Cooling Concepts for DEMO Reactors and their Impact on Design & Materials

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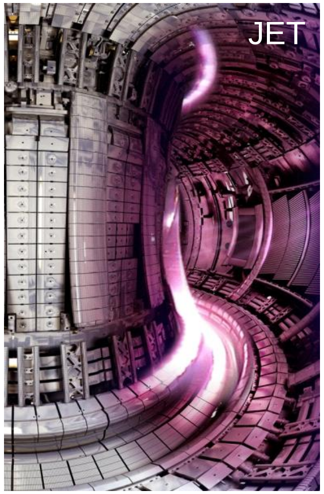
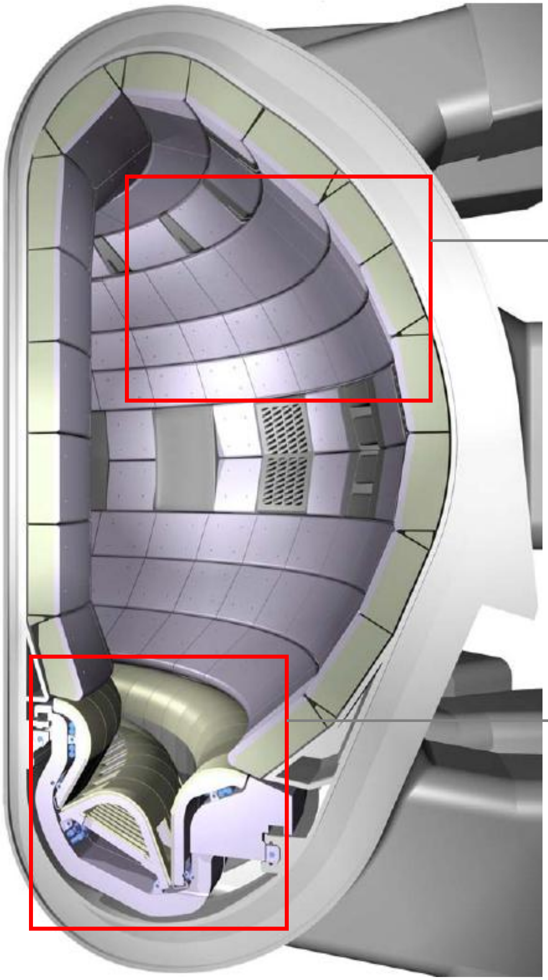


MIIFED 2013, 4 Dec. 2013, Monaco

In-vessel components related to critical materials issues

In-vessel components: functions & thermal loads



A cut section of a tokamak

First wall + Blanket

- thermal energy extraction
- tritium breeding

- fast neutron impingement

⇒ neutron wall loading (~2 MW/m²)

⇒ power exhaust: ~80%

Divertor

- particle exhaust (He ash)
- impurity barrier

- directed plasma bombardment

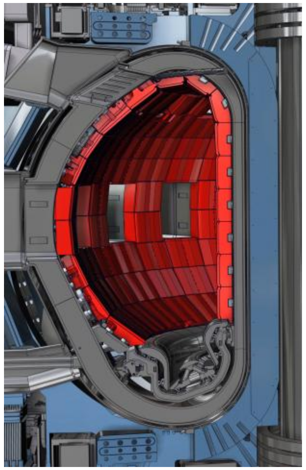
⇒ high-heat-flux loads (10~20 MW/m²)

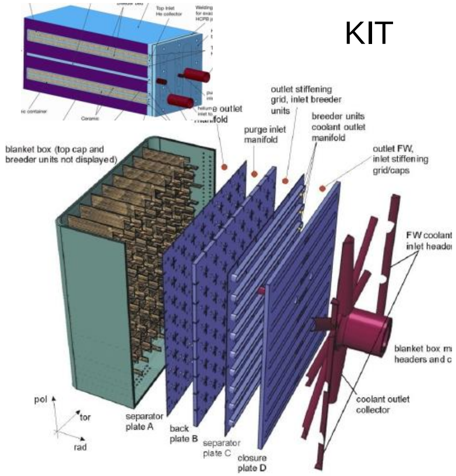
⇒ power exhaust: ~20%

heat transport
via coolant
to
power conversion

Cooling concepts for blanket & divertor

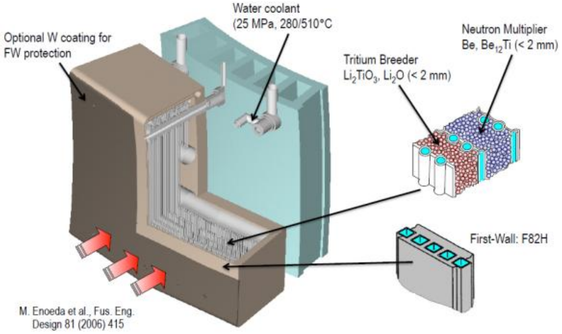
Blanket cooling concepts: pros & cons





KIT

He-cooled (EU)



