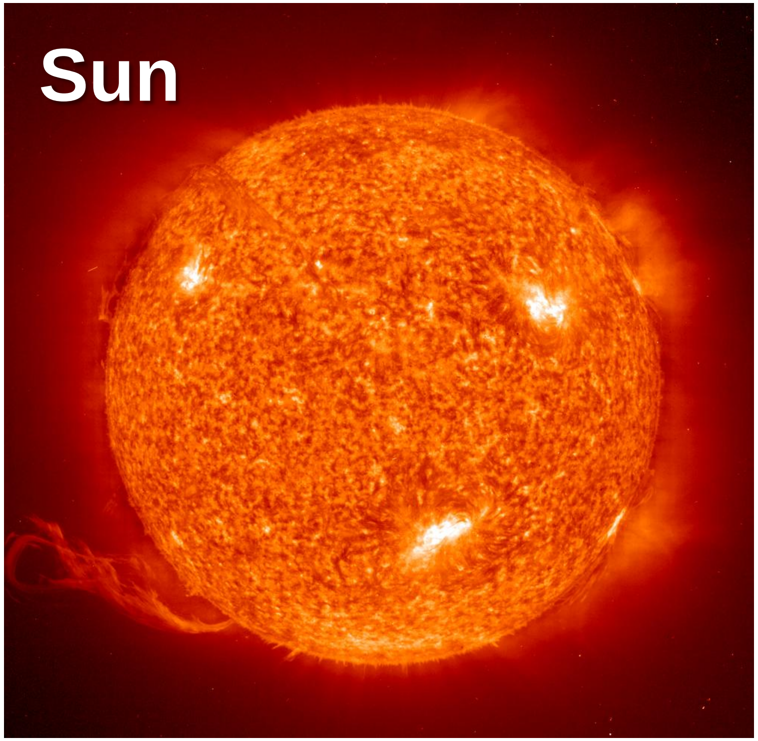
Tungsten as a structural material for nuclear fusion reactors

