MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Development Challenges for Tungsten-Based Materials and Joints Under Fusion-Relevant Neutron Loading in Plasma-Facing Components

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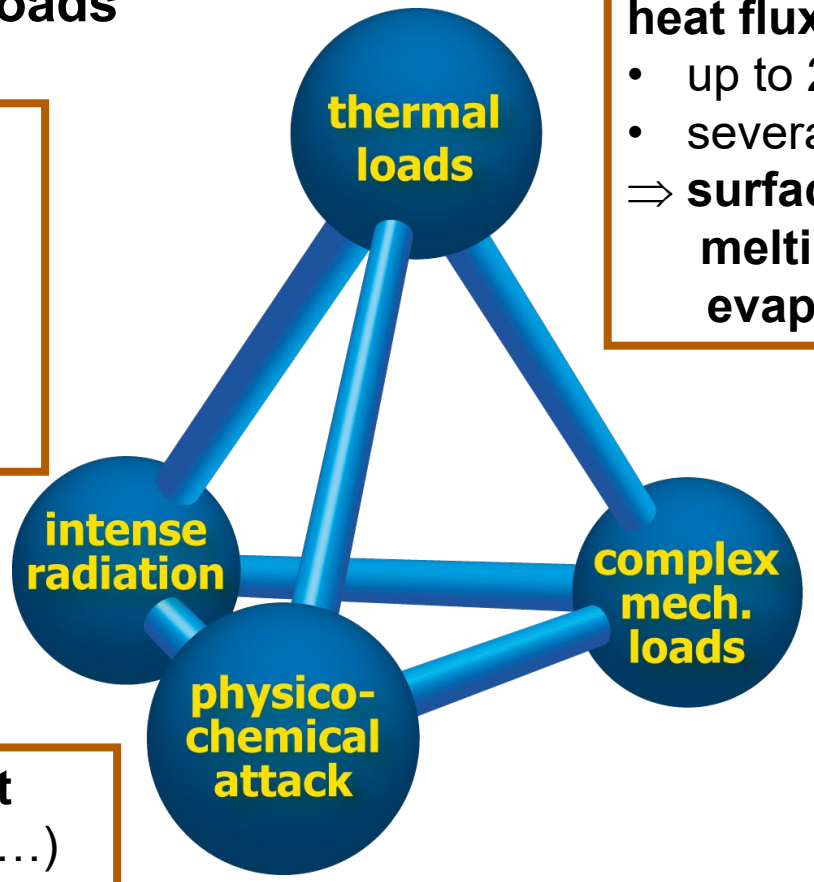
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Challenges to Plasma Facing Components (PFCs)

PFCs are subject to extreme loads

neutron irradiation
- up to 100 dpa
- H & He production

⇒ **change of chemical composition & mechanical properties**



heat fluxes
- up to 20 MW/m^2 (steady state)
- several GW/m^2 (ms pulses)

⇒ **surface modifications, melting, recrystallisation, evaporation**

plasma ions and atoms impact
- chemically reactive (H, O, N, …)
- energetic (up to keV)

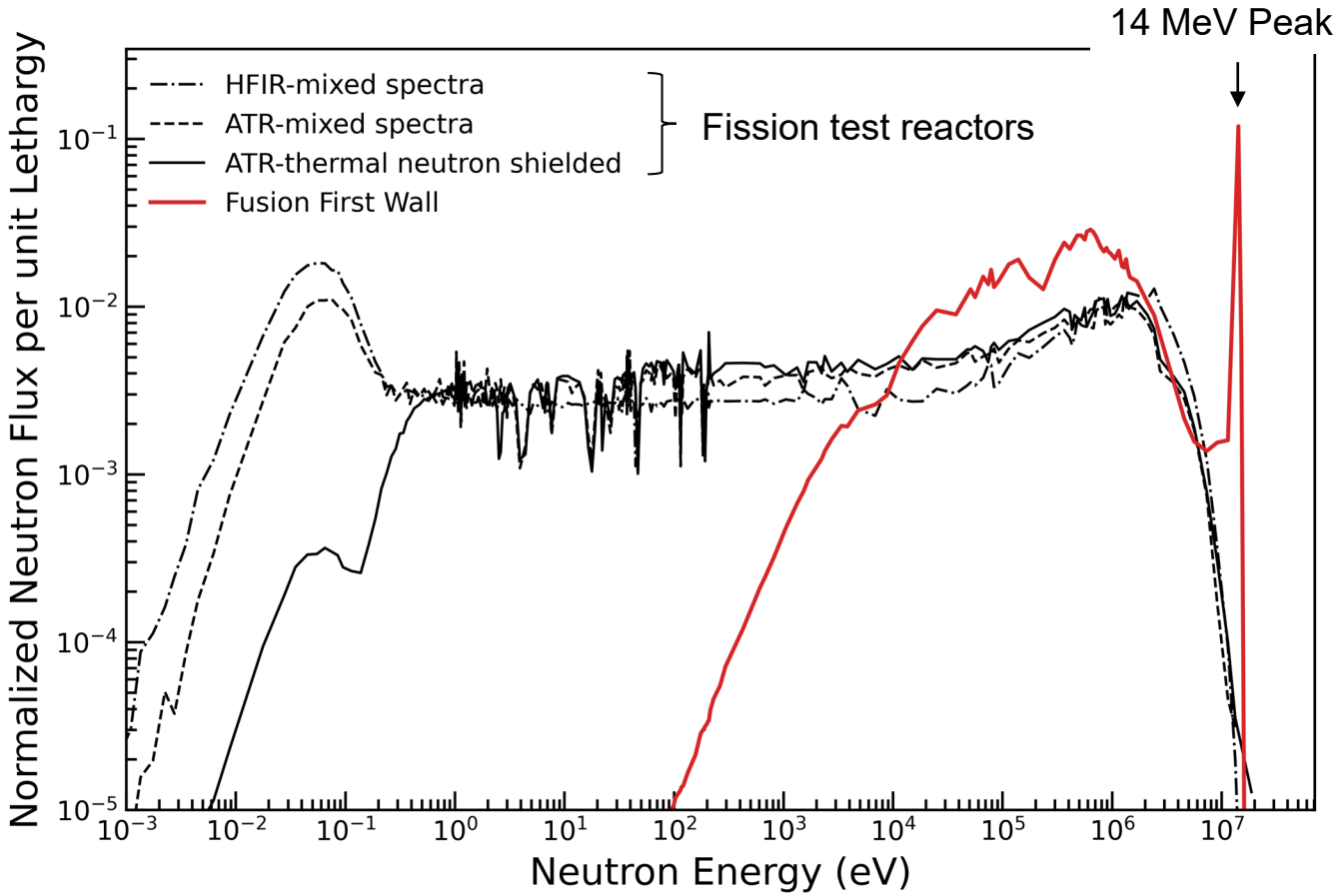
⇒ **erosion, migration, H retention, plasma contamination**

