Max-Planck-Institut für Plasmaphysik

(New) Materials and Components for the DEMO Divertor

R. Neu[1,2], A.v. Müller[1], B. Curzadd[1,2], J. Riesch[1], J. W. Coenen[3,4], H. Greuner[1], T. Höschen[1], K. Hunger[1], G. Schlick[5], U. Siefken[6], E. Visca[7], J.H. You[1]

[1]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[2]Technische Universität München, 85748 Garching, Germany
[3]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425, Jülich, Germany
[4]Department of Engineering Physics, University of Wisconsin Madison, WI 53706, Madison, USA
[5]Fraunhofer IGCV, 86159 Augsburg, Germany
[6]Louis Renner GmbH, 85232 Bergkirchen, Germany
[7]ENEA, 00044 Frascati RM, Italy

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

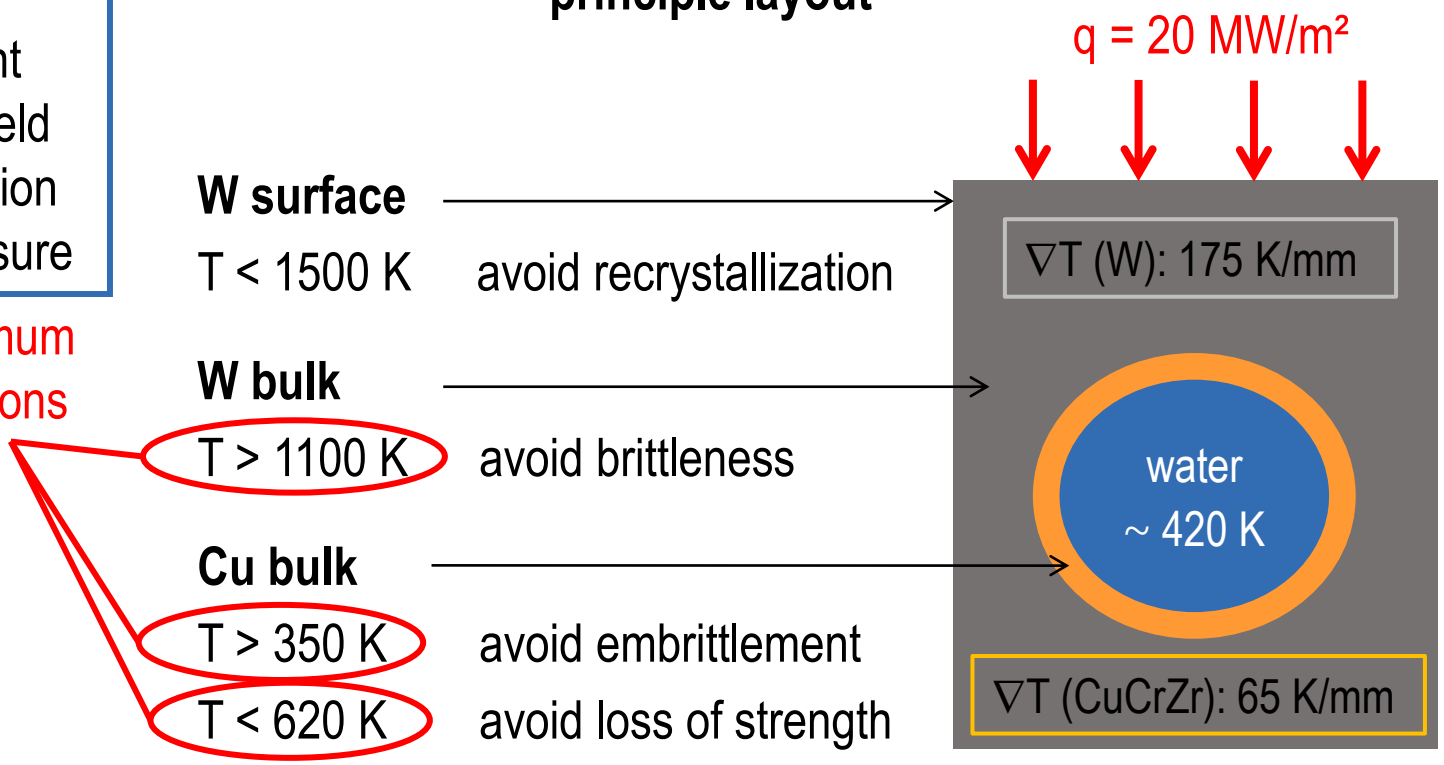
Boundary conditions for plasma facing components (PFCs)

W as PFM:
- high melting point
- low sputtering yield
- low tritium retention
- low vapour pressure

no overlap of optimum operational conditions

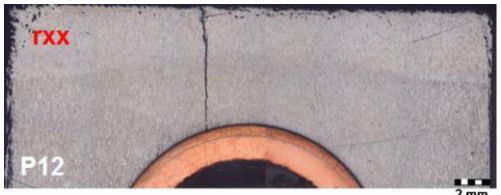
Cu (alloys) as heat sink:
- high thermal conductivity

principle layout



deep cracking observed for ITER mock-ups during cycling at 20 MW/m² due to low cycle fatigue (crack initiation) and brittle behaviour during cool down