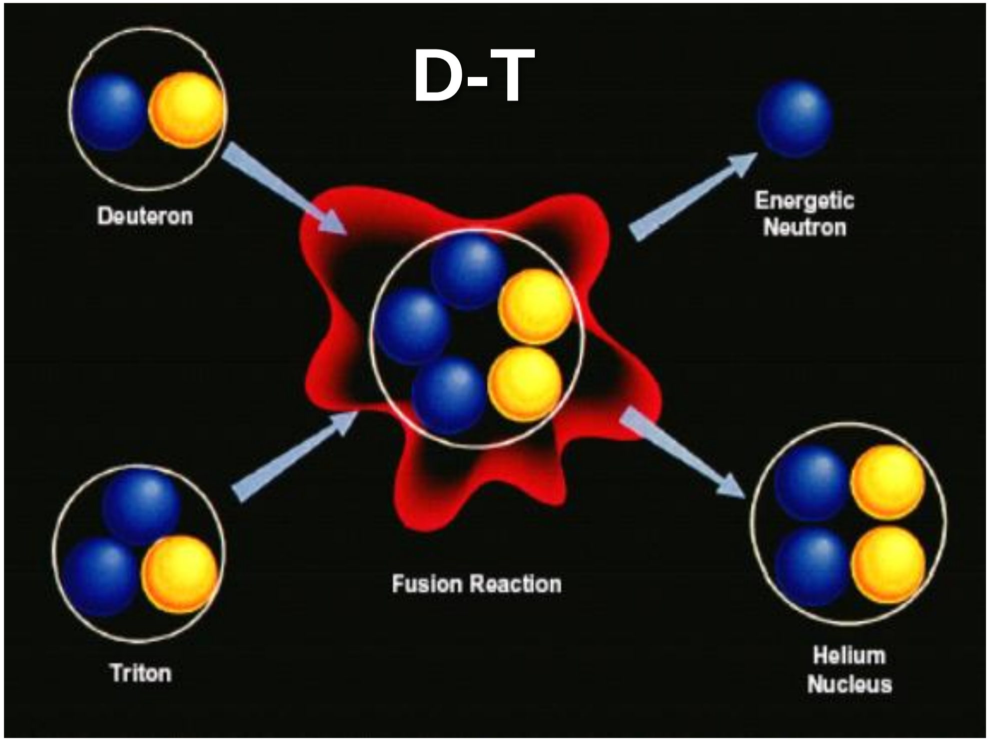
Michael Rieth

KARLSRUHE INSTITUE OF TECHNOLOGY, INSTITUTE FOR MATERIALS RESEARCH

Contents

Nuclear Fusion



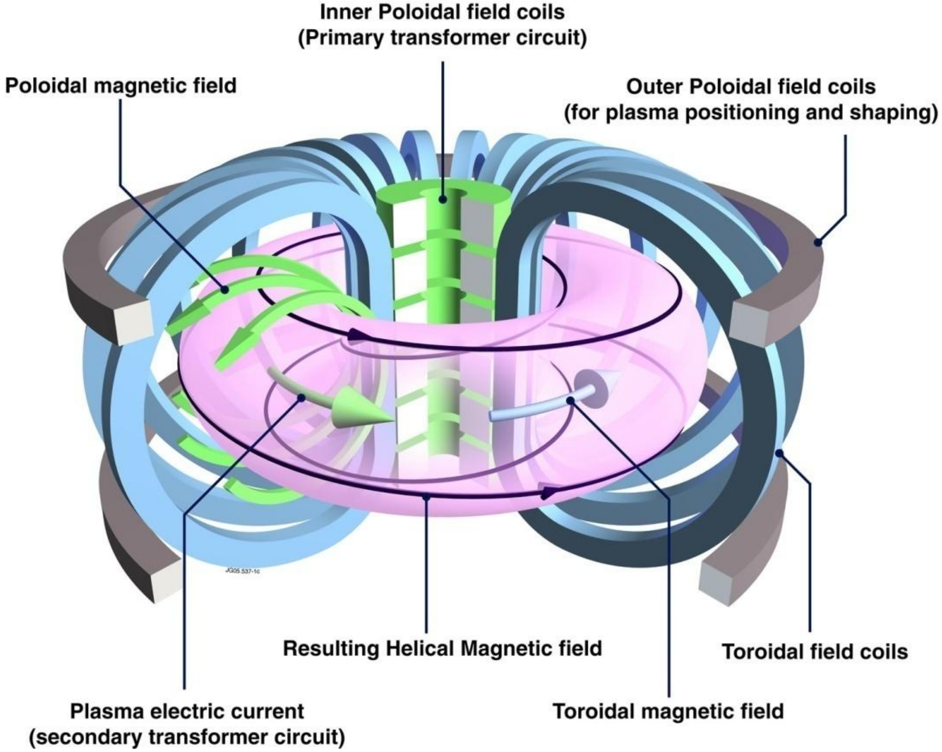


T = 15 Mio. °C
E_t = 3.7 x 10^{17} GW
→ ρ_E = 30 W / m³

E_t ~ 3.5 GW
ρ_E ~ 4 MW / m³
→T = 150 Mio. °C

Magnetic Confinement

Tokamak