mechanical stresses
- thermal gradients and shocks
- heterogeneous structures
- electromagnetic forces

⇒ **fracture, rupture, loss of mechanical integrity**

⇒ **strongly holistic approach necessary!**

Ion bombardment or neutron irradiation in fission reactors



[Gietl, et al. Fusion Eng. Des., 222 (2026): 115539]

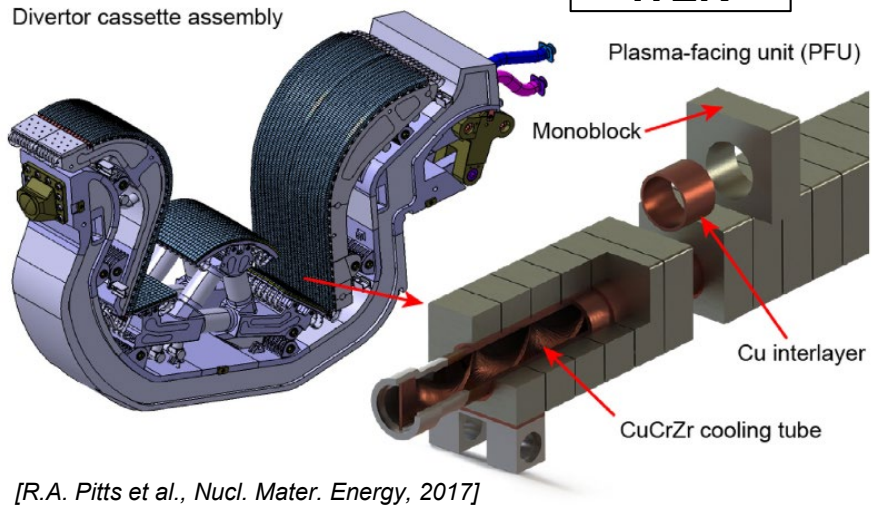
Specimens are irradiated in fission reactors due to lack of available fusion relevant neutron sources.

Ions are good to study fundamentals of radiation damage but cannot damage full components due to limited penetration depth.

A Fusion Prototypic Neutron Source is needed.

State of the art – Tungsten- and copper-based PFCs are used in the highest-loaded regions of a fusion device

ITER



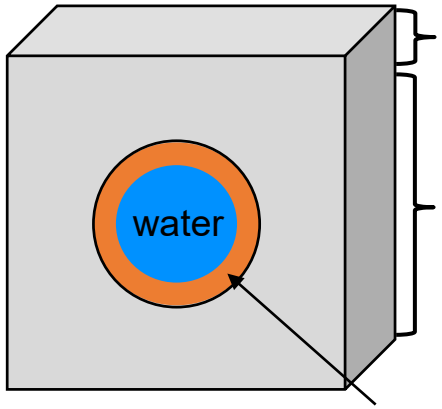
[R.A. Pitts et al., Nucl. Mater. Energy, 2017]

W as PFM
⇛ low sputtering yield
⇛ low tritium retention
⇛ high melting point

Cu (alloys) as heat sink and structural materials
⇛ excellent thermal conductivity
⇛ acceptable mechanical strength

The monoblock design is currently the preferred option for PFCs.

Tungsten monoblock design



Armor layer (W)

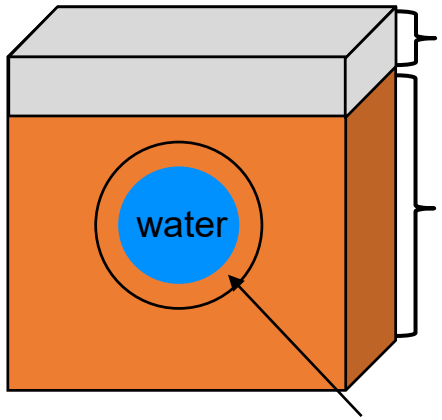
Heat sink (W)

Cooling channel (CuCrZr pipe)

+ damage tolerance

- amount of W
- scalability?