M. Enoeda et al., Fus. Eng. Design 81 (2006) 415

Water-cooled (Japan)

Water

- effective cooling, PWR database
- lower operation temperature (steel embrittlement/low efficiency), corrosion

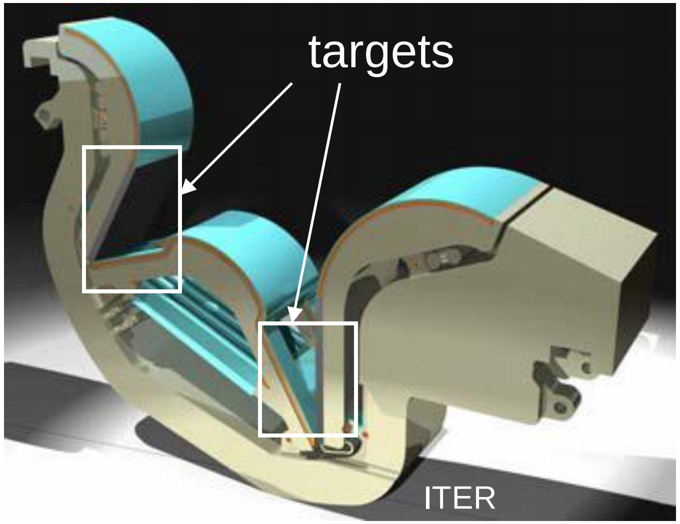
Helium

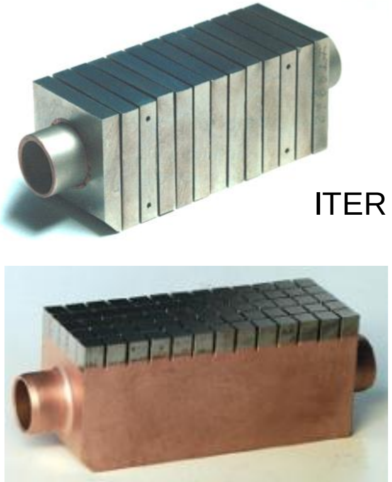
- chemical inertness, higher operation temperature (high efficiency)
- lower heat removal capability (pumping power cost, large tube size)

Liquid metals

- effective heat removal, simultaneous T breeding, low pressure
- MHD effect (pressure drop), safety issue

Divertor cooling concepts: pros & cons





Water-cooled

Helium-cooled

Water

- excellent cooling capability (~20 MW/m^2), mature technology (ITER)
- low operation temperature (tungsten brittleness, reduced efficiency)

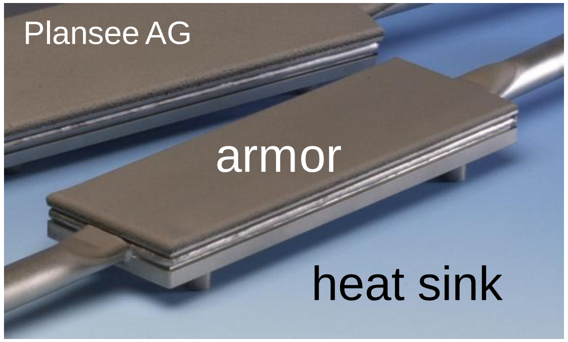
Helium

- high temperature (above DBTT of tungsten), compatible with He-cooled blanket
- low power exhaust capability, suitable structural material not available yet

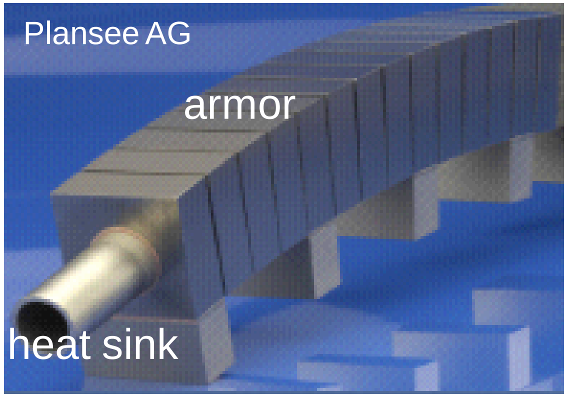
Lifetime: ~2 FPY (2.2 MWa/m^2, ~20 dpa)

Loads & materials requirements of plasma-facing components

Plasma-facing components



First wall module (W-coated)



Divertor target element (W mono-block)