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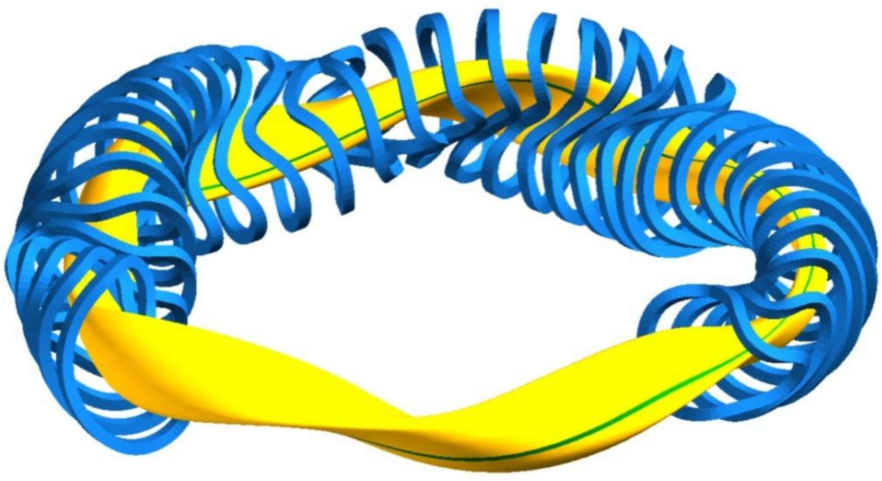
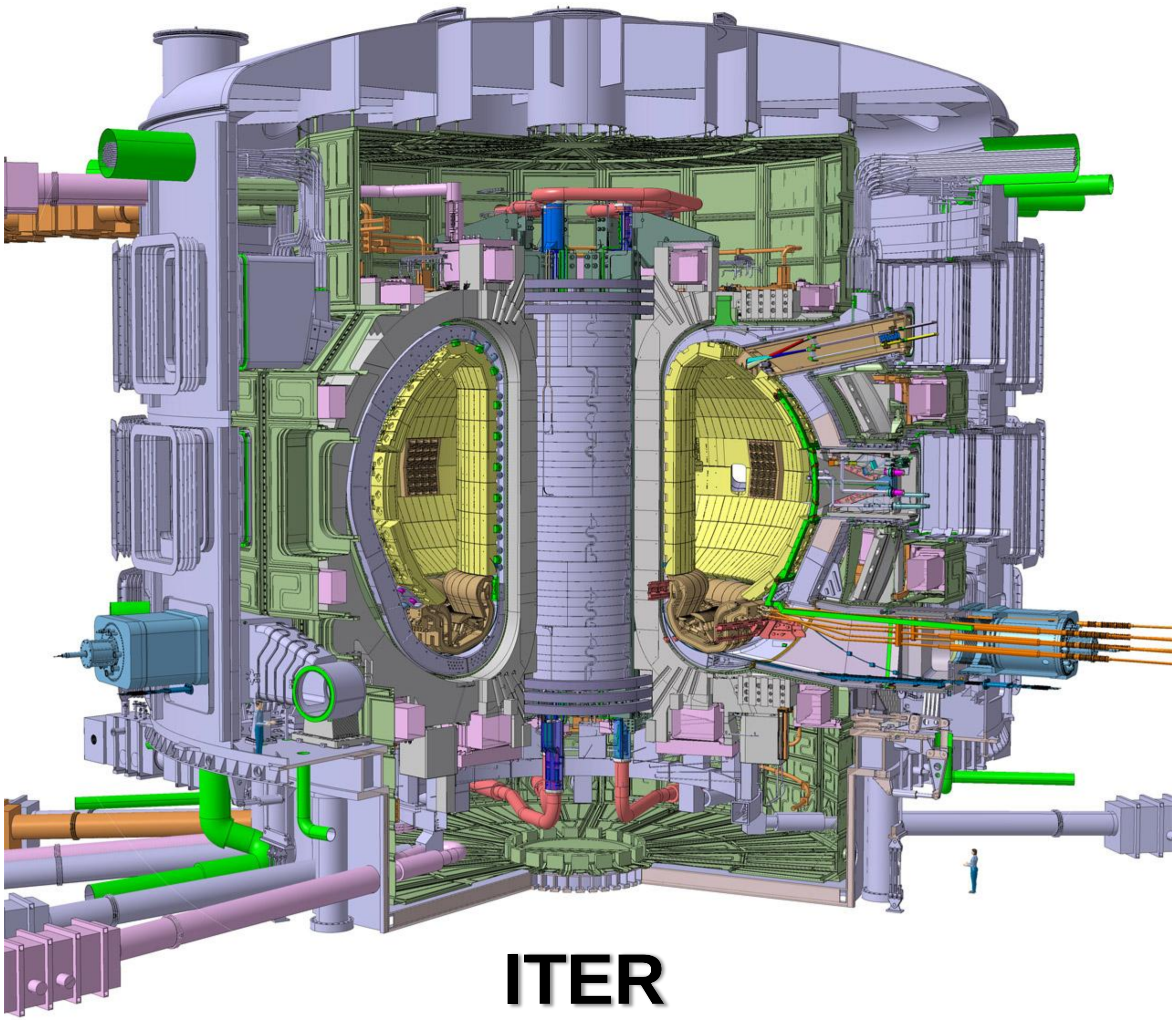


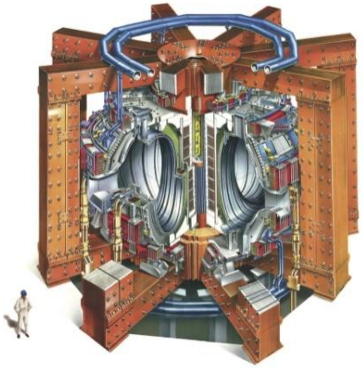
Research TOKAMAKs

Nuclear fusion is relatively easy to accomplish. The trick is to gain energy out of it!



ITER

JET



Where is the challenge?