Tungsten flat-tile design



Armor layer (W)

Heat sink (CuCrZr)

Cooling channel (CuCrZr pipe)

+ reasonable amount of W
+ highly conductive heat sink

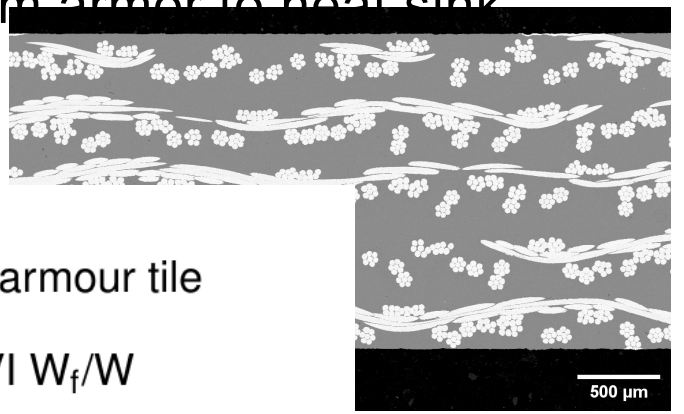
- high stresses at joint edges
- concern about cascade failure

Developments in Fiber-Reinforced Flat Tile Designs

Graded W-fiber reinforcement bridges the CTE mismatch from armor to heat sink

Previous Work

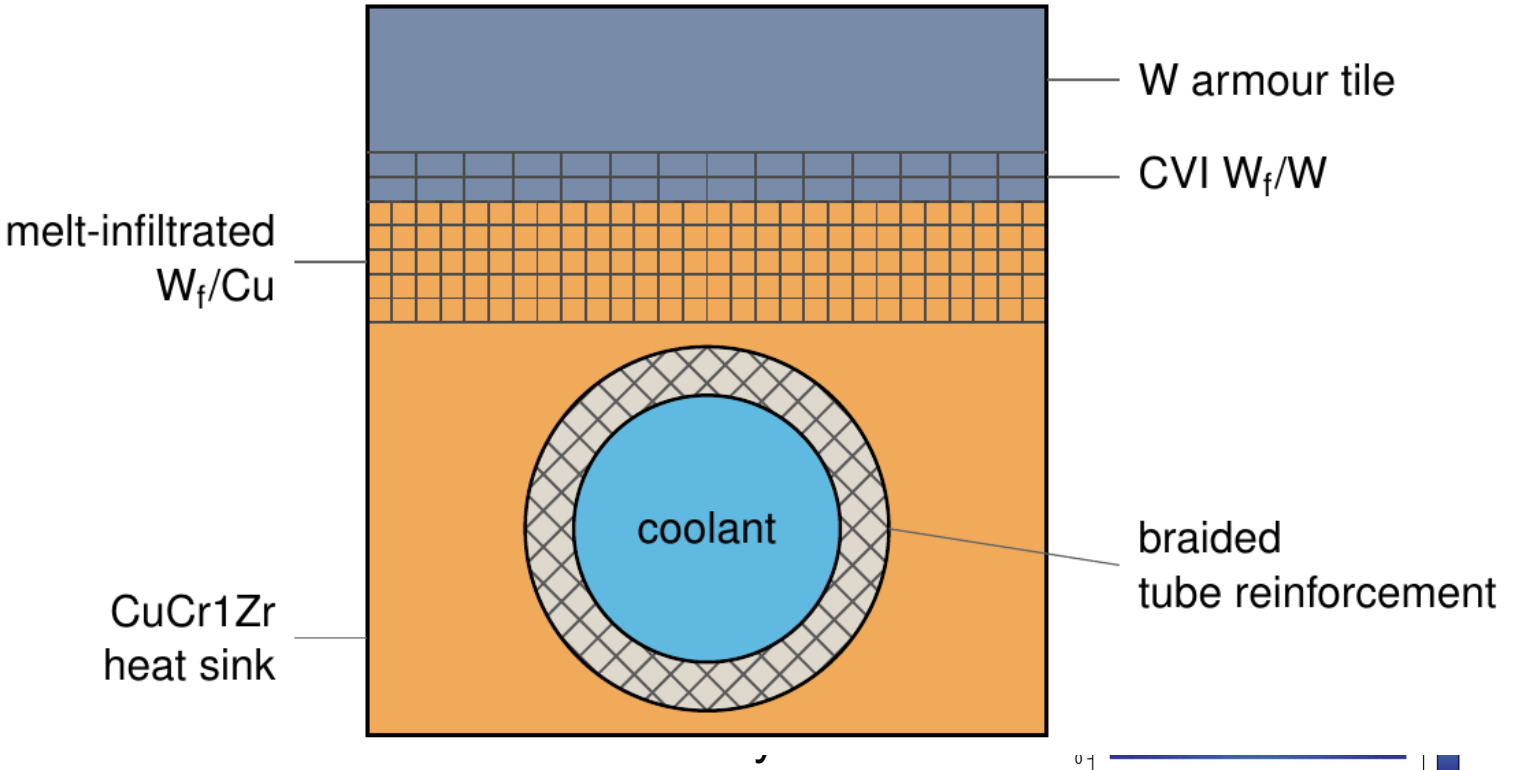
- Testing of la
  parts alread
- Cu infiltrate
  thermal and
- Topology op
- 3D weaving