Generic structure

- plasma-facing armor
- heat sink (cooling channel)

Loading characteristics

- plasma particle bombardment

$\Rightarrow$ *surface erosion*, *T implantation*

- high-heat-flux loads

$\Rightarrow$ *thermal shock, thermal stress*

- fast neutron irradiation

$\Rightarrow$ *cascade damage*, *transmutation*

Materials requirements for DEMO divertor

Heat sink (as structural material)

- high thermal conductivity
- toughness / high temperature strength
- machinability / weldability
- recovery from dpa damage (desired)
- watertight
- aqueous corrosion resistance
- reduced activation (desired)

↓

Water-cooled: copper alloys

Helium-cooled: tungsten

ODS ferritic-martensitic steel

Materials requirements for DEMO divertor

Armor (as functional material)

- low sputtering yield
- low tritium solubility
- high melting point
- high thermal conductivity
- thermal shock resistance
- involatility under oxidation
- reduced activation (desired)

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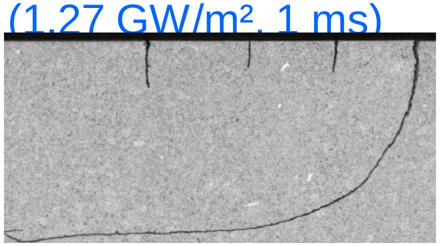
Tungsten?

Tungsten alloys?

Tungsten composites?

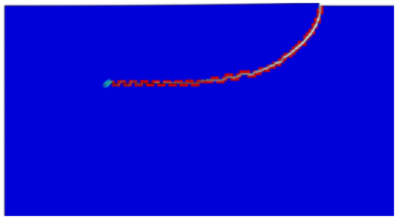
Cracking on W surface under transient load

(1.27 GW/m^2, 1 ms)