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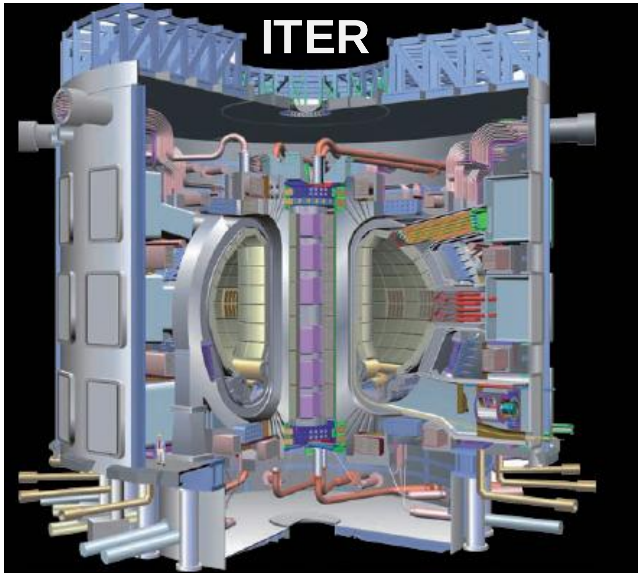
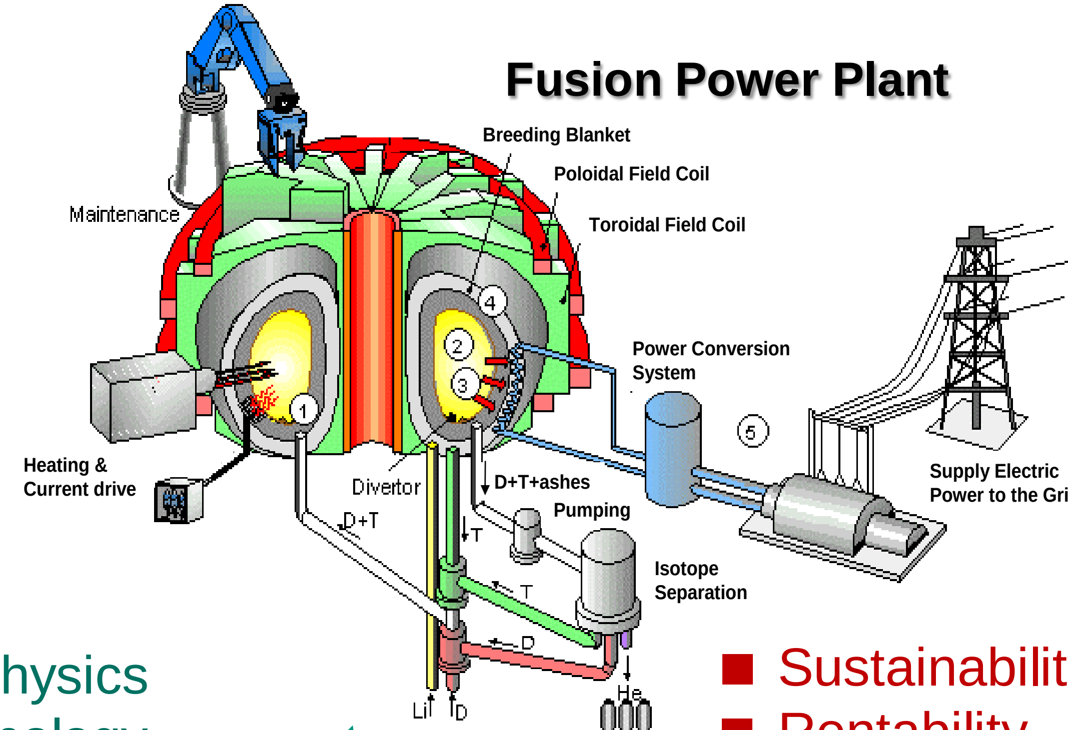


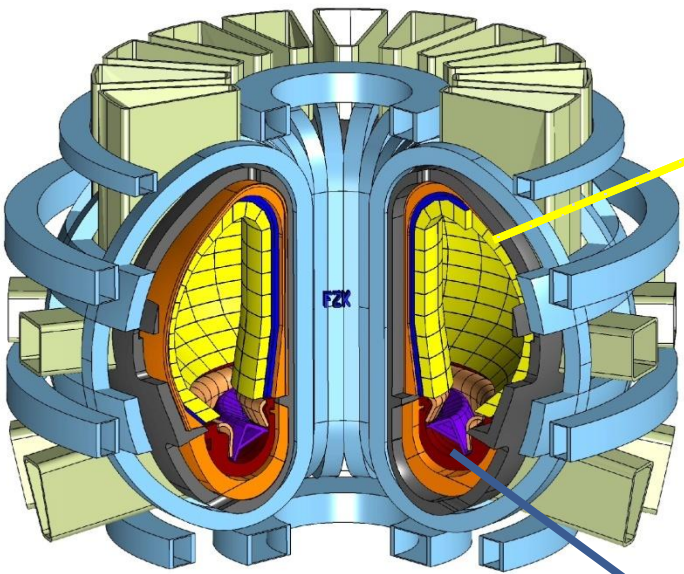


- Test device for plasma physics
- Safety → Standard technology

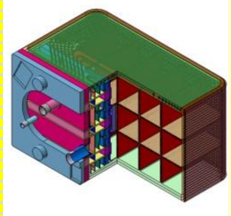
- Sustainability
- Rentability
- Safety
- Economy

complex superposition of intensive neutron/heat radiation and thermo-mechanical load/fatigue