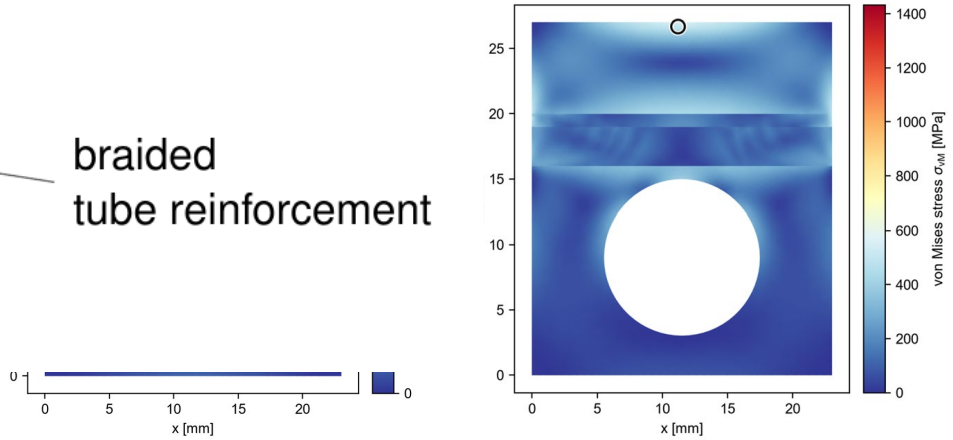


Cu using 16µm filaments
veaving production.

Future Work

- These techr
  mock-up he
- 3D woven ir
  production.

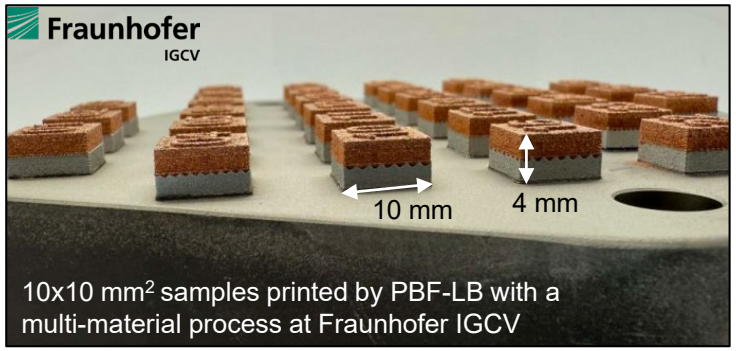




Von Mises stress fields of 2D simulated reinforced flat tile designs before and after optimisation.

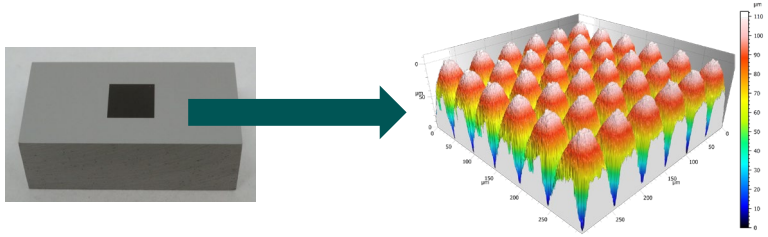
Optimized and tailored W/CuCrZr joints through additive manufacturing in PFCs

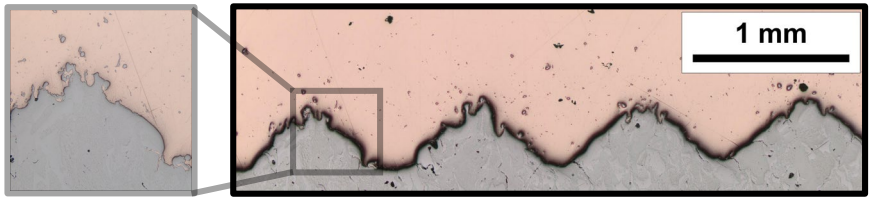
- Create a tailored W surface (design freedom)
- Assess the quality of printed W
- Filling of the structures with Cu or Cu alloy
- Assess the joining performance



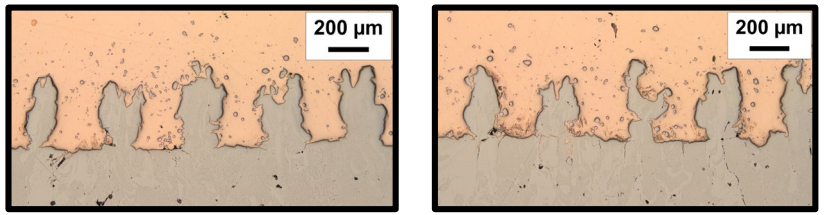
Heuristic approach: mushrooms and sinusoidal geometries

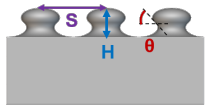
- Laser- and electron-beam powder-bed fusion
- Casting and multi-material PBF-LB for Cu alloy infiltration
- Alternative approach: surface texturing with femto-second laser