[M. Li FED 101 (2015) 1]



[G. Pintsuk, FED 88 (2013) 1858]

Advanced materials and designs for PFCs

Concepts for improving PFCs for the European DEMO

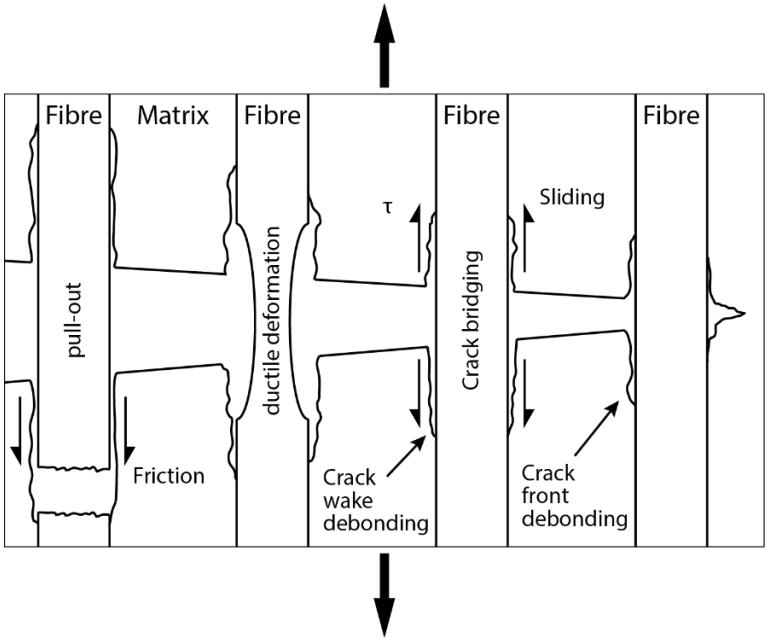
- optimisation of shape/size → lower temperature
- thermal break concept → homogenisation of temperature
- adaption of CTE by **functionally graded material**

} reduction of stresses

- improvement of material properties (strength, toughness) by **composites / fibre reinforcement**

⇒ **combination of concepts can further optimise function and lifetime**

[J.H. You, J. Nucl. Mater., 544 (2021) 152670]



Extrinsic toughening mechanisms in fibre reinforced materials:

→ stress redistribution by local energy dissipation

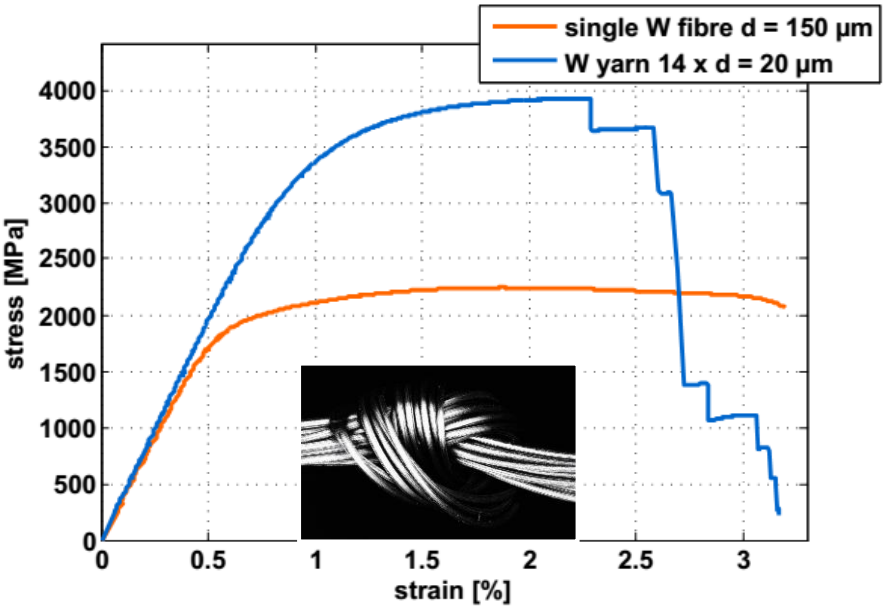
→ effective below DBTT & under embrittled state

[J. Riesch, Phys. Scr., T167 (2016) 014006]