High Heat Flux Components



DEMO



Blanket: ≤150 dpa/5 years, 2.5 MW/m^2

Reduced activation ferritic-martensitic steels

- EUROFER (9Cr-WVTa) 350-550 °C
- EUROFER-ODS 350-650 °C

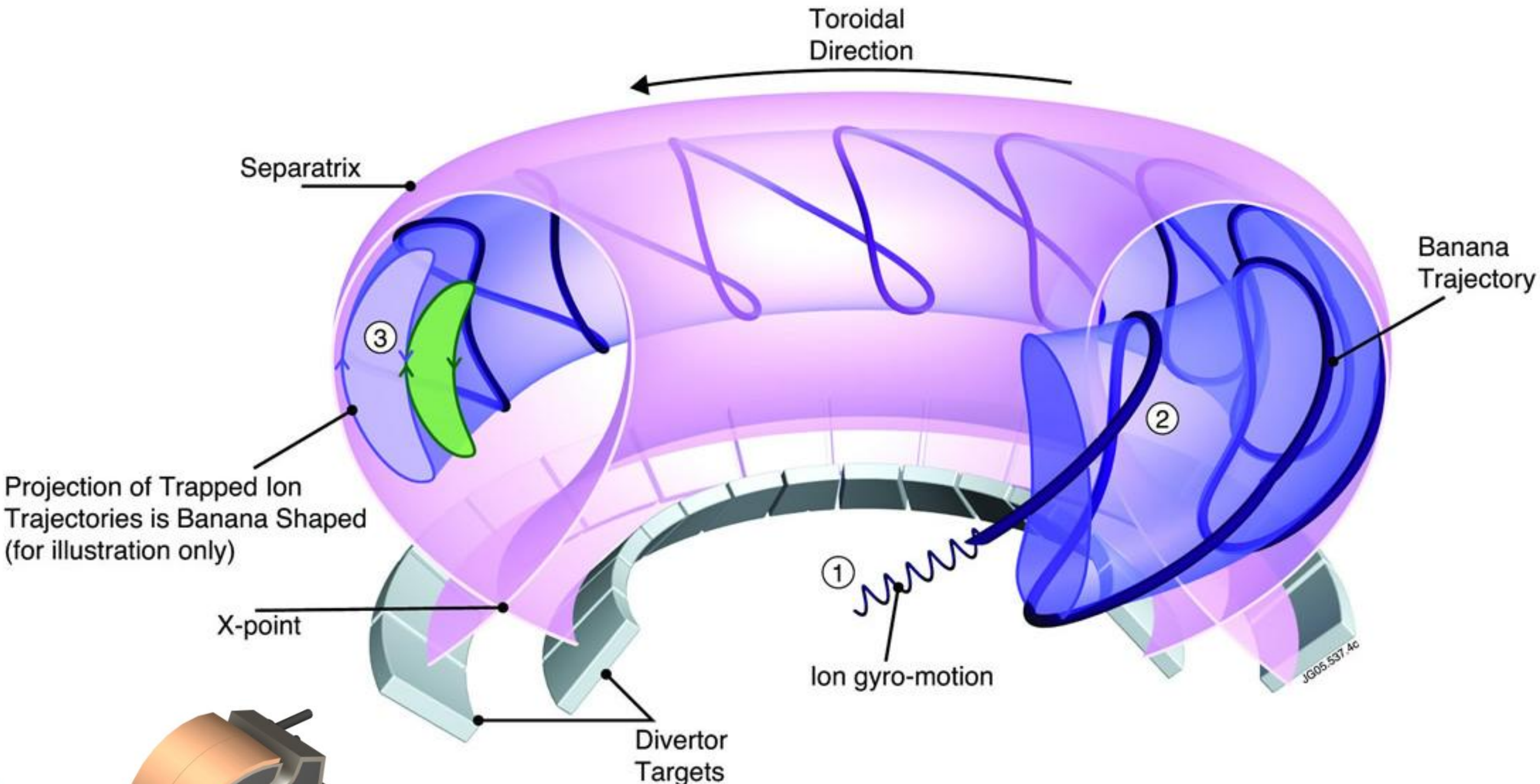
He cooled structure, liquid lithium or lithium-ceramics for tritium breeding → ~85 % power