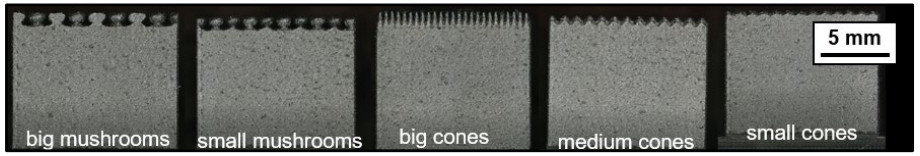


sinusoidal geometry

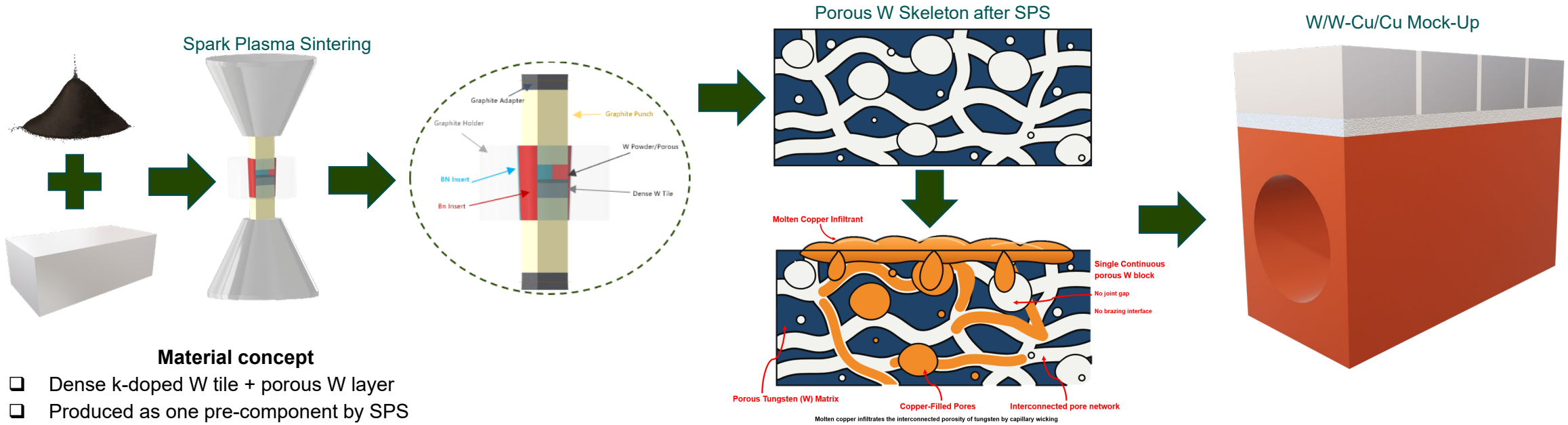




mushroom geometry



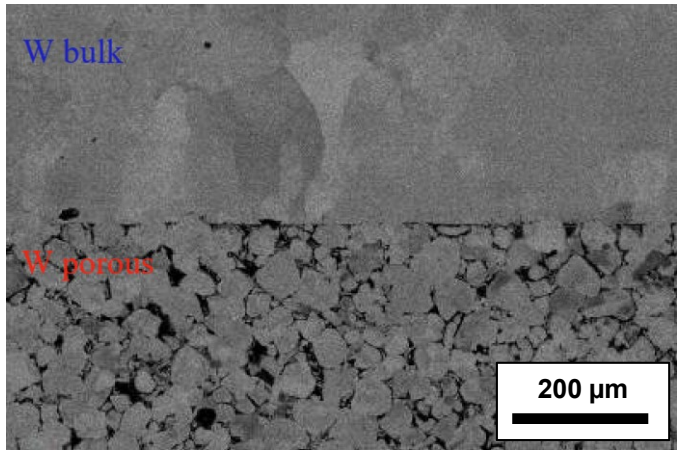
Development of a Monolithic to Porous Sintered Composite



Material concept

- ❑ Dense k-doped W tile + porous W layer
- ❑ Produced as one pre-component by SPS
- ❑ Dense W: 23 x 12 x 8 mm

W-W Sintering-Preliminary Trials



Key material challenge

- Achieve sufficient W-W bonding
- Avoid delamination during handling and later processing
- Preserve open interconnected porosity in porous W
- Prevent full densification of porous layer during SPS

Development Strategy

- Vary SPS temperature, pressure, dwell time, heating rate
- Adjust porous W powder size and packing density
- Characterize interface, porosity and mechanical stability (Archimedes method, Shear Testing)
- Identify processing window for stable but infiltratable W/W composite

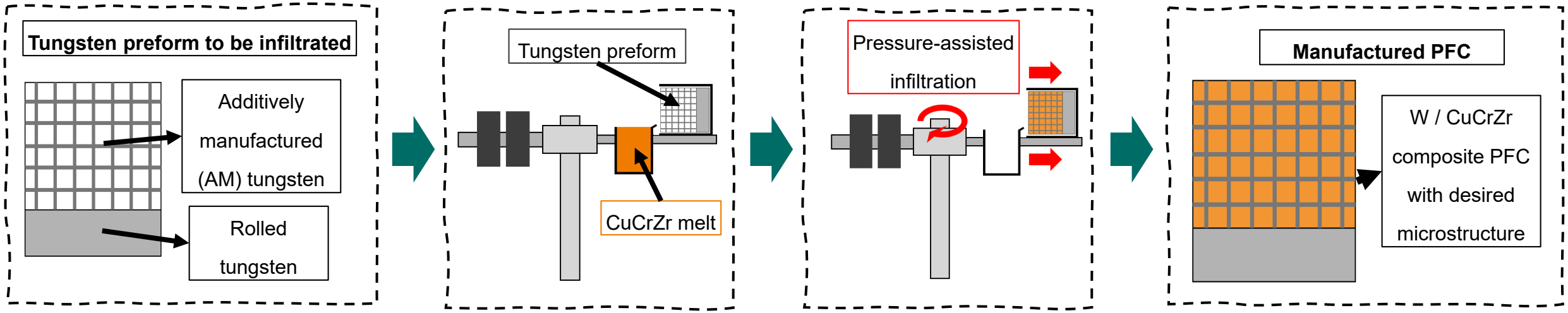
Casting technologies for W / Cu (alloys) composites

