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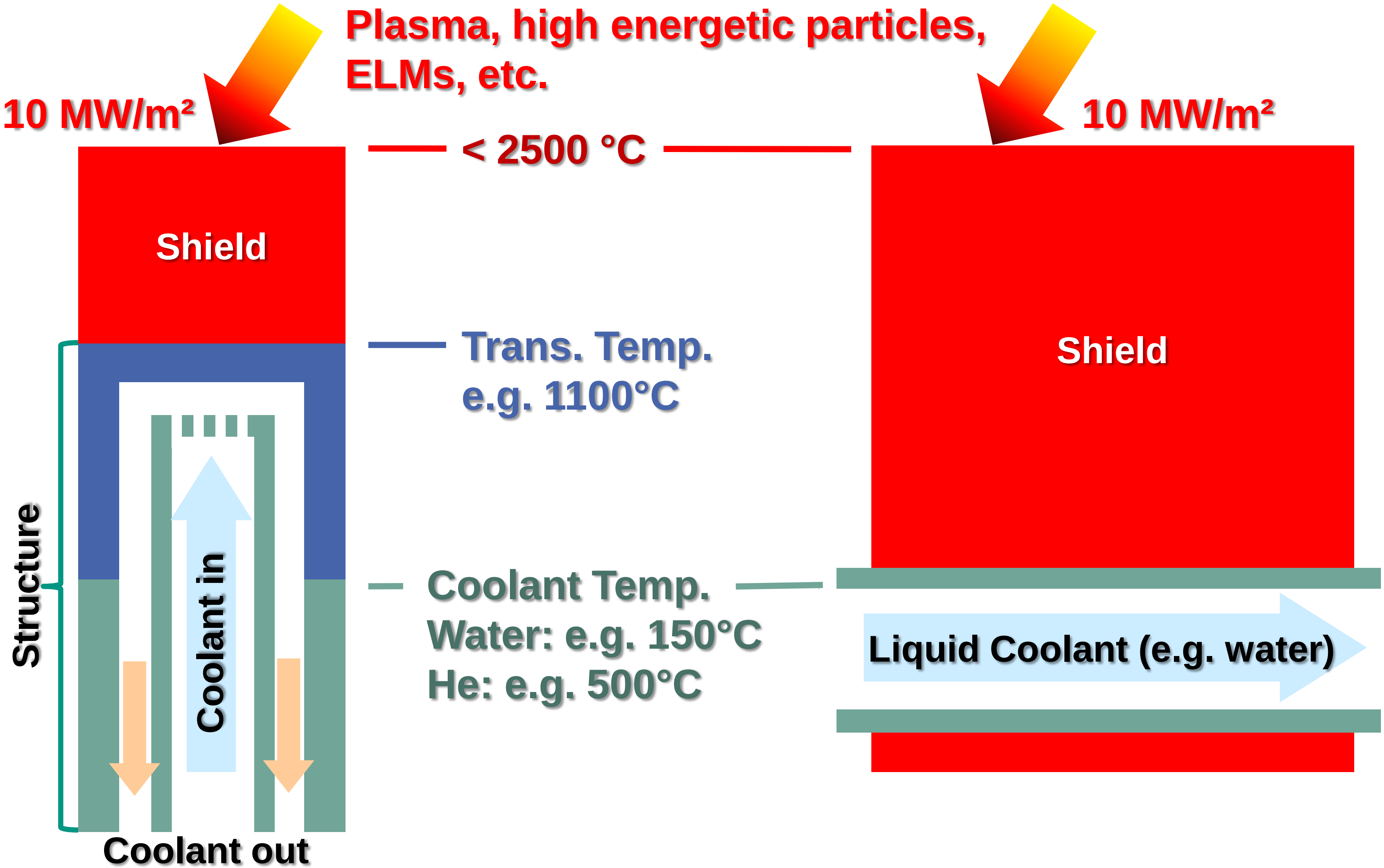
Divertor Concepts, Coolants, and Structural Materials

M. Rieth, P. Norajitra

FORSCHUNGSZENTRUM KARLSRUHE, INSTITUTE FOR MATERIALS RESEARCH

Divertor Concepts



Coolants & Structural Materials

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Coolants

- **Liquid Coolants**
  - Water
  - (Lead-)Lithium
- **Gas Coolant**
  - Helium

Structural Materials

- Copper (CuCrZr)
- Eurofer (9Cr1WVTa)
- Vanadium (V4Cr4Ti, …)
- SiC_f/SiC
- Tungsten (WTa, WV, …)
- other refractory alloys ?

Outline

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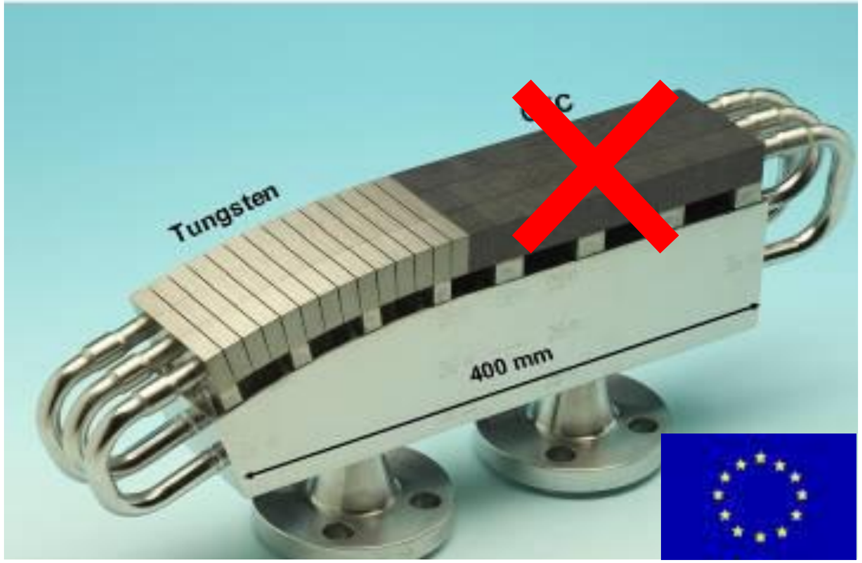
Discussion of existing divertor concepts

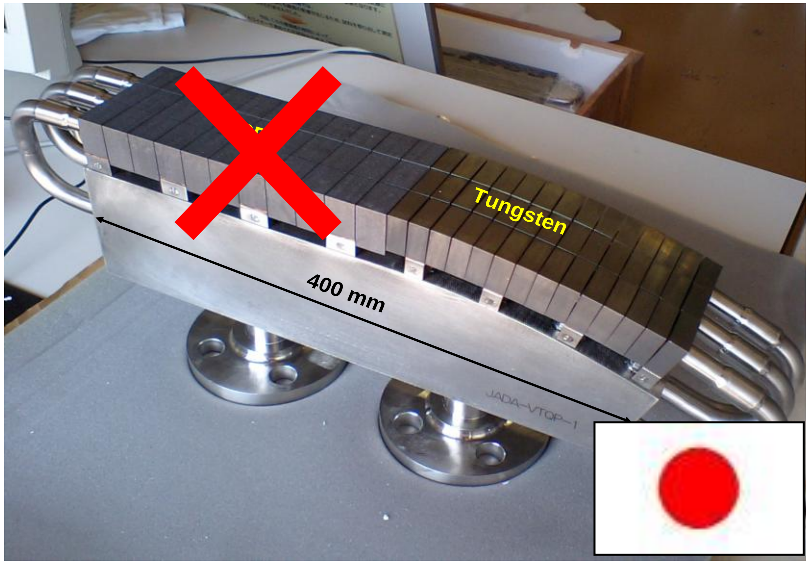
→ **Divertor Conceptual Designs for a Fusion Power Plant**
Fusion Engineering and Design 83 (2008) 893-902
P. Norajitra, S. I. Abdel-Khalik, L. M. Giancarli, T. Ihli, G. Janeschitz, S. Malang, I. V. Mazul, P. Sardin

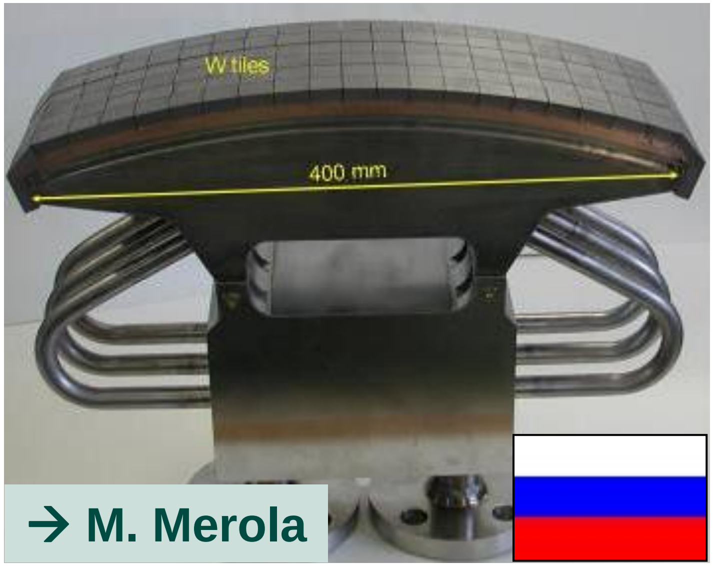
- ITER Concept (Cu + Water)
- ITER "Upgrade" (Steel + Water)
- "Russian Divertor" (Vanadium + Lithium)
- Silicon-Carbide Studies (SiC_f/SiC + Pb17Li)
- Helium Cooled Concepts (Tungsten + He)