W fibres and yarns

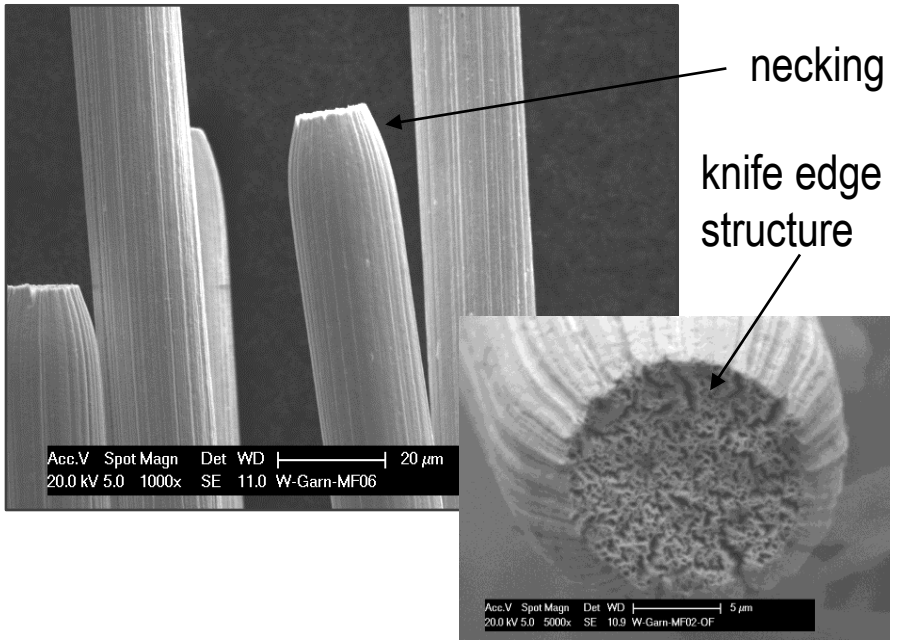
W fibres with small diameter (16 – 150 µm)

- highly deformed/fine grains:
  high strength, ductile already at room temperature
- potassium doping: **stable against recrystallization** up to ~ 2000 °C
- yarns show **increased flexibility and confirm higher strength** of thinner fibres



$\sigma_{UTS} > 3900\ MPa$

[J. Riesch, Phys. Scr. T170 (2017) 014032]



ductile failure behaviour confirmed

[H. Gietl, J. Comp. Mater. 52 (2018) 3875]

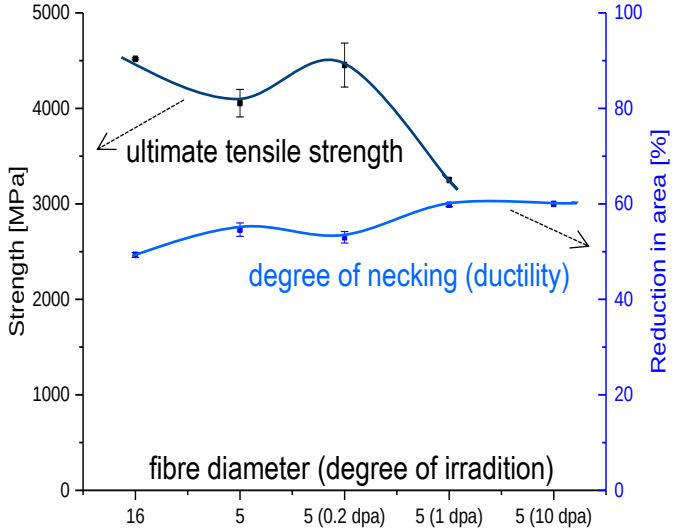
Ductile behaviour of irradiated W fibres

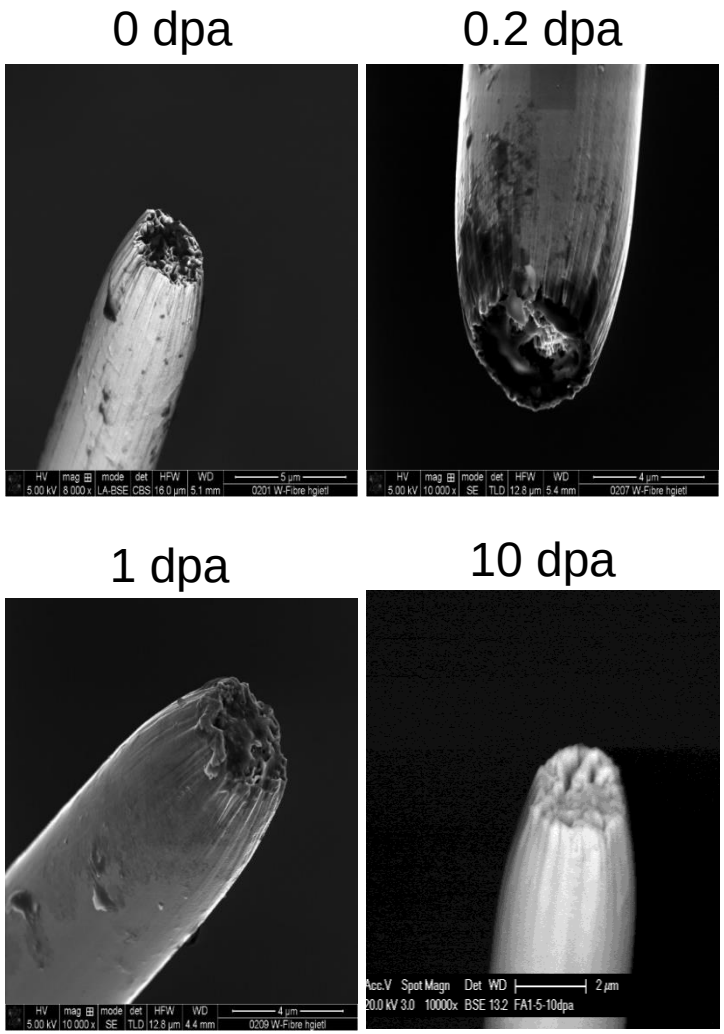
Exceptional properties (strength & ductility)
⇒ ideal ingredient for composites for high-temperature applications

