces (ILMs): Robust, non-permanent joining technology suitable for complex surfaces, dissimilar materials, and extreme environments (U.S. Patent 17/888,846)

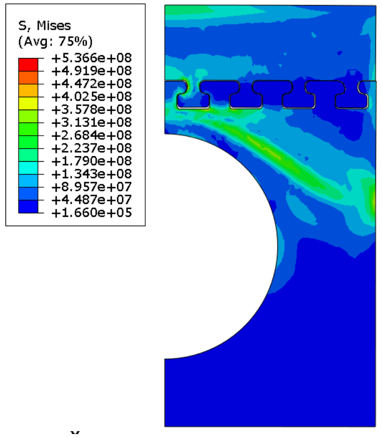
- Investigations on how ILMs can serve as robust joining technology for W-Cu interfaces in PFCs



- Strategic design of interlocking structures for tailorable mechanical robustness
  - Human intuitive design
  - Parametric optimization
  - Genetic algorithms







[N. K. Brown et al., Materials & Design, 2023]

[O. Bolmin et al., J. Mater. Sci., 2023]

Conclusion

- The development of additive manufacturing technologies is progressing, also in view of tungsten
  - Laser beam shaping
  - Multi-material fabrication
  - Wire based processes …

- Exploitation of design freedom given by additive manufacturing for plasma-facing component performance/resilience enhancement
  - Fabrication and high heat flux testing of a small-scale plasma-facing component mock-up based on an additively manufactured tungsten preform
  - Tailored tungsten-copper composite structures based on additive manufacturing
    - material distributions and macroscopic thermomechanical properties
    - interface structures

Many thanks for your attention!