He cooled divertor problematic (tungsten as structural material)

ITER Divertor Concept (Cu & H_2O)





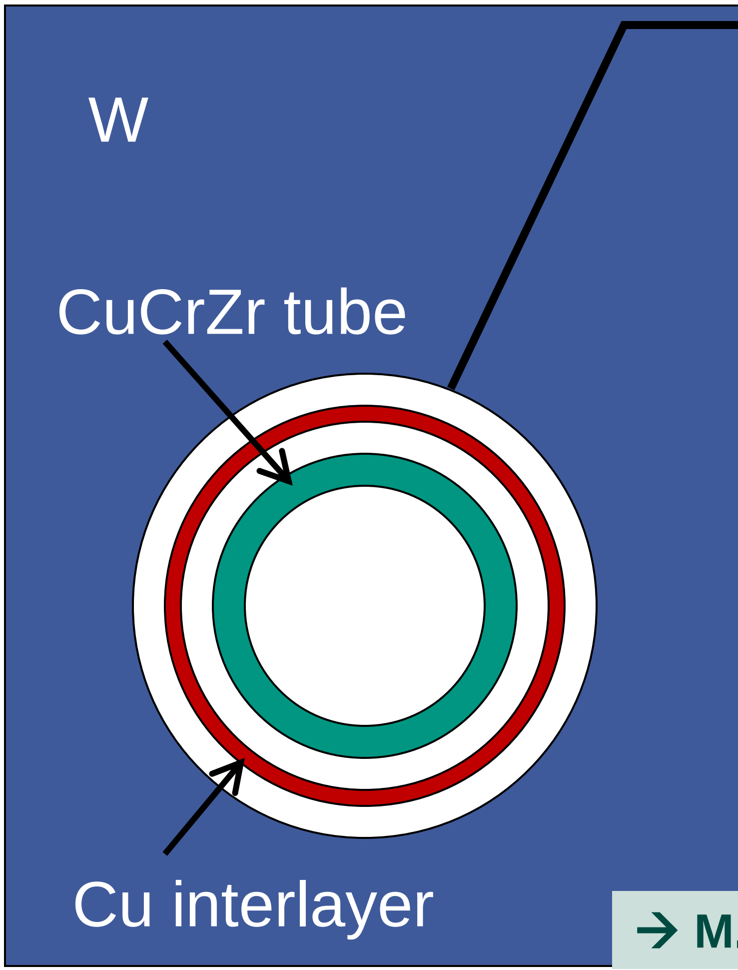


→ M. Merola

- tungsten monoblocks
- Cu interlayer
- CuCrZr heat sink
- 1000 cycles at 5 MW/m²

ITER Divertor Concept (Cu & H_2O)

Fabrication Technology



Hot Isostatic Pressing
Brazing
Hot Radial Pressing

→ **M. Merola, 2008**

ITER Divertor Concept (Cu & H_2O)

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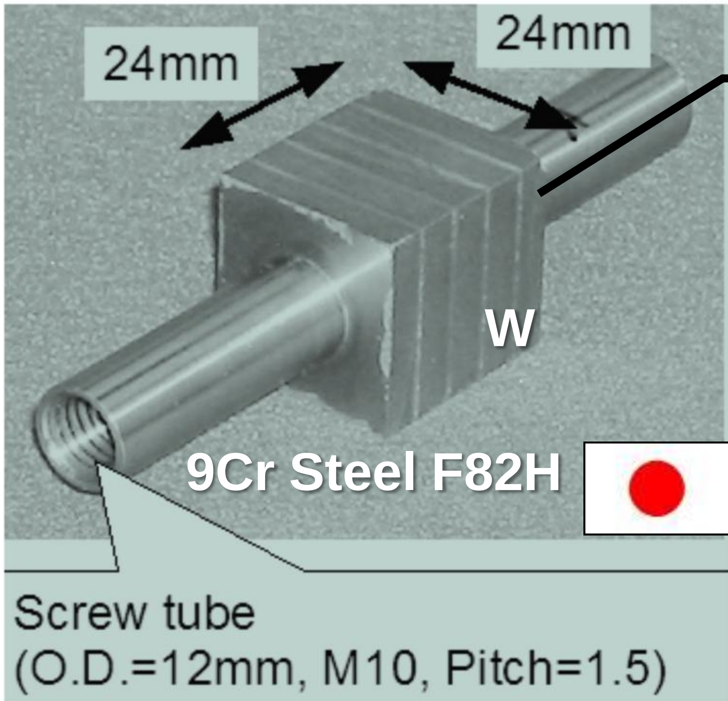
Advantages	Drawbacks
■ Fabrication processes available ■ Proof for 1000 cycles at 5 MW/m² with potential for 15 MW/m² or more ■ Cost effective	■ Cu is NOT applicable under DEMO conditions → T retention, embrittlement, swelling (~50 dpa !!!)

“Upgrade” of ITER Concept (Steel & H_2O)



- Hot Isostatic Pressing
- 970 °C @ 150 MPa
- Tempering 750 °C, 1.5 h

→ S. Suzuki, S. Konishi, 2008

→ B. N. Kolabasov, 2008

→ L. Giancarli et al., 2005

Drawbacks

- Mismatch between thermal expansion (Steel --- Tungsten)
- Irradiation damage on 9Cr Steel problematic (T_{op} = 100-300 °C)
- Feasibility not demonstrated yet (theor. 10-15 MW/m² by water cooling)

Vanadium & Liquid Lithium

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→ B. N. Kolabasov et al., 2008

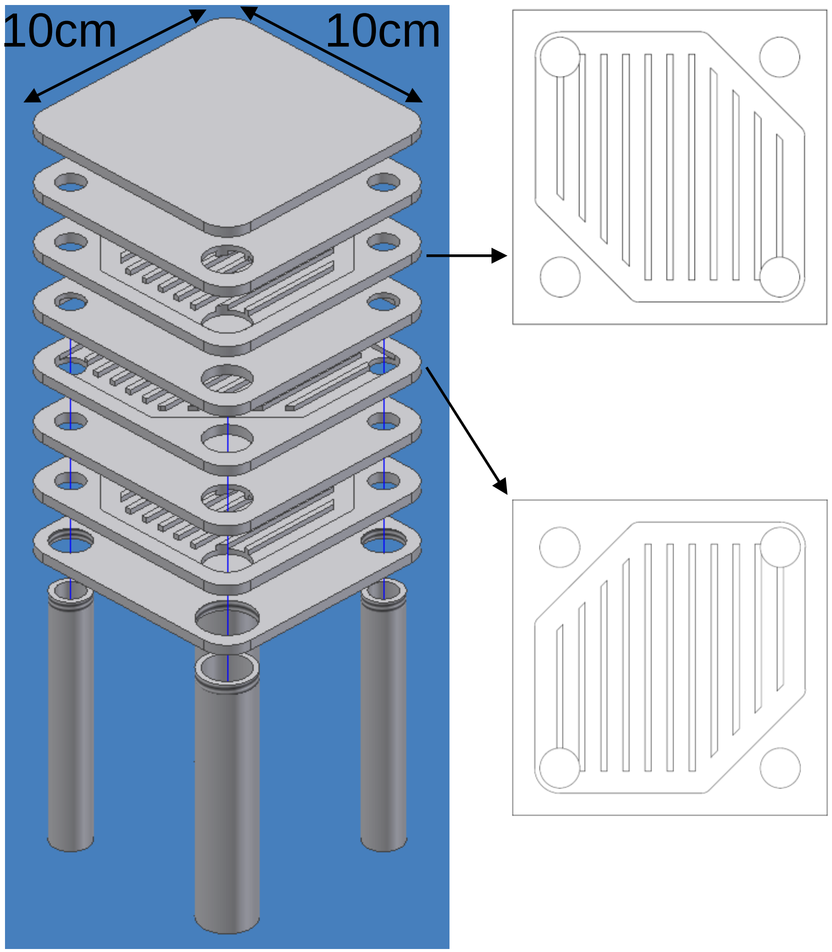
- V-4Cr-4Ti cooling channels
- Electr. insulation against MHD pressure loss
- Li inlet temperature 250 °C
- Li outlet temperature 300 °C
- Li flow velocity 5 m/s
- Heat flux ~10 MW/m^2