⇒ successful development **W_f / W and W_f / Cu** composites

Small fibre diameter (∅=5 µm) allows damage of complete volume by W ions (irradiation by 20.5 MeV W-ions simulating n-damage)

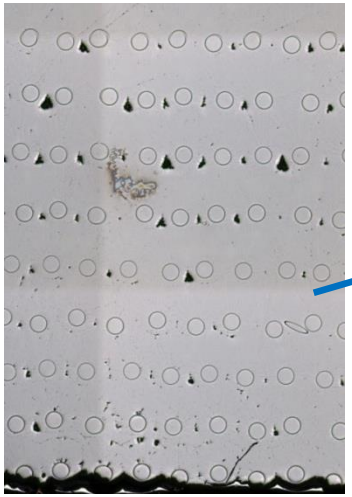
⇒ **no strong degradation up to 10 dpa**

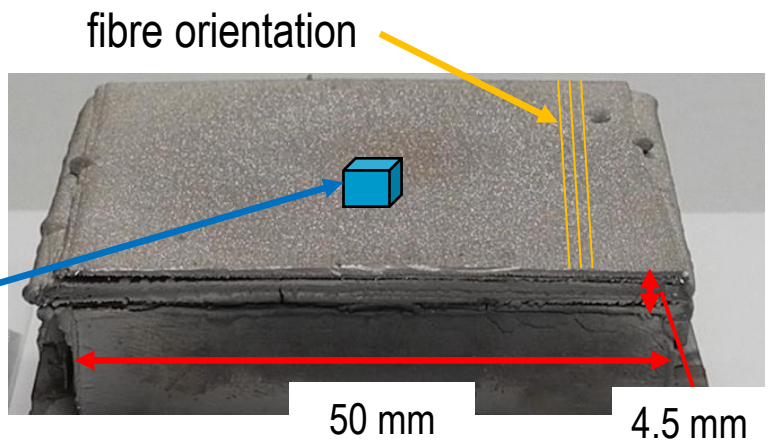




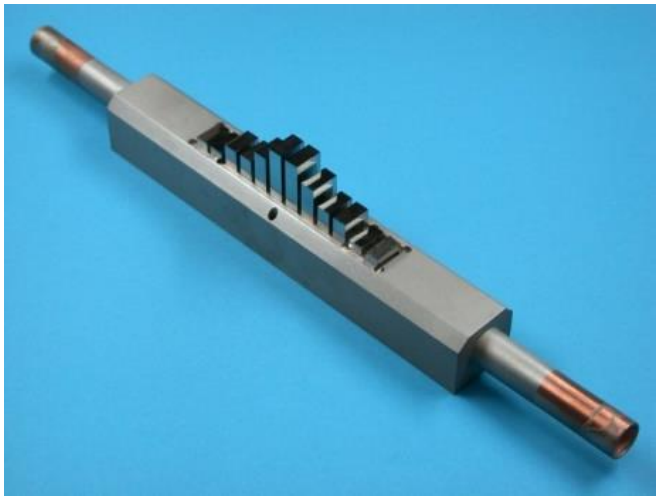
[J. Riesch, 17th Int. Conf. on PFMC, 2019, Eindhoven]

Production of bulk tungsten fibre reinforced tungsten (W_f / W)

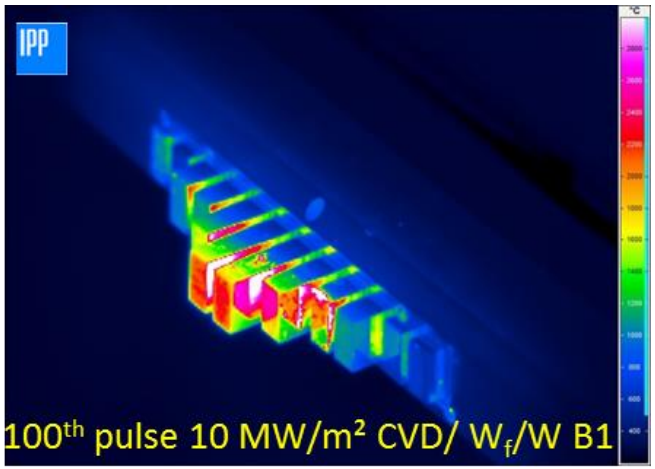




[J. Riesch, Phys. Scr., T167 (2016) 014006]