- A promising class of plasma facing components are W / Cu (alloys) composites

- Large melting point difference
- Good wettability of Cu alloys on W

→ Well suited for composite casting

Centrifugal investment casting (still in the planning phase)

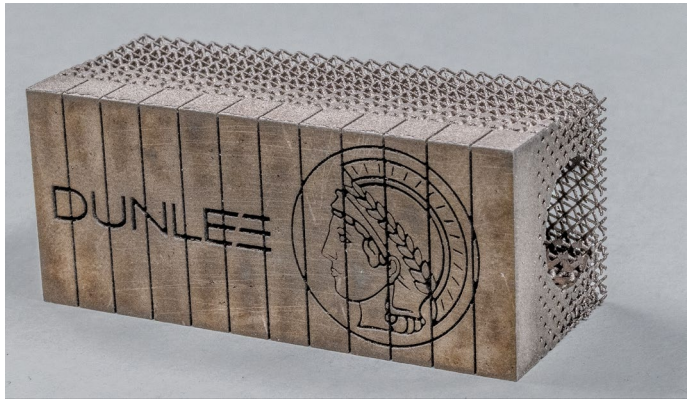


⊕

- Pressure-assisted casting → dense + low porosity specimens
- Fast cooling rates + grain refinement → small grains + satisfactory mechanical properties

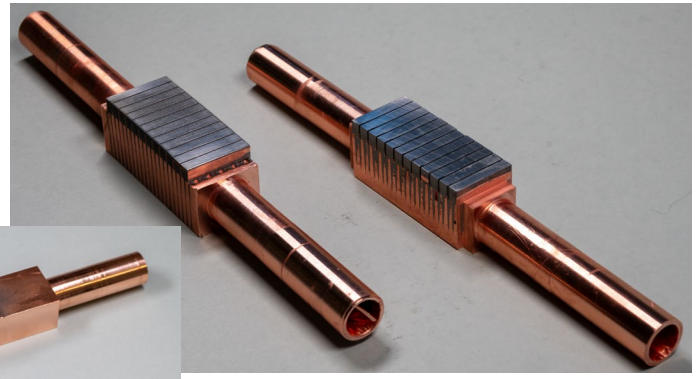
PFC mock-ups based on tailored AM structures