Drawbacks

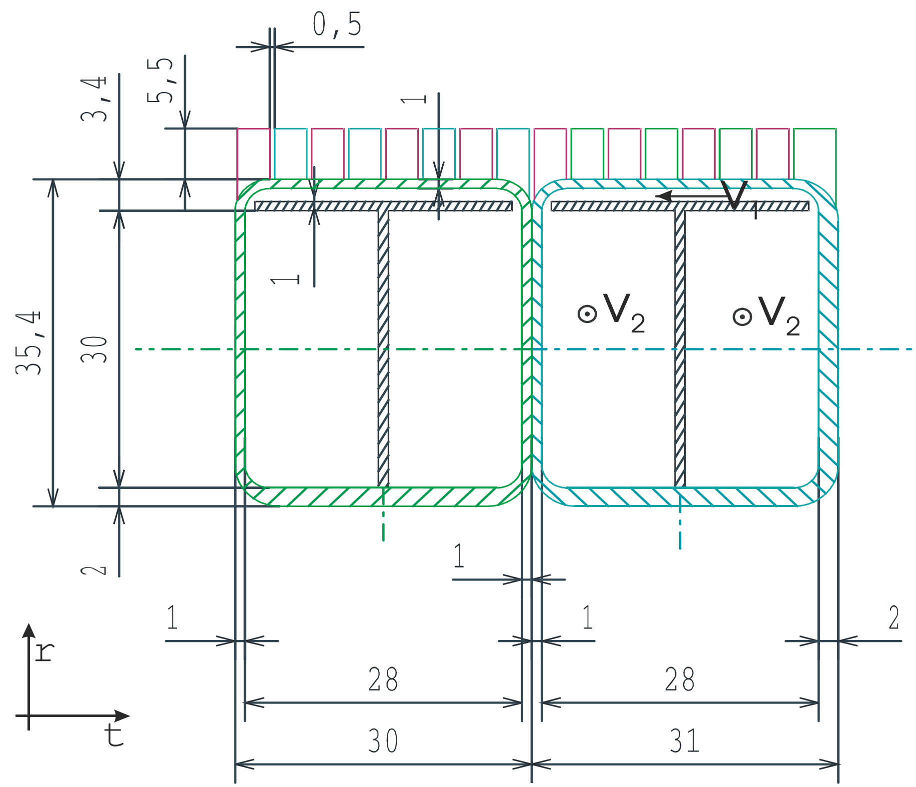
- V suffers from hydrogen / tritium embrittlement
- T retention
- Irradiation embrittlement below 500 °C
- Coating for Li ?!

SiC$_f$/SiC & Lead-Lithium

→ **K. Noborio, Y. Yamamoto, Y. Takeuchi, T. Hinoki, S. Konishi, 2008**



→ **A. Li Puma, L. Giancarli, H. Golfier, Y. Poitevin, J. Szczepanski, 2003**



SiC_f/SiC & Lead-Lithium

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Theory

- Heat flux max. 5 MW/m²
- Inlet temperature 600 °C
- Flow velocity 1-1.5 m/s

Drawbacks

- Loss of thermal conductivity under irradiation
- Helium transmutation 5-10 times higher than in steel
- Open fabrication/joining issues

Tungsten & Helium, 5 MW/m² Concepts

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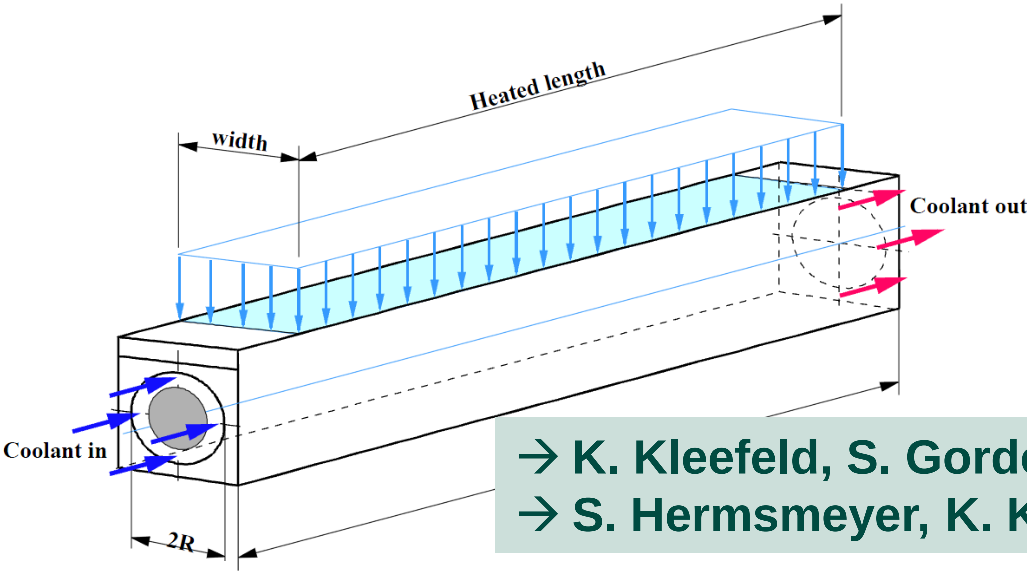
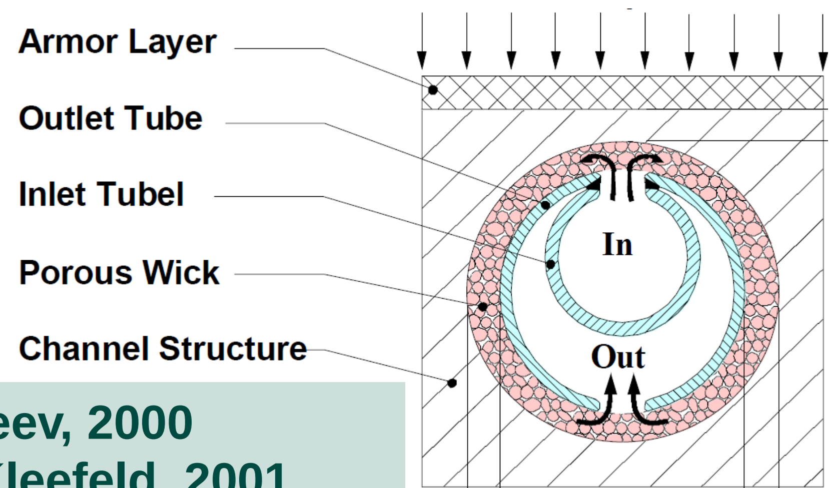
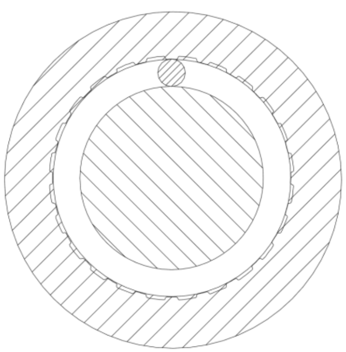
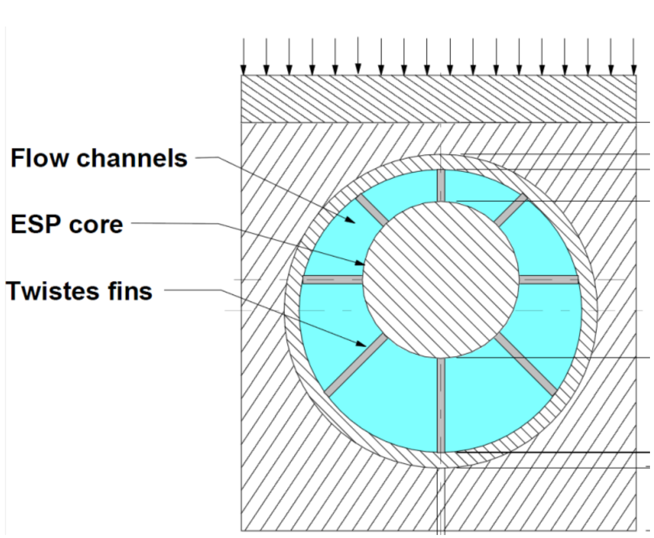
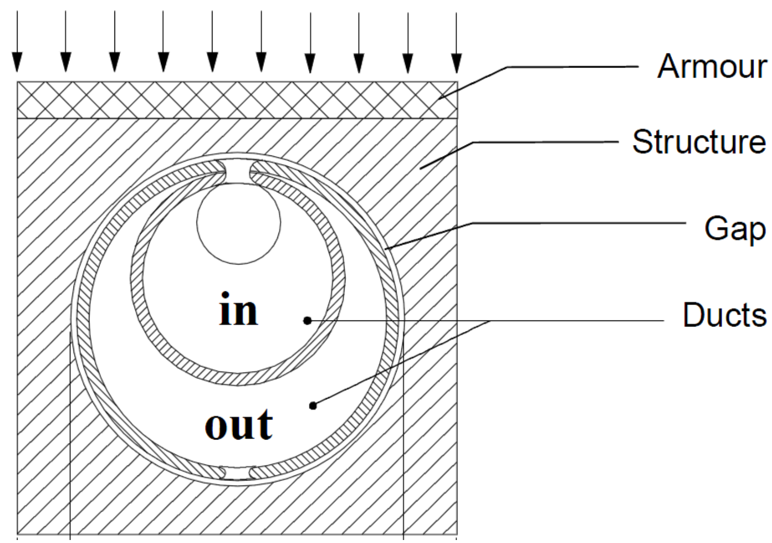