Electron beam pulse

J. Linke (PFMC 2011)

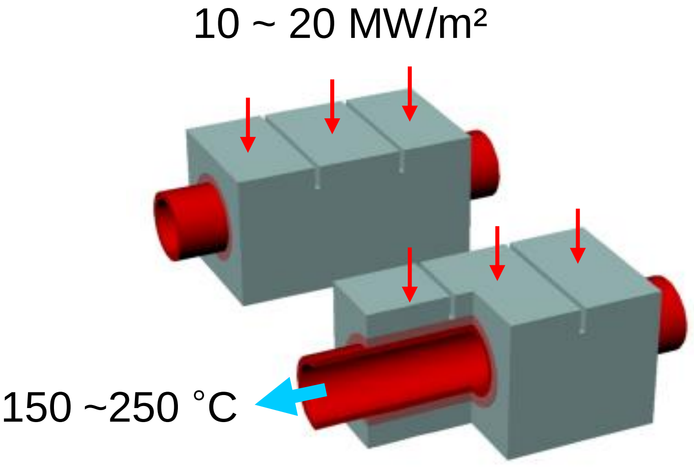


XFEM simulation

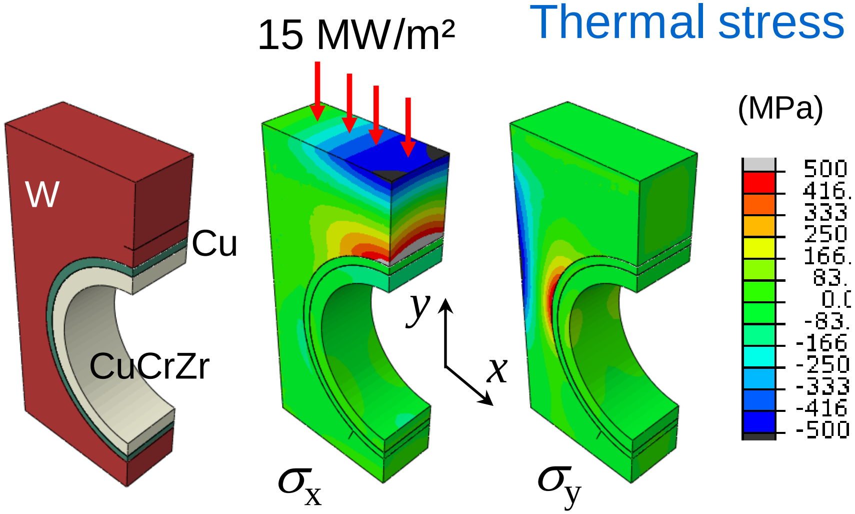
M. Li, JH You

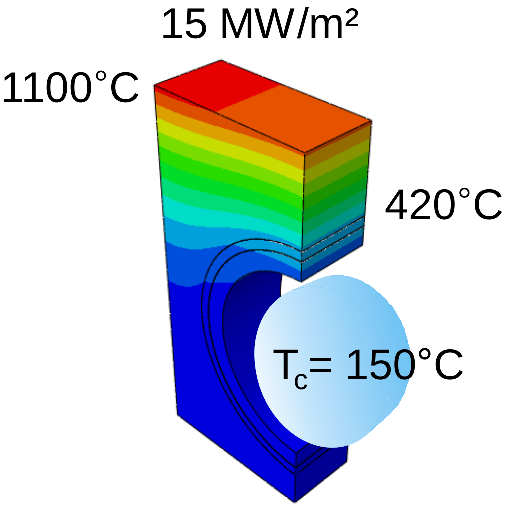
Design constraints for divertor target

Water-cooled divertor

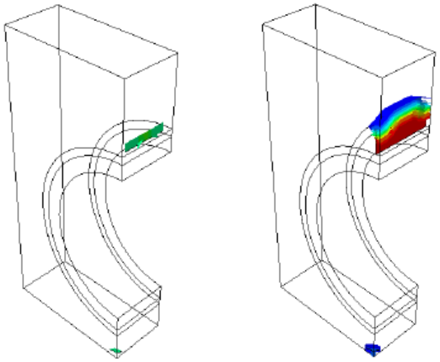


Thermal stress





Cracking in armor



15 MW/m² T_c=200°C

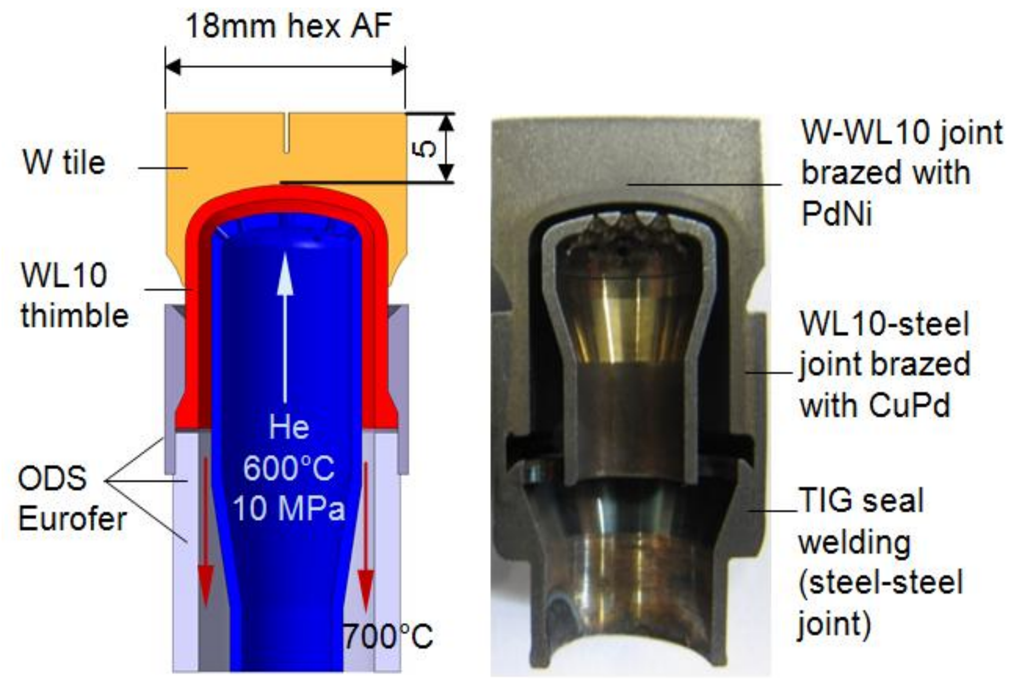
15 MW/m² T_c=250°C

Copper alloys: 250°C < T < 320°C

Tungsten: ~600°C < T < 1300°C

Helium-cooled divertor

5~10 MW/m^2



10 MW/m^2, He flow rate: 240 m/s, 6.8 g/s

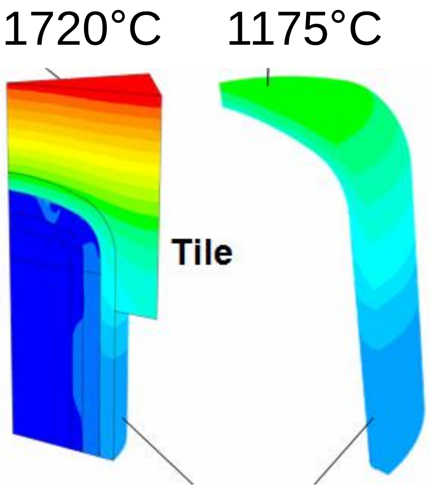
W tile: 1720°C (*2500*), 244 MPa (*445*)

W thimble: 1175°C (*1300*), 280 MPa (*400*)

ODS steel: 700°C (*700*)

Tungsten (600~800°C < T < 1300°C)

ODS ferritic steel (350°C < T < 700°C)



Tungsten thimble:
irradiation behavior?