actively cooled W_f/W mock-up

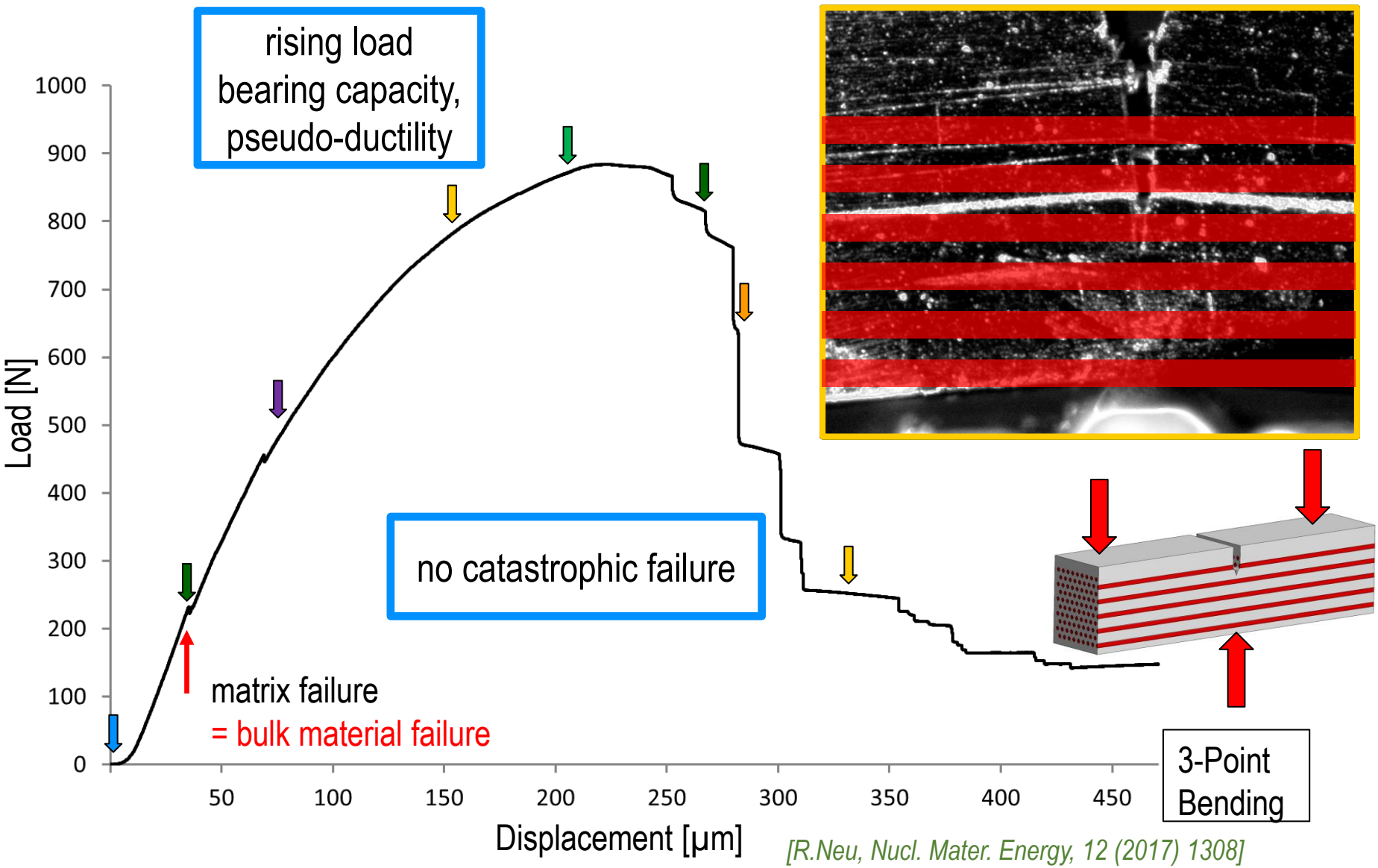


Production of W_f / W by Chemical Vapour Deposition
(CVD, decomposition of WF_6)

- layers of woven W wire fabric (distance 200 – 300 µm): K-doped, ø 150µm, 1µm Yttria interface layer
- fibre volume fraction ≈ 10 - 30%, unidirectional orientation
- density ≤ 99%

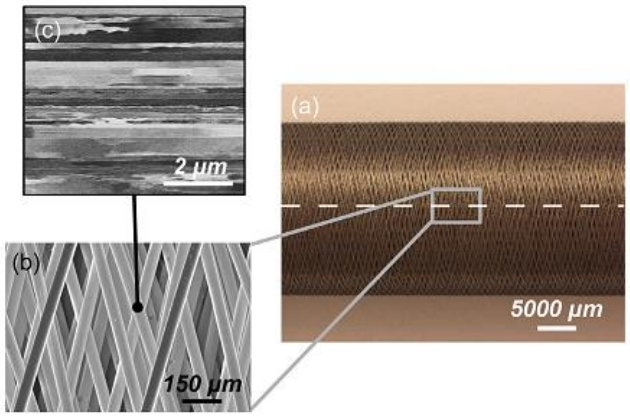
Samples for mechanical and high heat flux testing

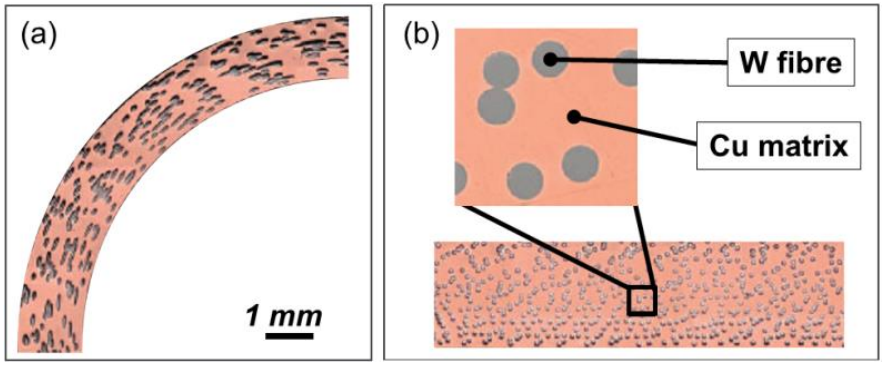
Testing of mechanical properties of W_f / W