→ K. Kleefeld, S. Gordeev, 2000
→ S. Hermsmeyer, K. Kleefeld, 2001







Tungsten & Helium, 10 MW/m² Concepts

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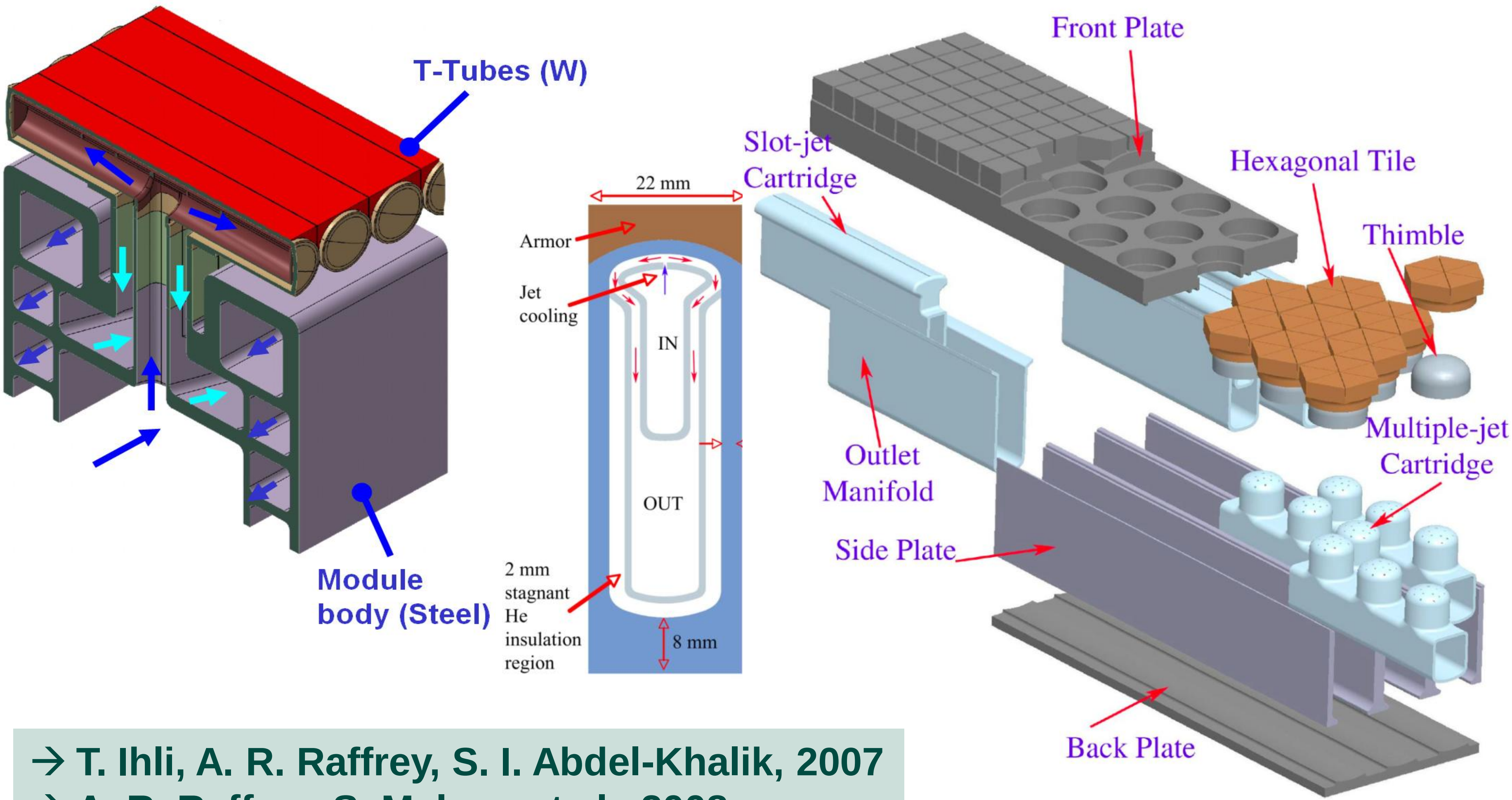
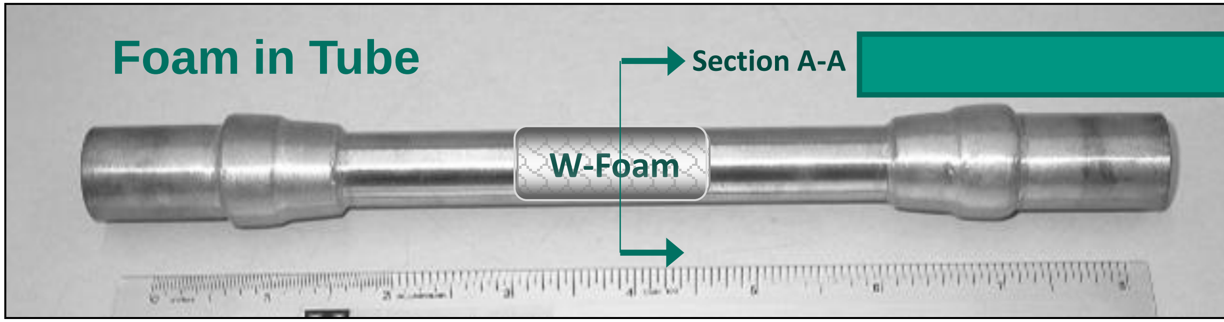
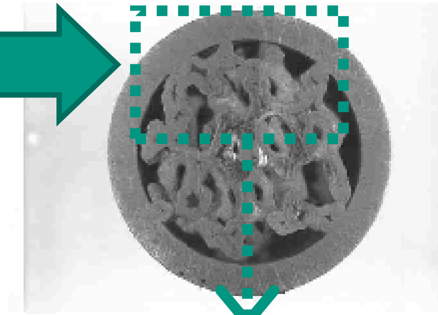
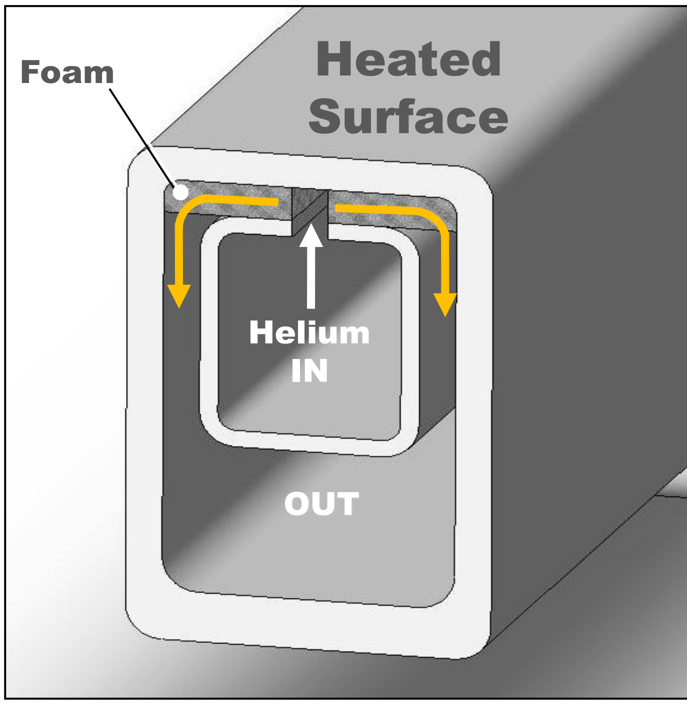


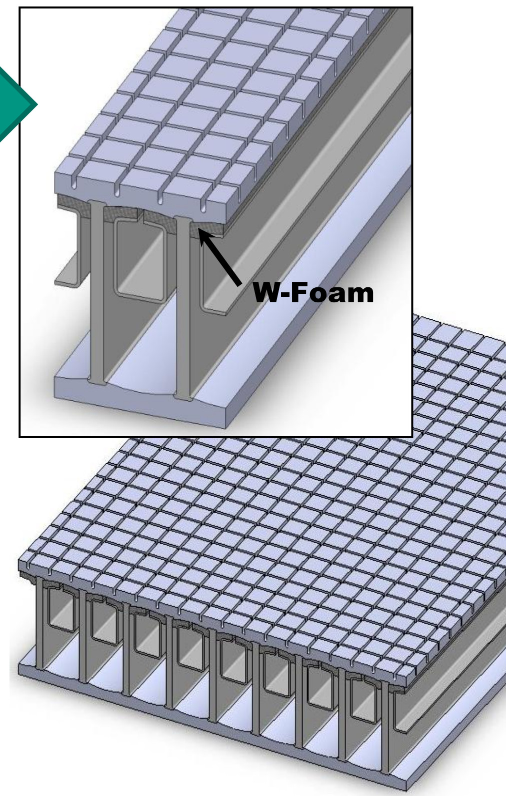
→ T. Ihli, A. R. Raffrey, S. I. Abdel-Khalik, 2007
→ A. R. Raffrey, S. Malang et al., 2008