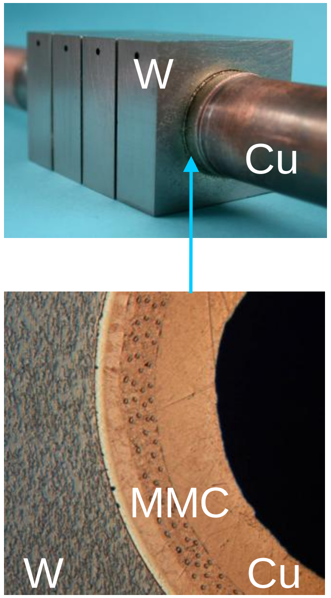
Novel materials for water-cooled divertor target

Heat sink: high-temperature strength

Armor: enhanced toughness

Fiber-reinforced copper composites

Tungsten wire

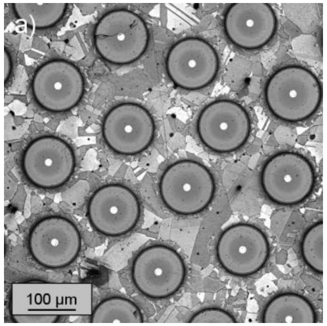


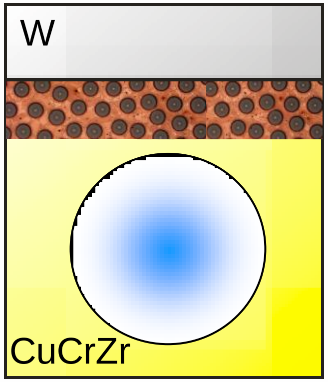
A. Herrmann (IPP)

W wire-reinforced Cu composite

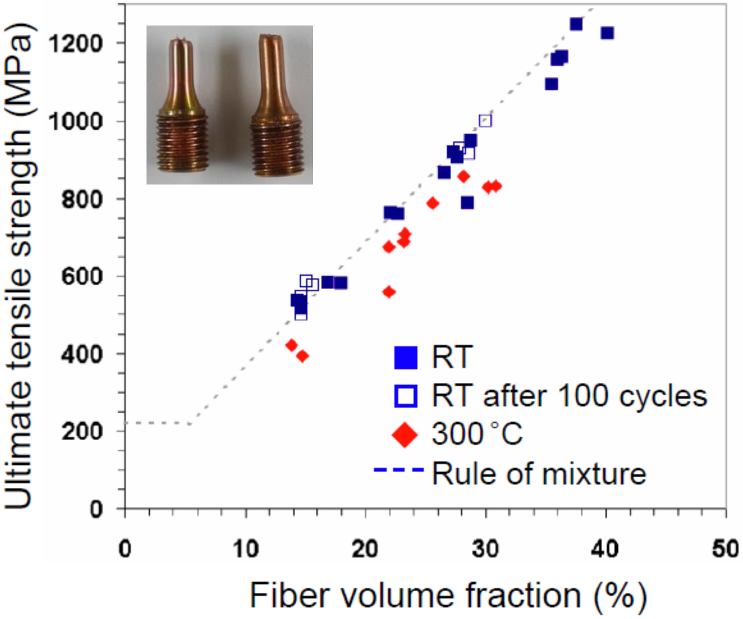
25 heat flux cycles (10 MW/m^2)