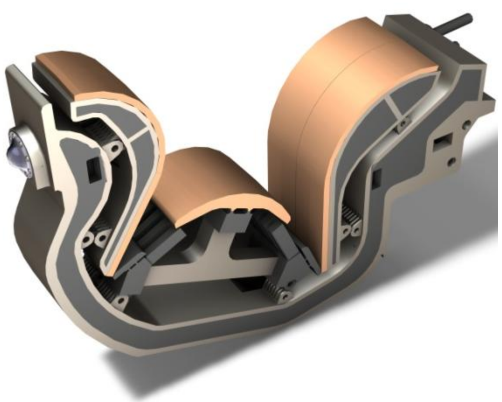
Divertor: ~30 dpa/2 years, ≥10 MW/m^2

Materials unknown
Operating temperature 350-1300 °C ?

Cooled tungsten shield to remove He and other particles from plasma → ~15 % power

DEMO Divertor: a demanding Component!





Coolants & Structural Materials

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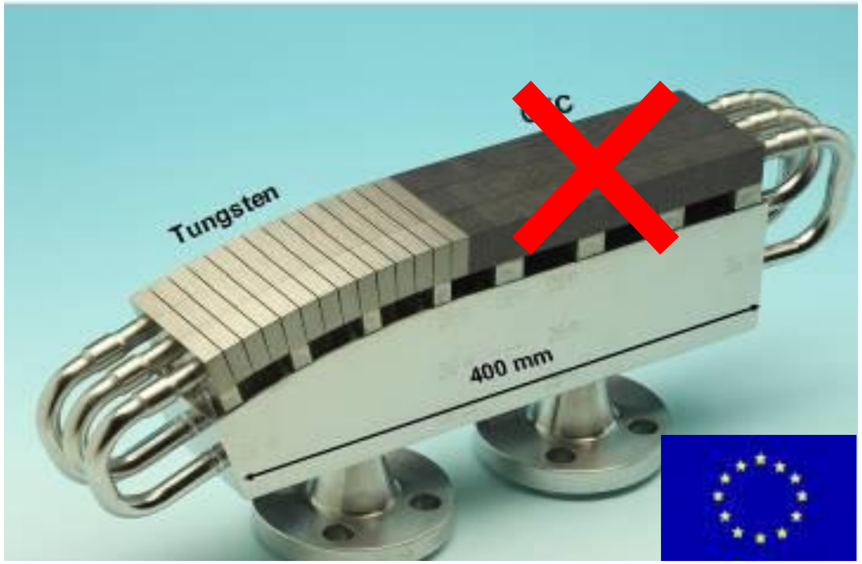
Coolants

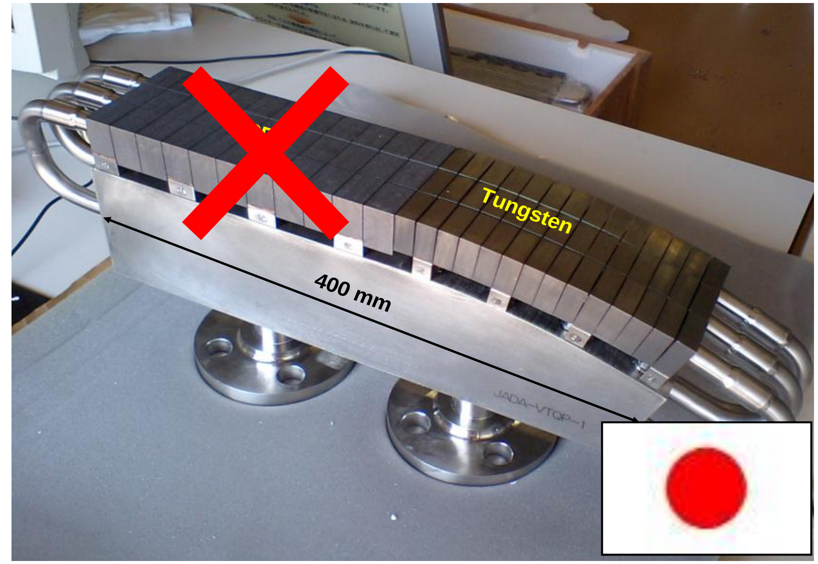
- **Liquid Coolants**
  - Water
  - (Lead-)Lithium
- **Gas Coolant**
  - Helium