[R.Neu, Nucl. Mater. Energy, 12 (2017) 1308]

W fibre-reinforced Cu heat sink





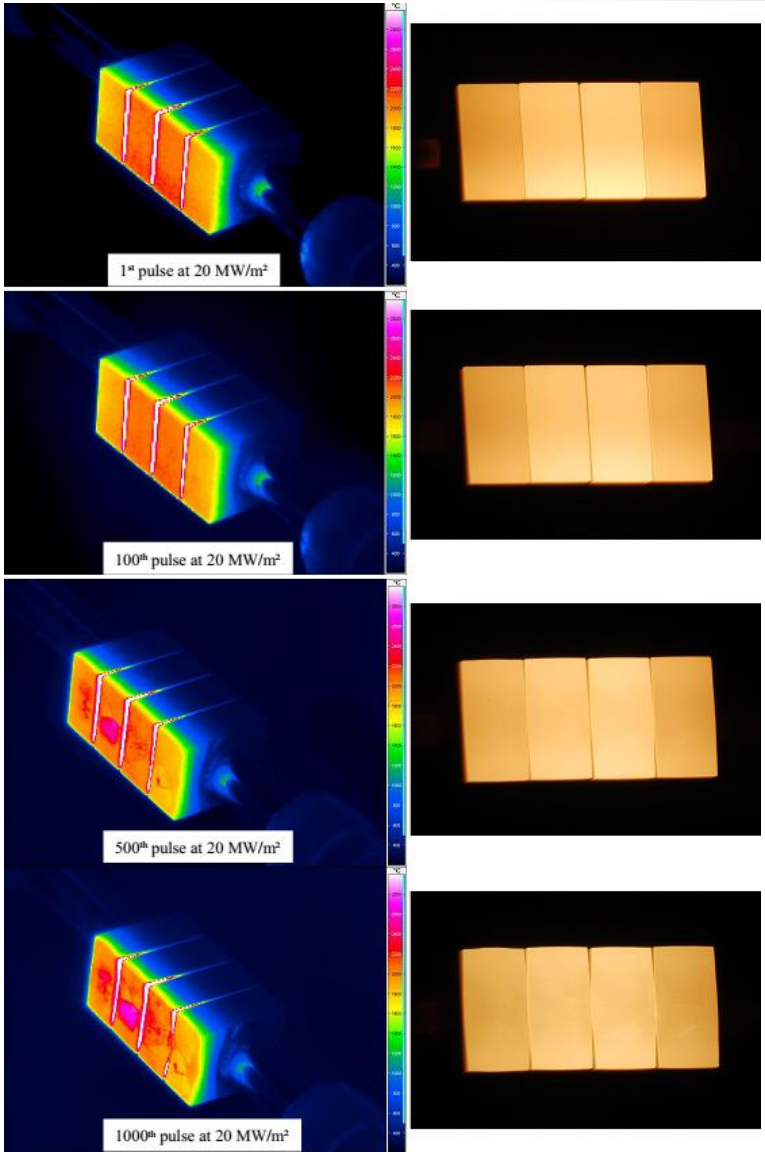
cylindrical multi-layered braiding made out of continuous W fibres or yarns with a nominal diameter of 50 µm

micro-sections of a W_f - Cu heat sink pipe produced by means of liquid Cu melt infiltration

*[A.v. Müller, Phys. Scr. T171 **2020** 014003]*

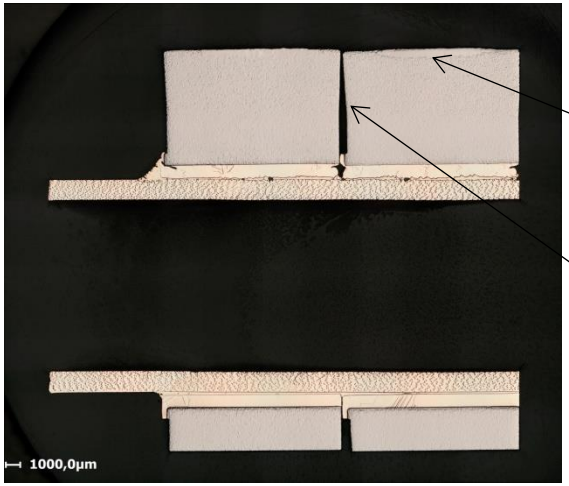
brazed joint between W mono-blocks and W_f - Cu heat sink pipe

High heat flux testing of W_f - Cu PFC mock-ups



- hot-water cooling conditions:
  130°C, 40 bar, 16 m/s → DEMO relevant
- 1000 load cycles at 20 MW/m^2 without indication of failure
- 100 load cycles at 25 MW/m^2,
  screening up to 32 MW/m^2 (@ 20°C, 10 bar)