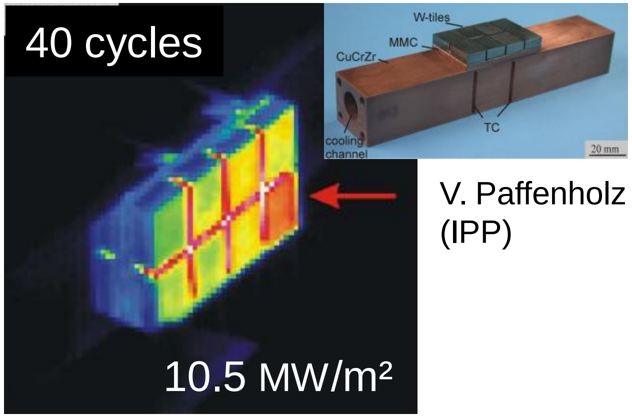
SiC fiber





Strength of SiC$_f$/Cu composite





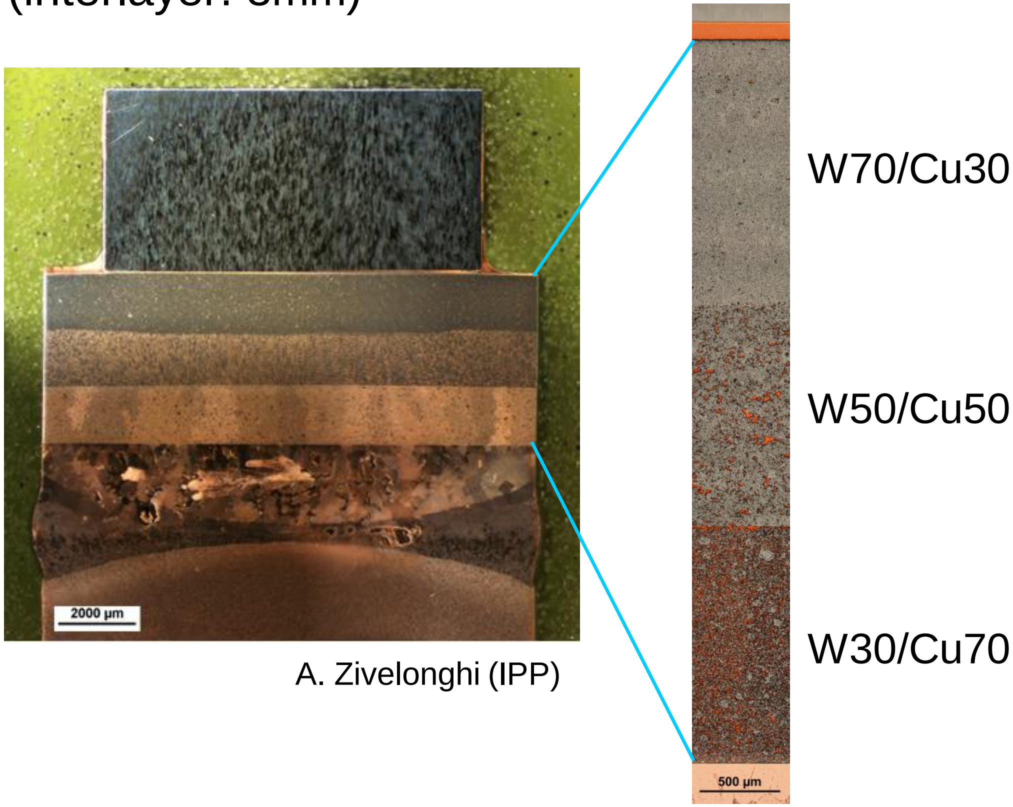
V. Paffenholz (IPP)

IR image during a HHF test

W/CuCrZr composite for graded heat sink

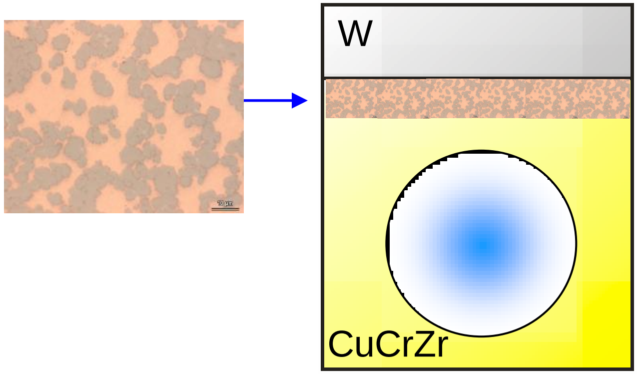
Test mock-up with graded interlayer

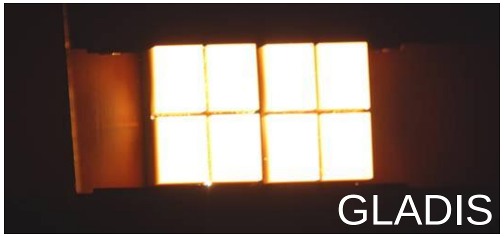
(interlayer: 3mm)



A. Zivelonghi (IPP)

High-heat-flux fatigue test

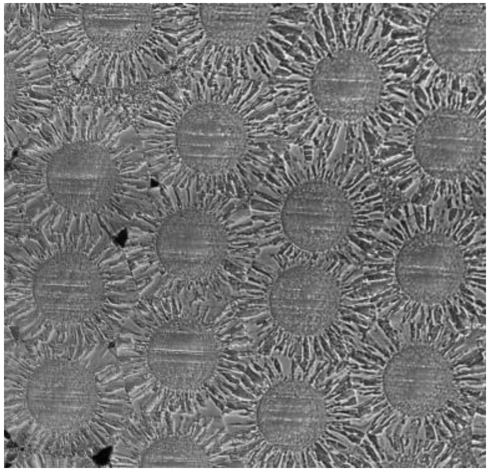




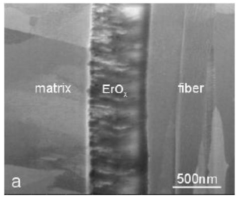
10 MW/m²: 100 cycles
15 MW/m², 10 cycles