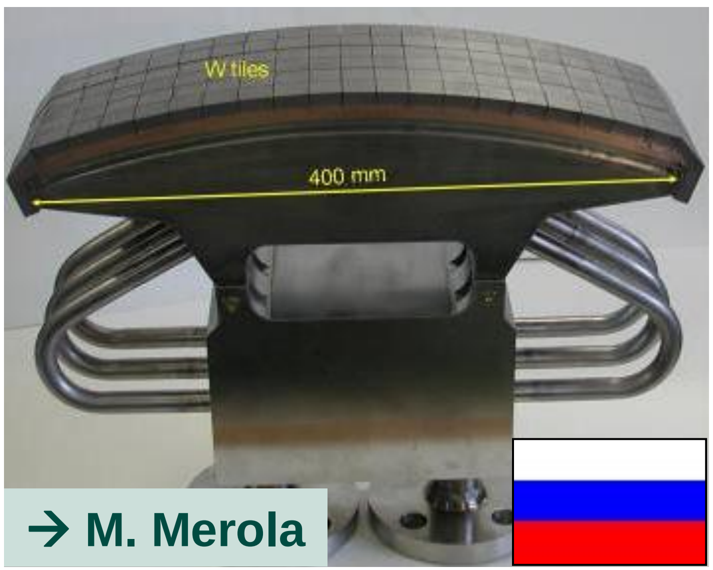
Structural Materials

- Copper (CuCrZr)
- Eurofer (9Cr1WVTa)
- Vanadium (V4Cr4Ti, …)
- SiC_f/SiC
- Tungsten (WTa, WV, …)
  plus Eurofer (or ODS)

ITER Divertor Concept (Cu & H_2O)





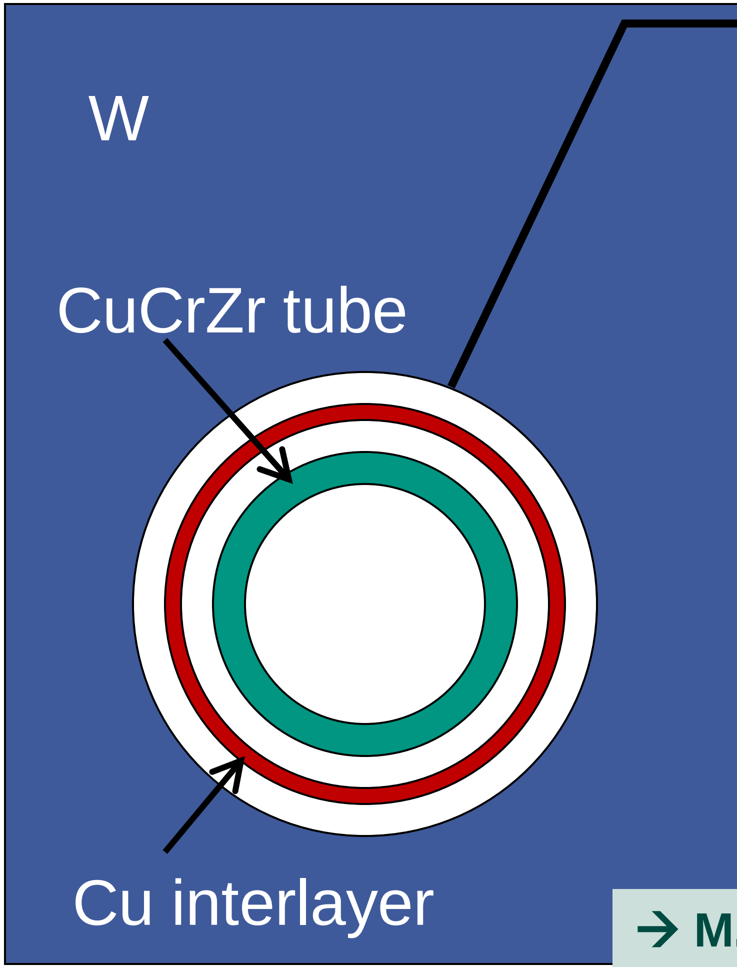


→ M. Merola

- 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)

Advantages

- Fabrication processes available
- Proof for 1000 cycles at 5 MW/m² with potential for 15 MW/m² or more
- Cost effective

Drawbacks

- Cu is NOT applicable under DEMO conditions → T retention, embrittlement, swelling (~15 dpa/year !!!)