*[A.v. Müller, Phys. Scr. T171 **2020** 014003]*



recrystallized surface layer

plastic deformation

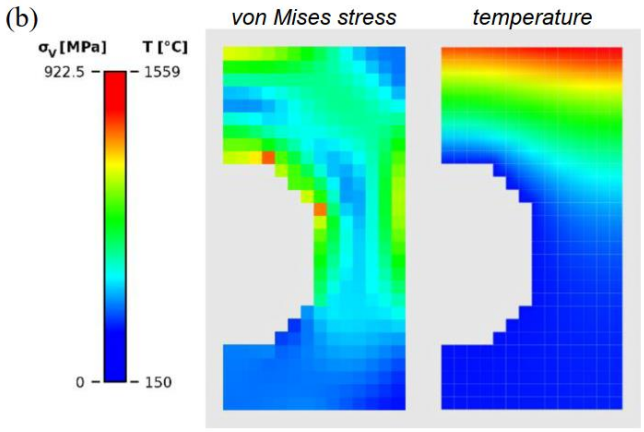
- no damage of bonding & W_f - Cu tube after 1000 cycles at 20 MW/m²

Use of additive manufacturing for topology optimisation

Stress/temperature distribution W monoblock @15 MW/m²

(a)

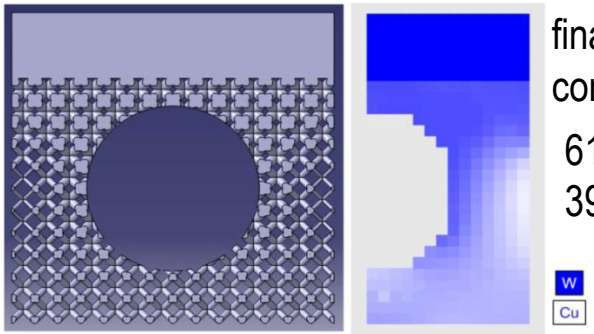
Q_N (MW m^{-2})	σ_{max} (MPa)
5	260.5
10	576.1
15	922.5
20	1264.2



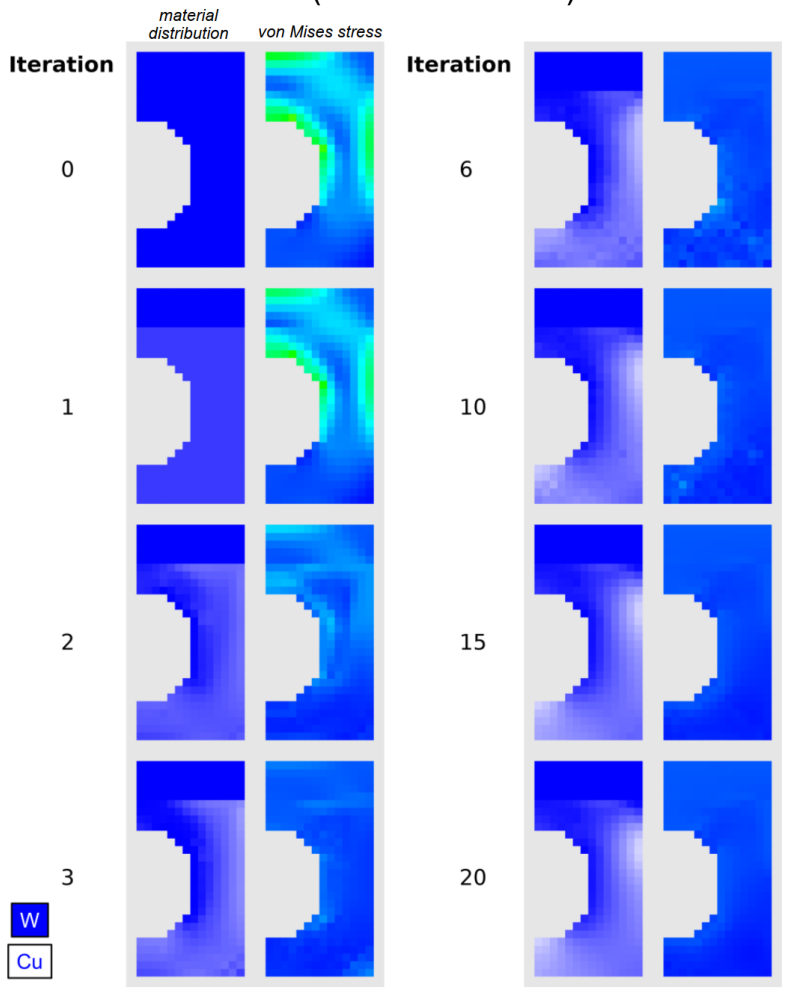
Reduction of thermal stresses by a factor of 6!