W_f/W composite for toughening of armor

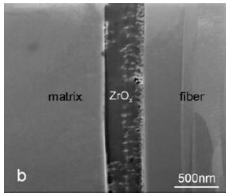
Microstructure / Interface



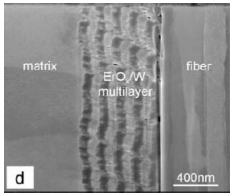
ErO_x



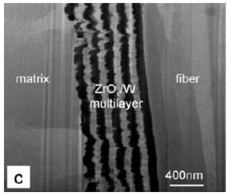
ZrO_x



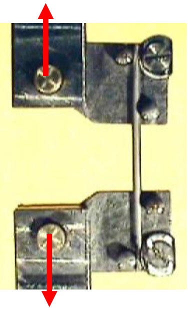
ErO_x/W

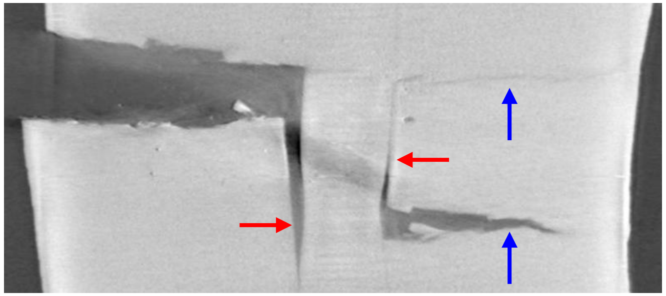


ZrO_x/W

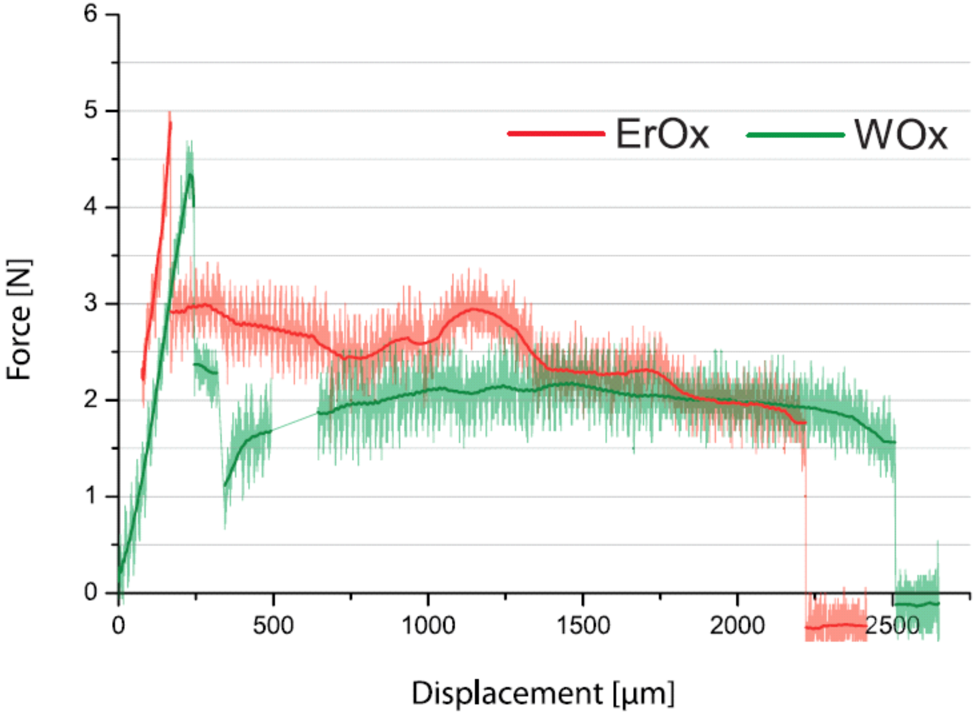


Bending test (single-fiber composite)





In-situ synchrotron tomography



Du, You, Composite Sci. Tech. (2010)

Riesch, You, Acta Mater. (2013)