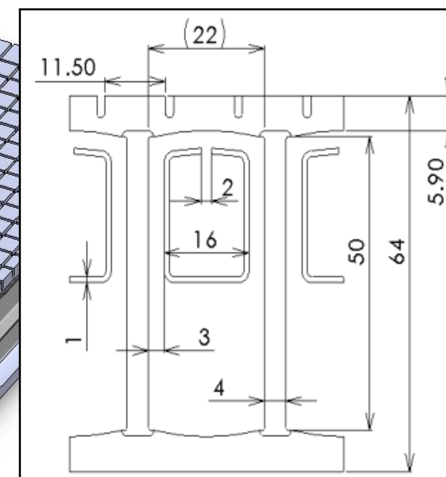
Tungsten & Helium, 10 MW/m² Concepts





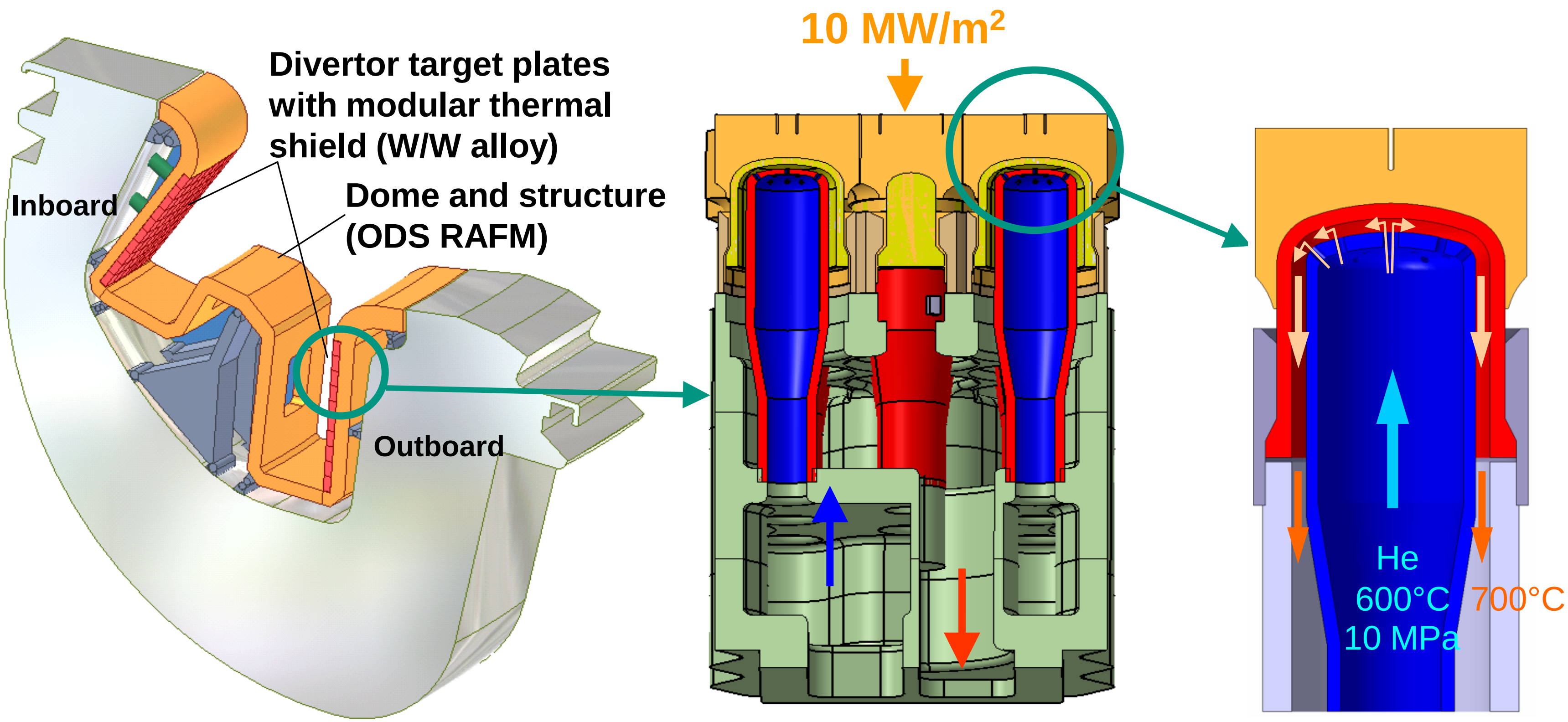






→ S. Sharafat et al., 2005-2009

Tungsten & Helium, 10 MW/m² Concepts



Divertor Cassette

9-Finger Module

Finger

→ **P. Norajitra et al., 2002-2009**

Tungsten & Helium

Facts

- Heat flux 5-10 MW/m^2
- Various concepts available (proof for finger module)
- Flexible operation temperatures

Drawbacks

- Brittleness (fracture behaviour) of tungsten (even without irradiation)
- Unsolved fabrication issues (e.g. brazing for irrad. conditions)

Evaluation of Divertor Concepts

- ~~Copper (CuCrZr)~~ → **Irradiation**
- ~~Low Activation Steel (Eurofer)~~ → **Compatibility, …**
- ~~Vanadium (V-4Cr-4Ti, …)~~ → **H/T, …**
- ~~SiC_f/SiC~~ → **Irradiation, …**
- ~~Tungsten (W, WL10, …)~~ → **Brittleness, …**

Ranking of Divertor Concepts

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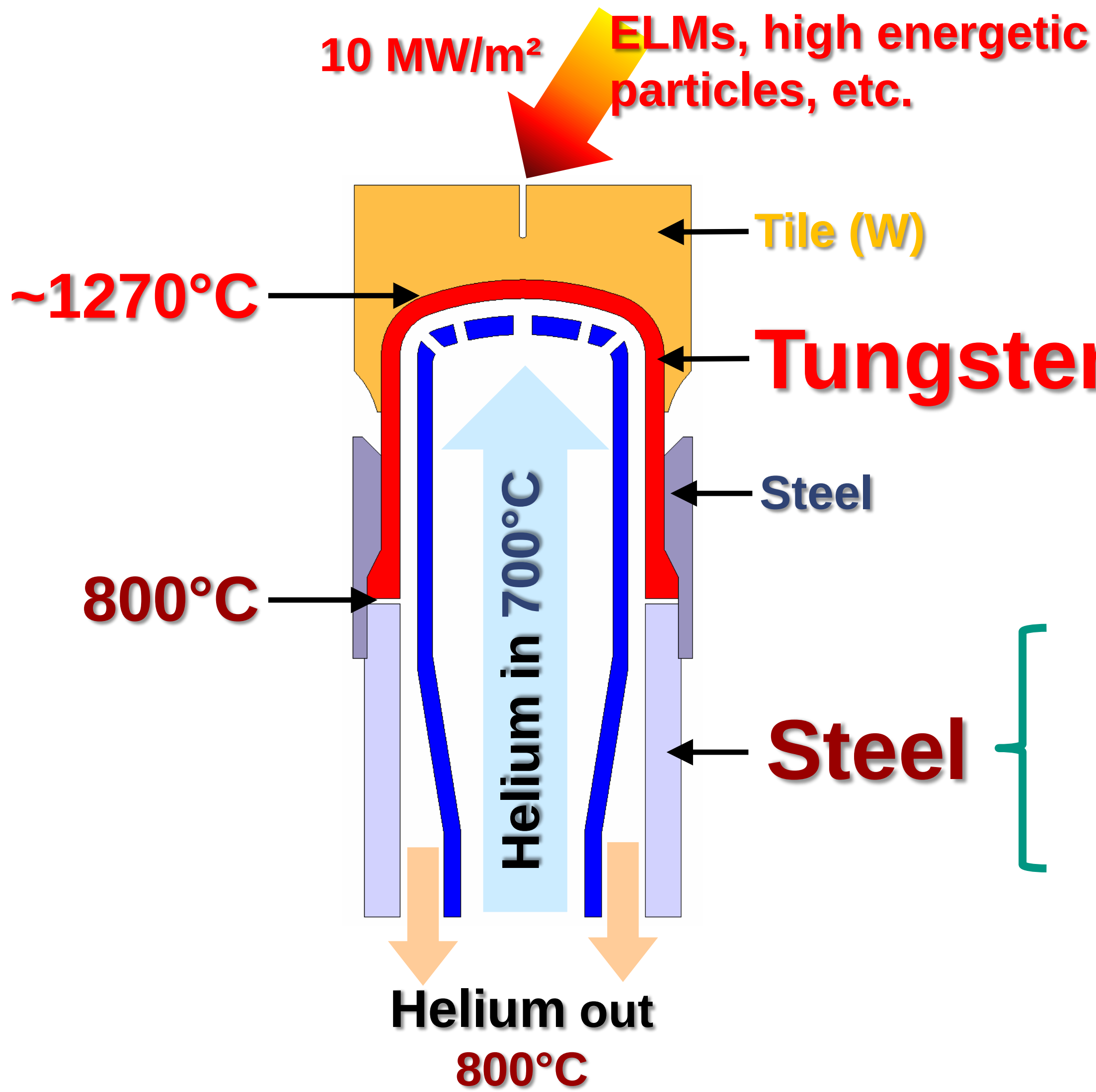
Feasibility (even for reduced heat flux of 5 MW/m²)

- Copper (CuCrZr) **no go!**
- Vanadium (V-4Cr-4Ti, …) **no go!**
- Low Activation Steel (Eurofer) **not likely!?**
  → **coolant? concept? …**
- SiC_f/SiC **not yet!** → **long-term option, R&D needed**
- Tungsten (W, WL10, …) **not yet! ever?**
  → **without solution for ductility problem there will be no tungsten divertor!**