Note: extremely high flexibility for geometry, here deliberately classical geometry for comparison!

structure reproduced by bcc lattice



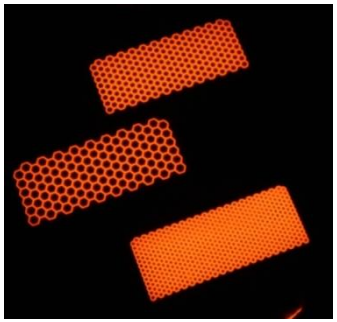
Optimisation of W/Cu distribution (10 MW/m² case)

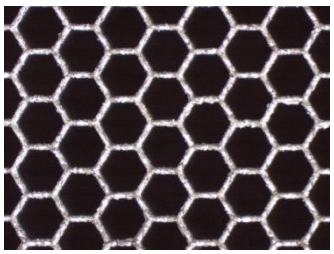


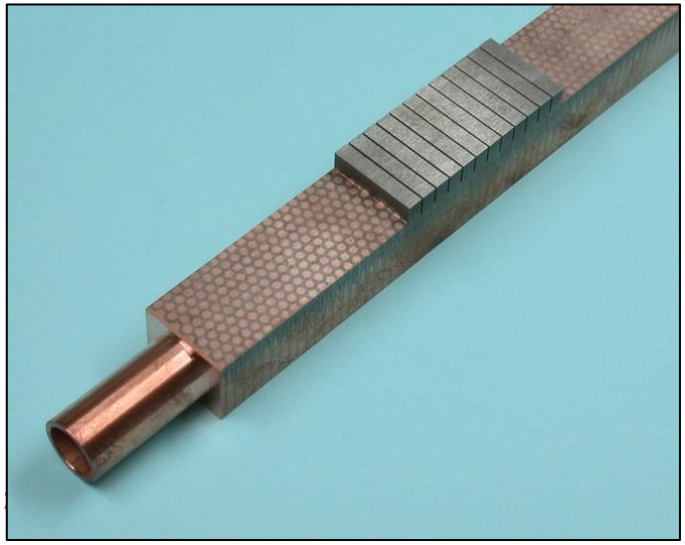
*[B. Curzadd et al., Nucl. Fusion 59 **2019** 086003]*

Additive manufacturing of actively cooled W components

laser powder bed fusion of honeycombs

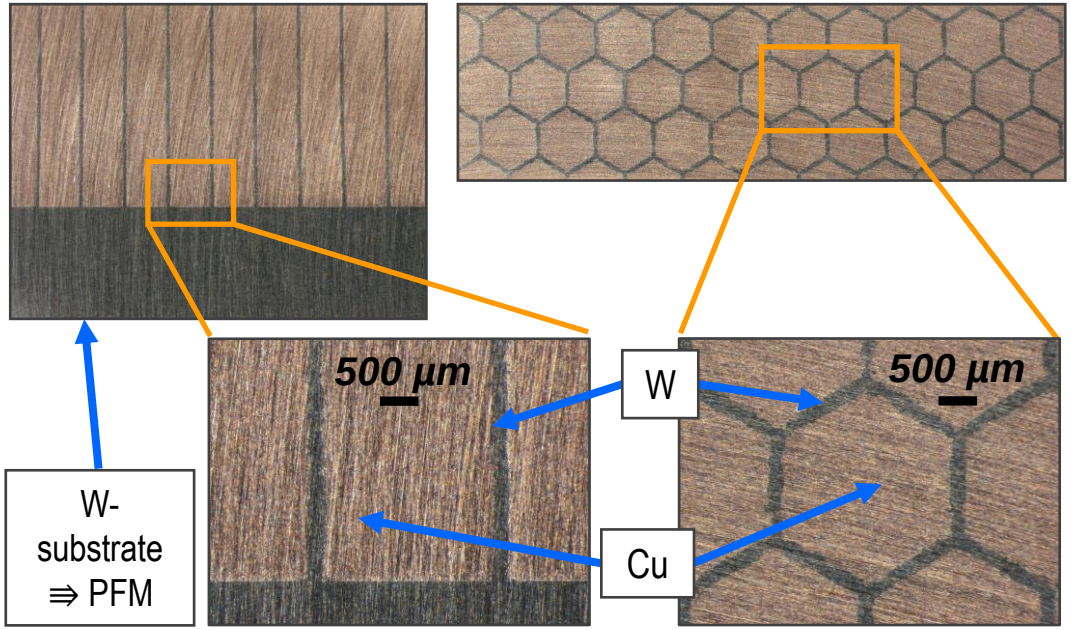






longitudinal cross section

perpendicular cross section



*[A.v. Müller et al., Nucl. Mat. Energy 19 **2019** 184]*

- **successful additive manufacturing** of honeycomb and optimized W preforms
- nearly **perfect Cu infiltration** of AM W skeletons
- HHF tests of optimized AM W mock-ups imminent

Summary and Conclusion

- **New composite materials can help to improve DEMO PFCs to allow for larger operational margin (higher cooling water temperatures / higher thermal loads) and lifetime**
  - increasing **high temperature strength of Cu** in the cooling structure, ameliorating consequences of Cu(-alloy) neutron damage
  - increasing **fracture toughness of W**
  - **adjusting the thermal missmatch** between armour and cooling sink
  - tailored material distribution by **additive manufacturing to reduce thermal stresses**
- **Very promising behaviour of composites materials and composite PFCs in high heat flux tests**

Outlook:

First results for W fibres and W_f-Cu confirm superior behaviour under neutron irradiation!