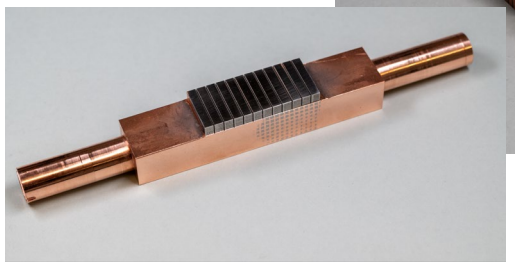
Tailored W AM lattice structure



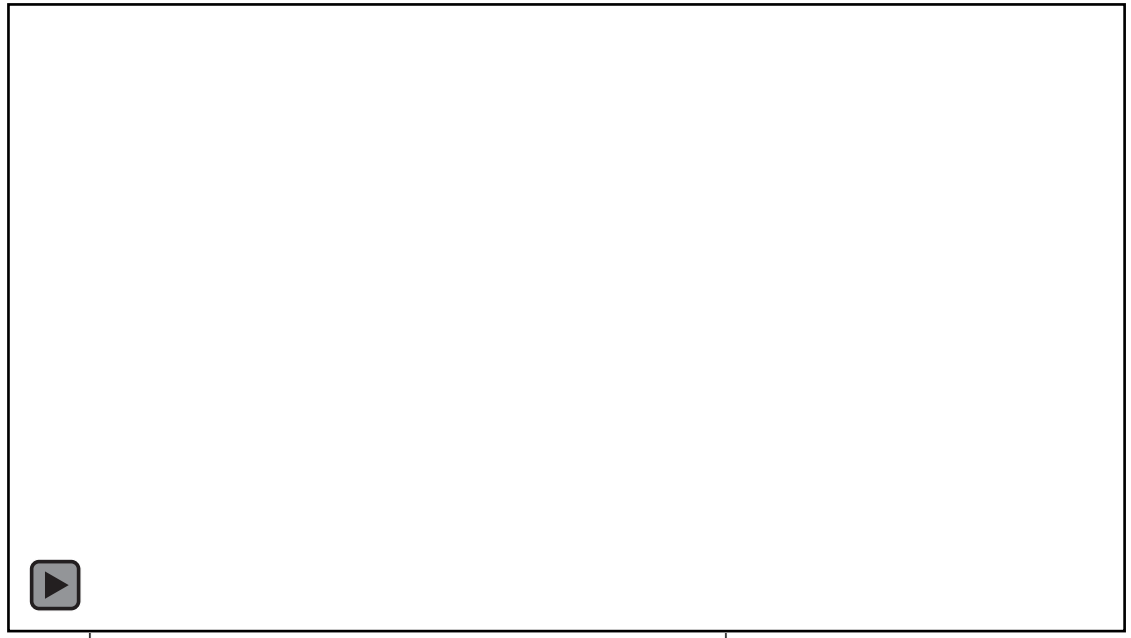
Melt infiltration with Cu

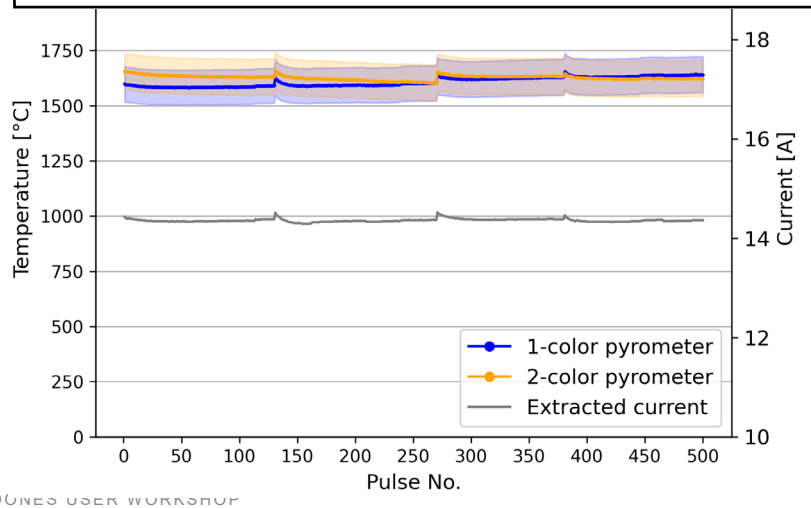
Small-scale mock-ups





HHF testing in GLADIS

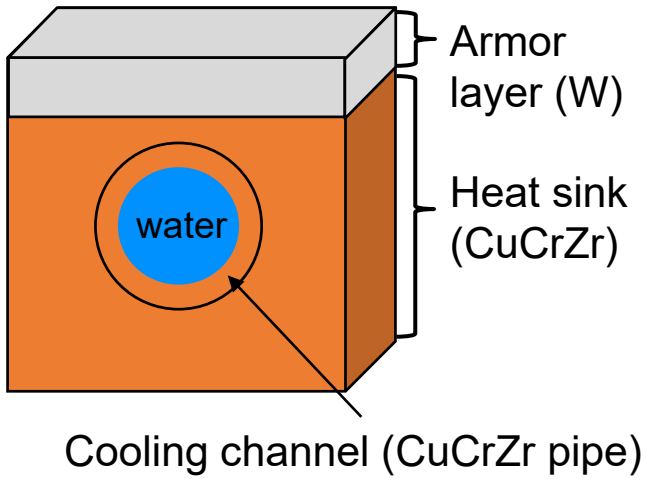




Stable surface temperature response over 500 pulses at 20 MW/m²

Gaps for PFC joint qualification

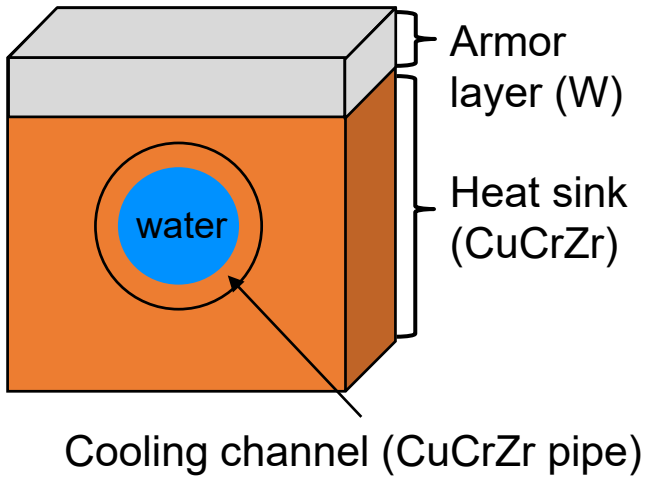
Very limited irradiation data for PFC relevant **welds, brazes, diffusion bonds, HIP interfaces and dissimilar-material joints**



- **Base material, heat-affected zone, bond/fusion zone and interlayers** produces local variations in dpa, He/H accumulation, microstructure and residual stress.
- Fission and ion irradiations **cannot** reproduce the relevant neutron spectrum, displacement damage and gas production.
- No facility currently supports **full-scale blanket/divertor joint qualification** under fusion-neutron loading and representative thermomechanical conditions.