Conclusions

Water-cooled target

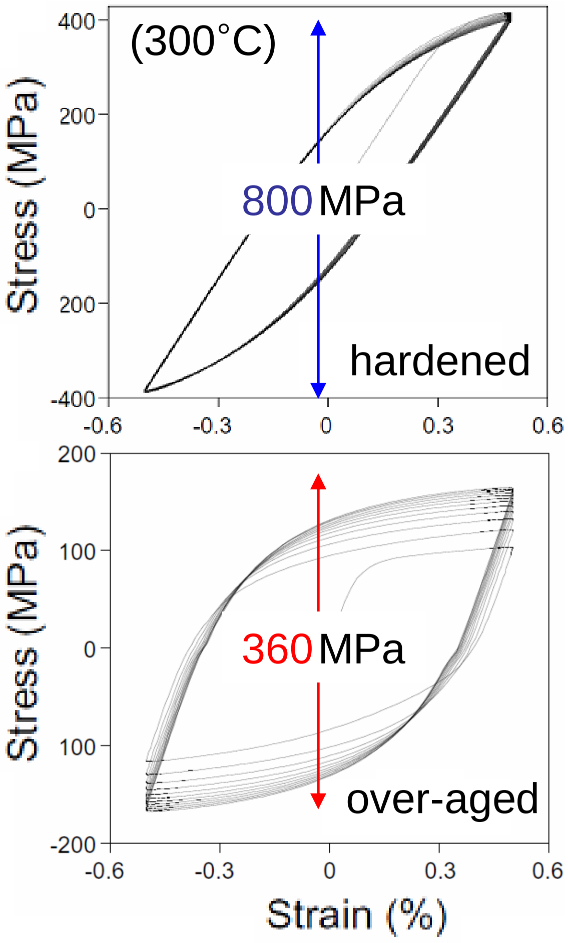
- Envisaged goal of power exhaust implies elevated operation temperature.
- This requires use of advanced materials (e.g. composites) as compulsory option.
- For novel materials, materials-design interface is a critical R&D element.

Helium-cooled target

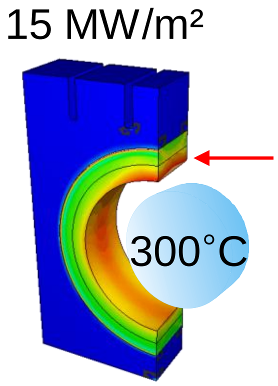
- Design studies (& tests) predict power exhaust capability of 5~10 MW/m^2.
- Tungsten Irradiation data, demanded for structural design, is still missing.
- Metallurgical issues (e.g. tough tungsten, joining) are the most critical engineering challenge.

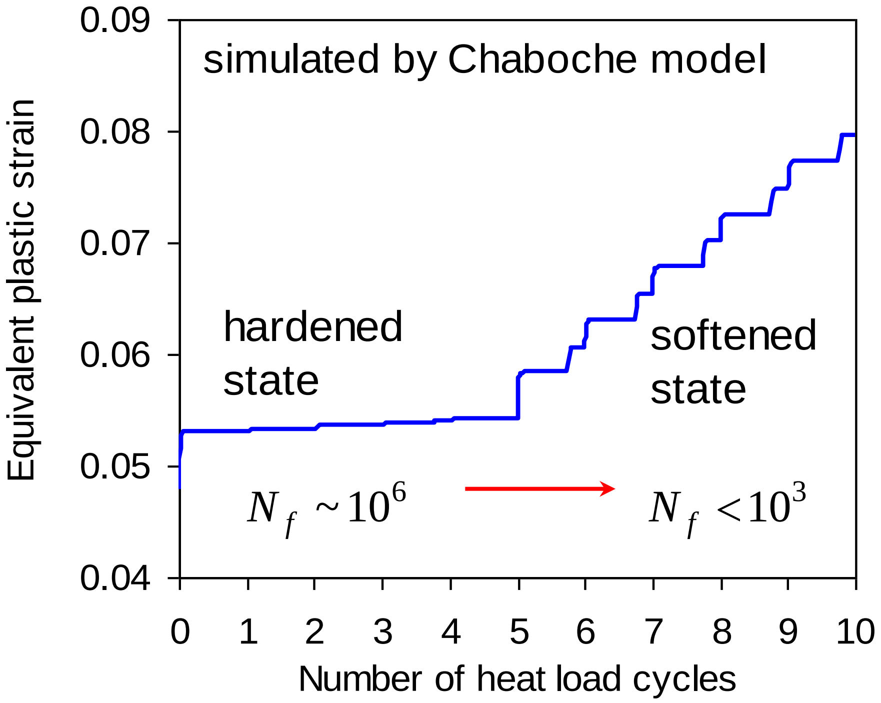
Plastic fatigue of heat sink tube

Softening of CuCrZr by over-ageing



Impact of softening on plastic fatigue (FEM)





JH You, M Miskiewicz, JNM (2008)

You, Miskiewicz, Fus. Eng. Des. (2008)