He Cooled Divertor Problematic



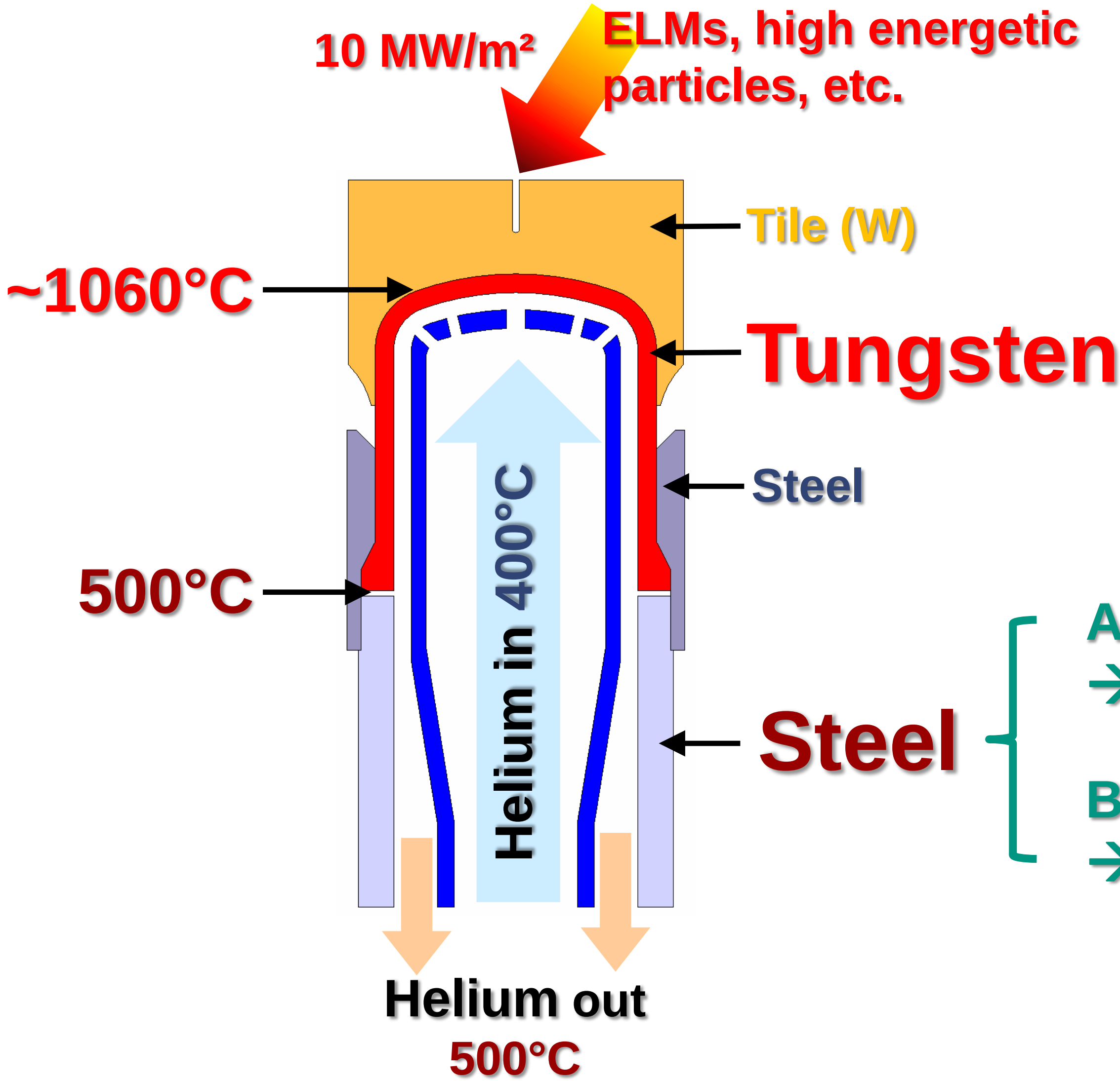
Recrystallization
→ T_{op}<1300 °C ! ✓

Brittle Fracture
→ T_{op}>800 °C (???)

Aging, Creep
→ T_{op}<550 °C !

Brittle Fracture
→ T_{op}>350-400 °C ! ✓

He Cooled Divertor Problematic



Tungsten:

- Recrystallization → T_{op}<1300 °C ! ✓
- Brittle Fracture → T_{op}>800 °C (???)

Steel:

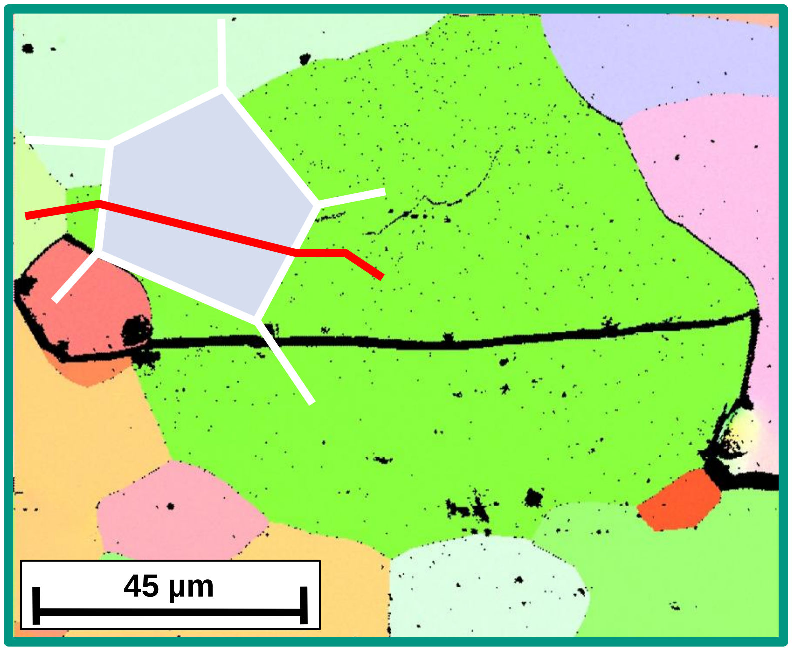
- Aging, Creep → T_{op}<550 °C ! ✓
- Brittle Fracture → T_{op}>350-400 °C ! ✓

Tungsten Problematic

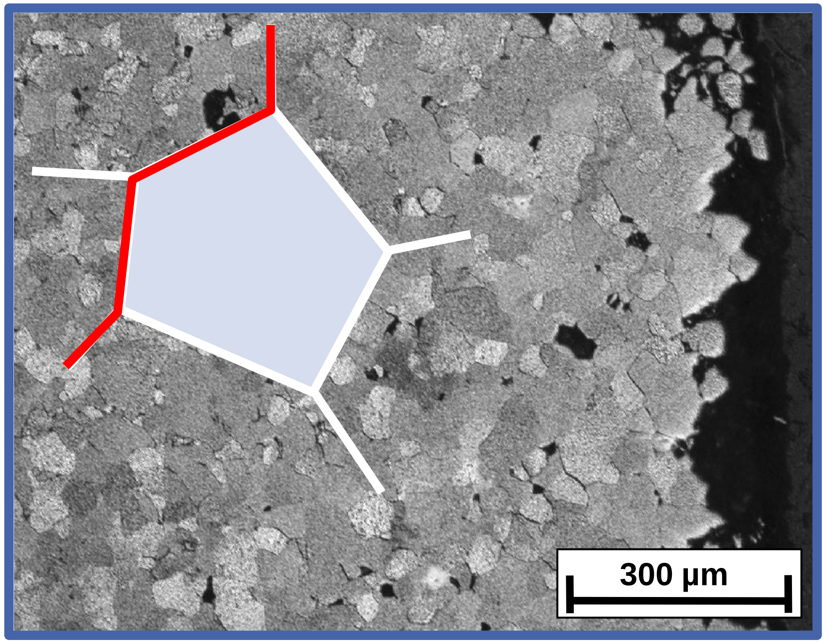
Question: **Is tungsten a brittle material?**

Answer: **No! Tungsten is even more brittle!**

Trans-Crystalline



Inter-Crystalline

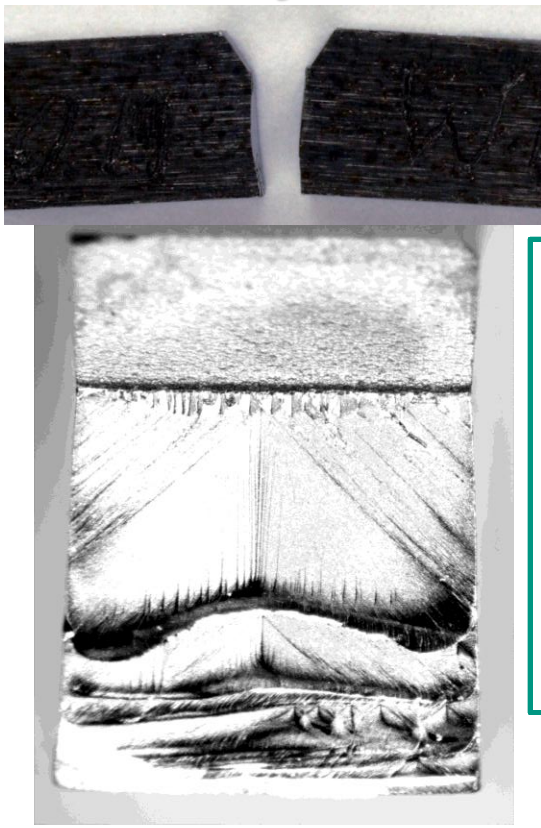


→ **R. Pippan et al., ÖAW**

Tungsten Problematic

Inter-crystalline fracture needs less energy than trans-crystalline!