Gaps for PFC joint qualification

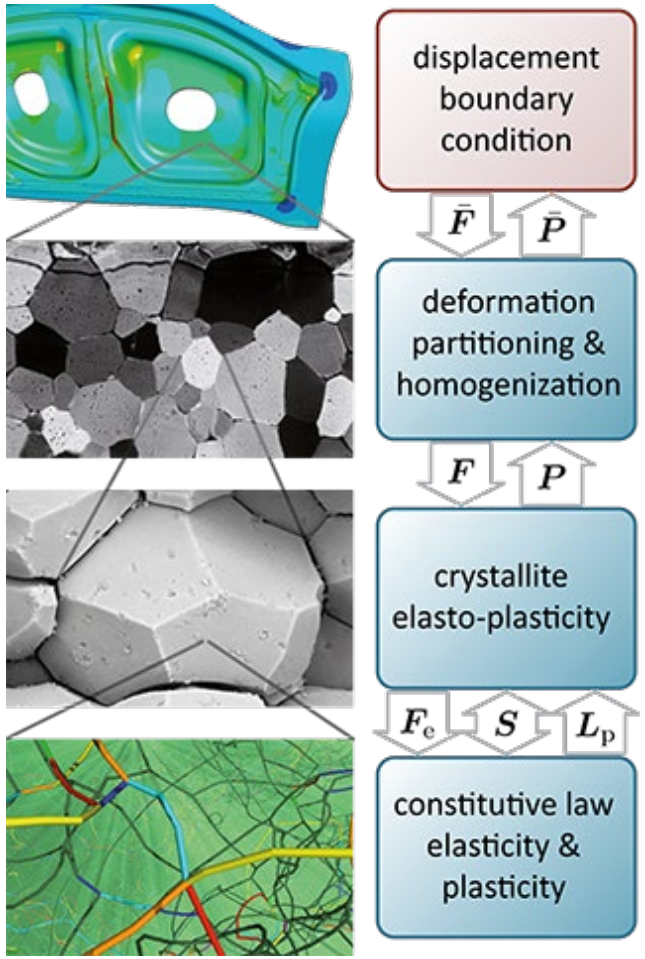
Coupons testing as a first step



- Irradiation of **joint coupons and representative local geometries** in a fusion-relevant neutron field for screening and down selection of:
  - **W–CuCrZr** brazed, diffusion-bonded and HIP joints**;**
- Miniature tensile, fatigue and fracture testing, supported by microscopy, residual-stress measurements and leak-tightness assessment.
- Data for **joint lifetime models, manufacturing specifications, inspection criteria and design-code qualification**.

Joint qualification pathway:
Coupons → representative joint sections → irradiated subcomponents → full-scale mock-ups → in-device validation

How Modelling Can Bridge the Joint-Testing Gaps



[Roters, Franz, et al., Computational Materials Science 158 (2019): 420-478., https://damask2.mpie.de/*]*

- **Link scales:** connect neutron-induced changes to changes in joint properties.
- **Predict failure:** use models to assess interfacial cracking, fatigue, debonding etc.
- **Scale up DONES data:** transfer results from irradiated coupons and small joint sections to **component-scale geometries and loading conditions**.

- **Simulate combined loads**
- **Support lifetime and uncertainty assessment:** combine models, experiments and probabilistic methods to estimate failure margins and inspection intervals.

Modelling approaches

Rate theory/cluster dynamics → micromechanics/crystal plasticity → cohesive-zone fracture → component-scale finite-element analysis

FUsion material Modelling and Experiments:

Linking microstructural evolution to mechanical properties for predictive modeling and simulation of component failure. **[set-up phase]**

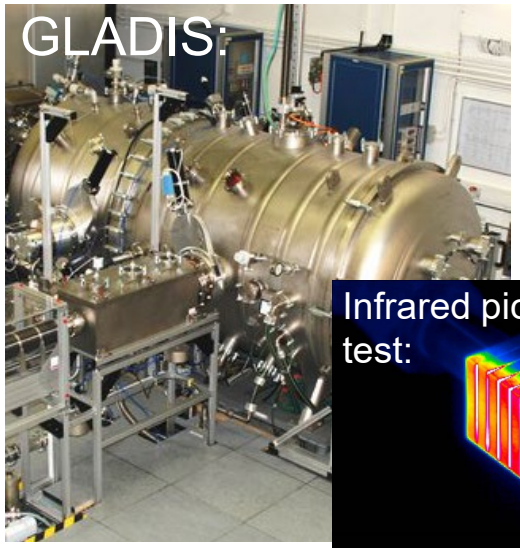
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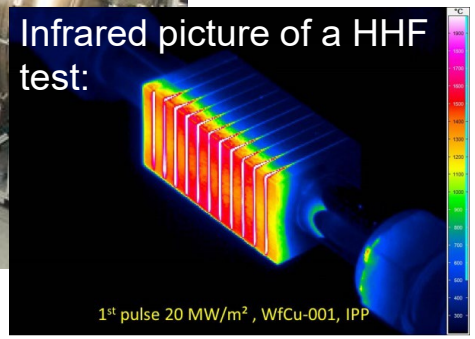
Model development

	Material properties	Microstructure
Modeling	Crystal plasticity, dislocation dynamics for mechanical properties	Phase field, molecular dynamics for microstructural evolution including radiation defects
Experimental	Mechanical properties evaluation, e.g. tensile testing, hardness measurements	Microstructural Characterization Techniques, e.g. SEM, EBSD

Validation capabilities at IPP Garching

- GLADIS
- Tandem Laboratory
- *In-situ SEM* mechanical and micromechanical testing (set-up phase)





We are developing a validated modelling capability that links microstructural evolution to mechanical properties under combined loading.

Summary and future work

With funding from the:
Federal Ministry of Research, Technology and Space
FKZ:
13F1021 & 13F1042

- Combined loading on PFC cannot be tested experimentally.
- A flat tile design based on tungsten fiber-reinforced materials has been developed.
- Different types of copper-to-tungsten joints are pursued.



- Copper-to-tungsten joints require experimental evaluation, especially with regard to neutron irradiation.
- Set up micromechanical laboratory at Plasma Material Interaction and Components (P2W) division at the Max Planck Institute for Plasma Physics.
- Establish modelling capabilities for material degradation at P2W.
- Fabricate flat tile mock up and perform high heat flux test.