Trans-Crystalline

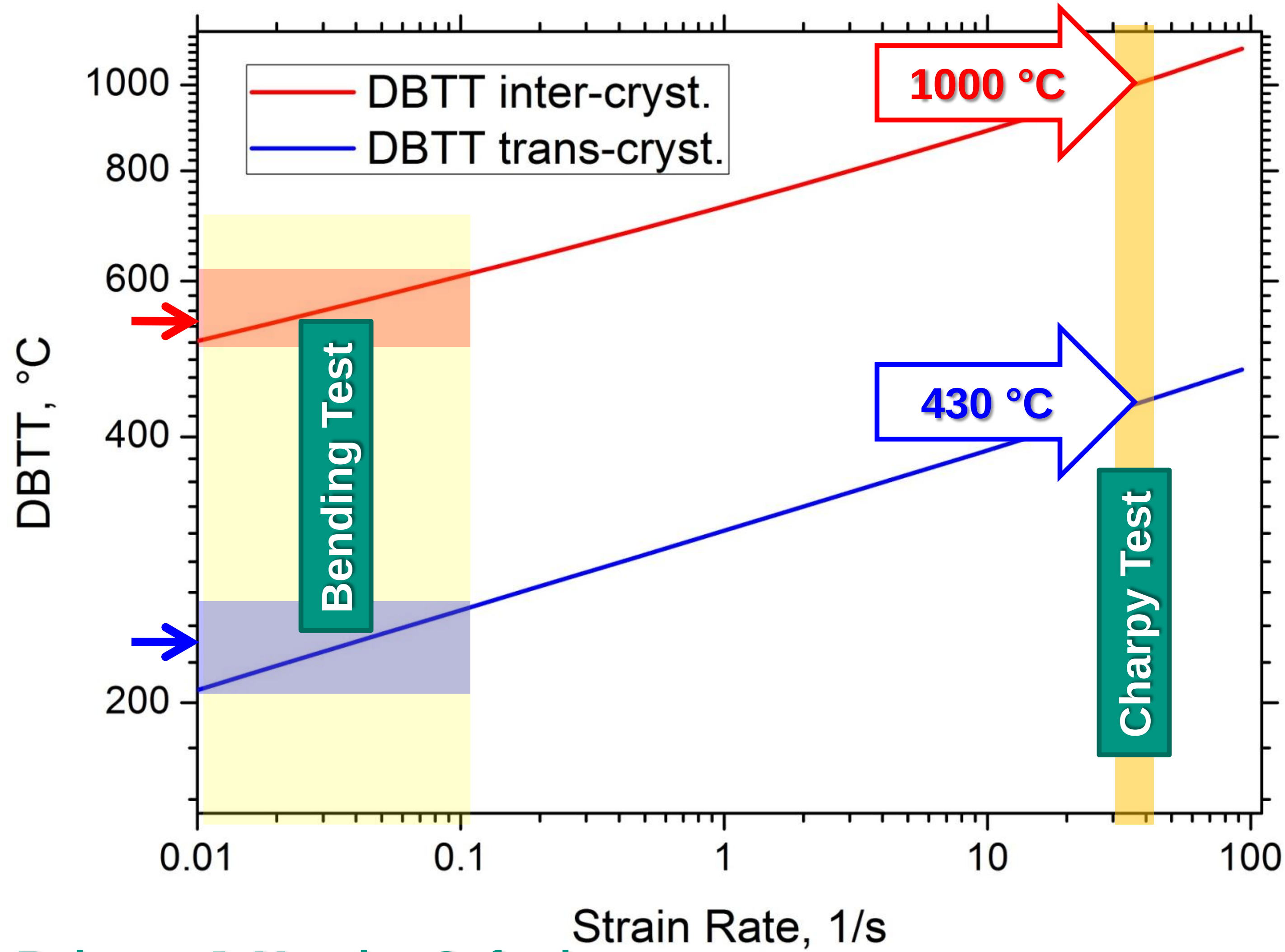


Single-Crystal

Inter-Crystalline

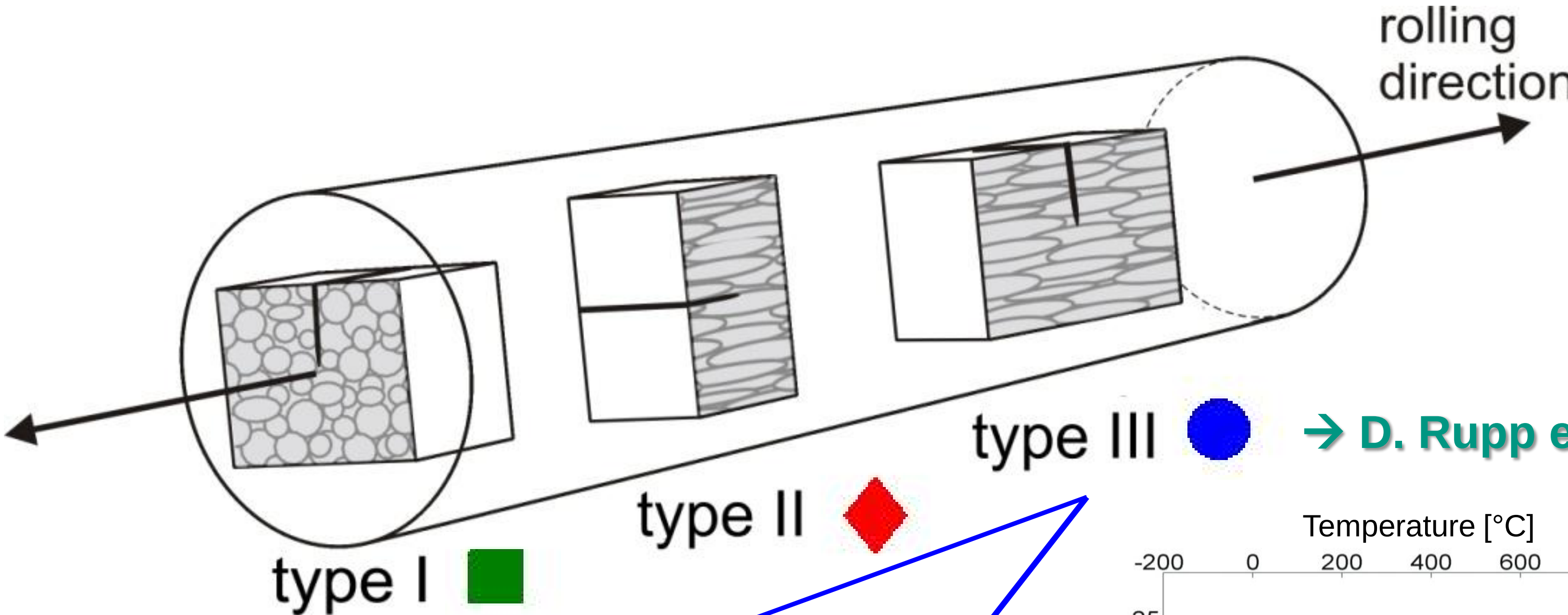
Re-crystallized
Poly-Crystal

DBTT is Strain-Rate Dependent

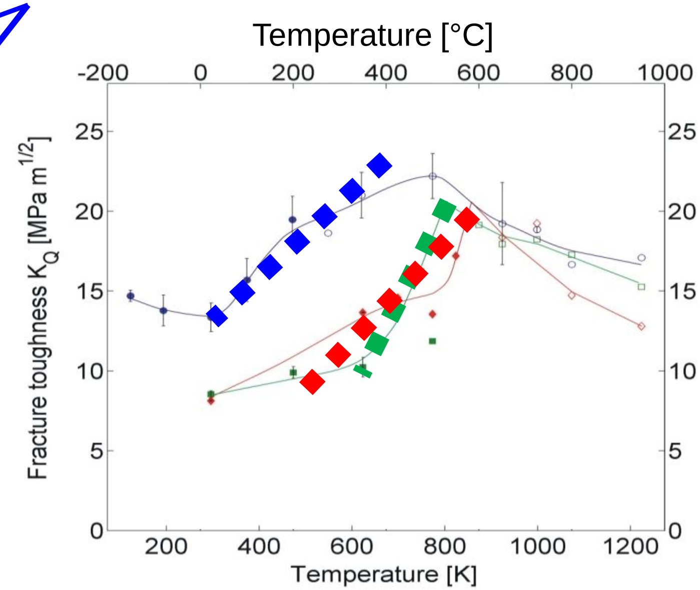


→ **S. Roberts, J. Murphy, Oxford**

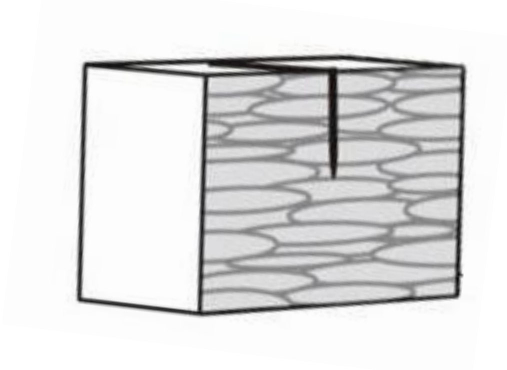
Influence of the Grain Shape

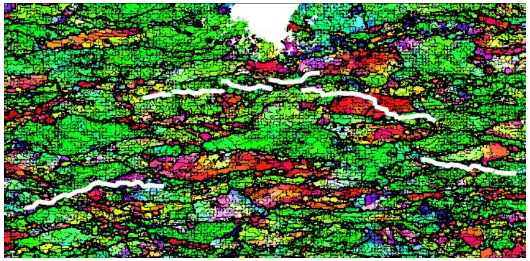


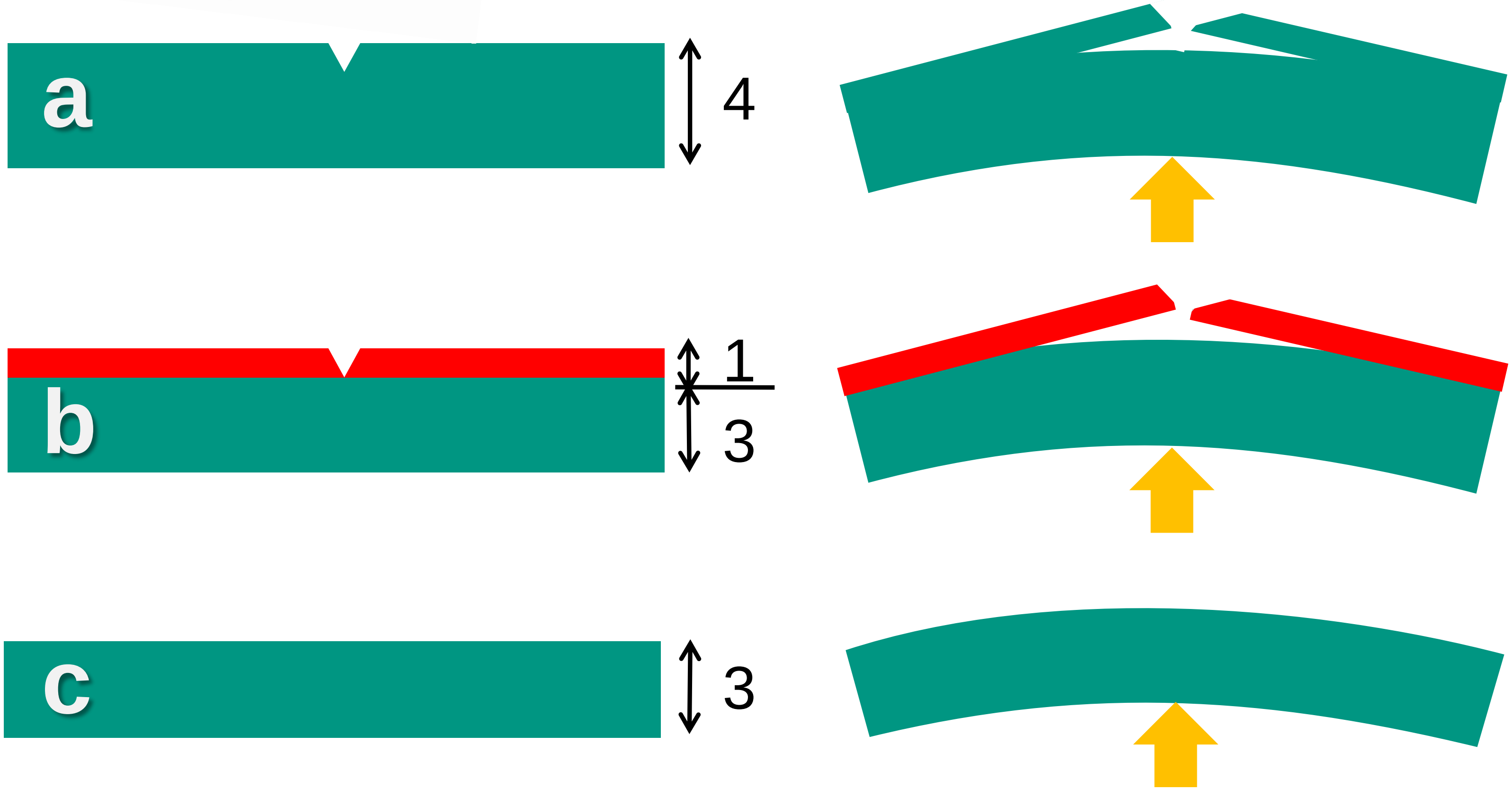
→ D. Rupp et al., FZK



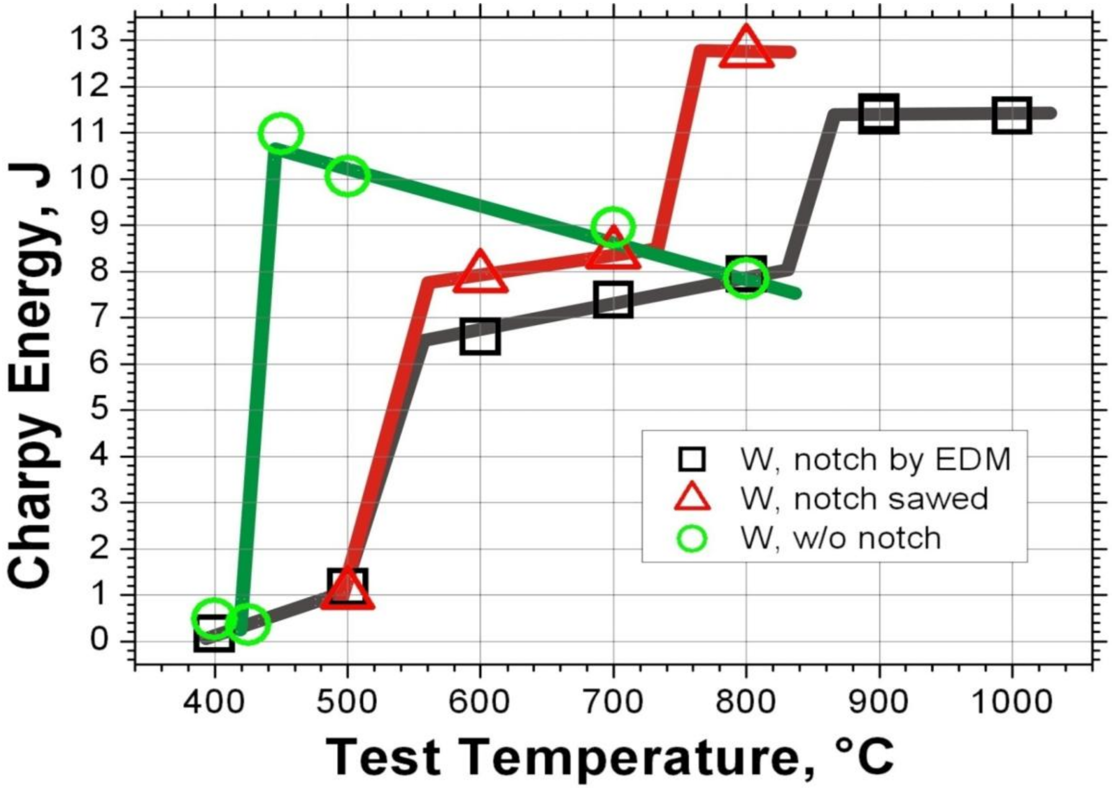
Notches Influence Grain Boundary Fracture



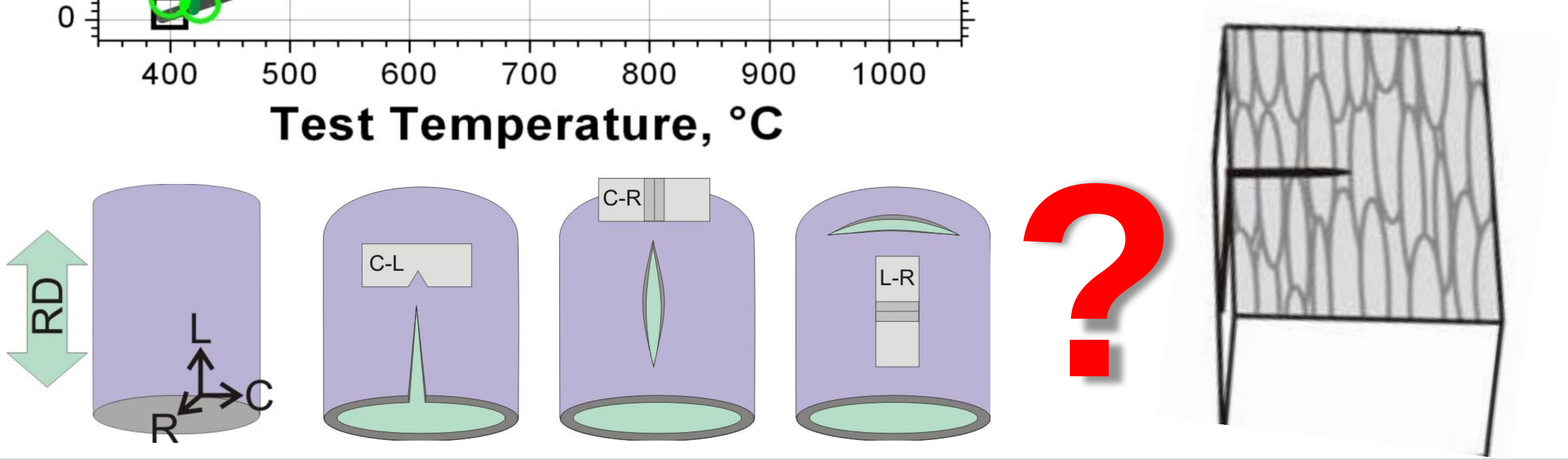




Fracture Behaviour of Tungsten



→ J. Reiser et al., FZK



Summary

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There is no feasible divertor concept (yet)

- No match between materials and required properties (ductility, thermal conductivity, recrystallization temperature, strength, compatibility, etc.)
- Not even a basic concept with reduced capabilities (change boundary conditions, reduced heat flux, …)

There is no structural divertor material (yet)

- Eurofer (heat conductivity, thermal expansion, 550°C limit, …)
- SiC_f/SiC (irradiation defects, joining, 5 MW/m² limit, …)
- Tungsten (ductility/irradiation, fabrication of simple structures)

Alternatives/Outlook

- Tungsten alloys, nanostructured and composite materials → ongoing
- Replacement by molybdenum → high activation!!!
- Liquid wall divertors or something completely different???