Department of Materials, University of Oxford, 20. May 2010

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Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

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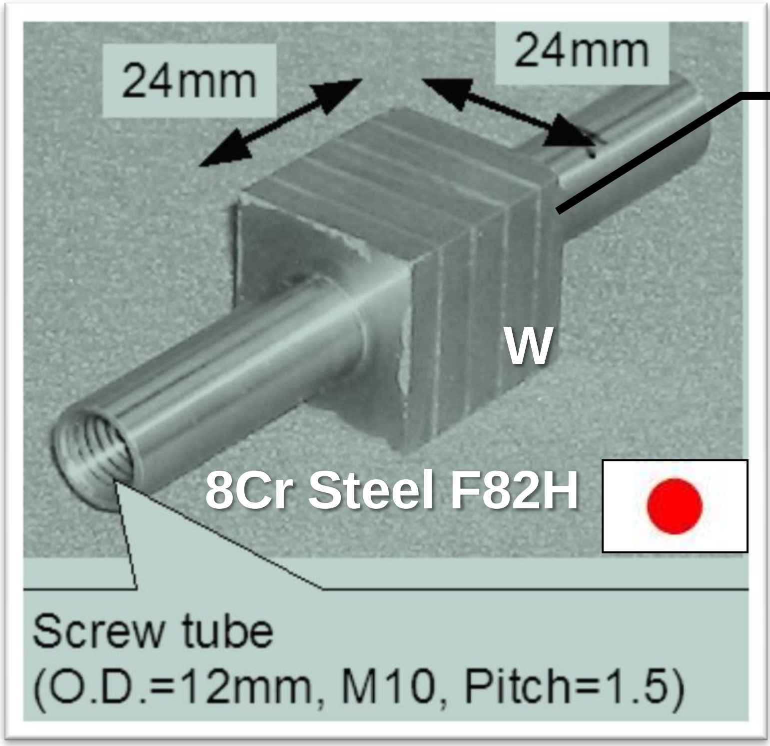
"Upgrade" of ITER Concept (Steel & H_2O)



- 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 with 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/m²

Drawbacks

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

SiC_f/SiC & Lead-Lithium

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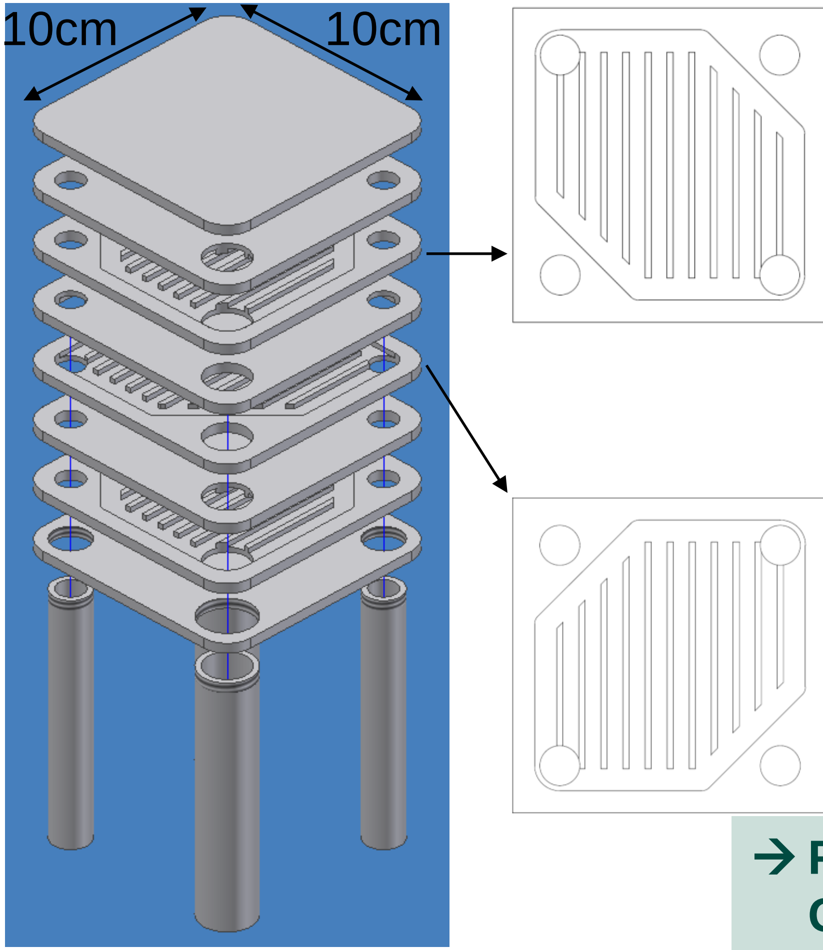
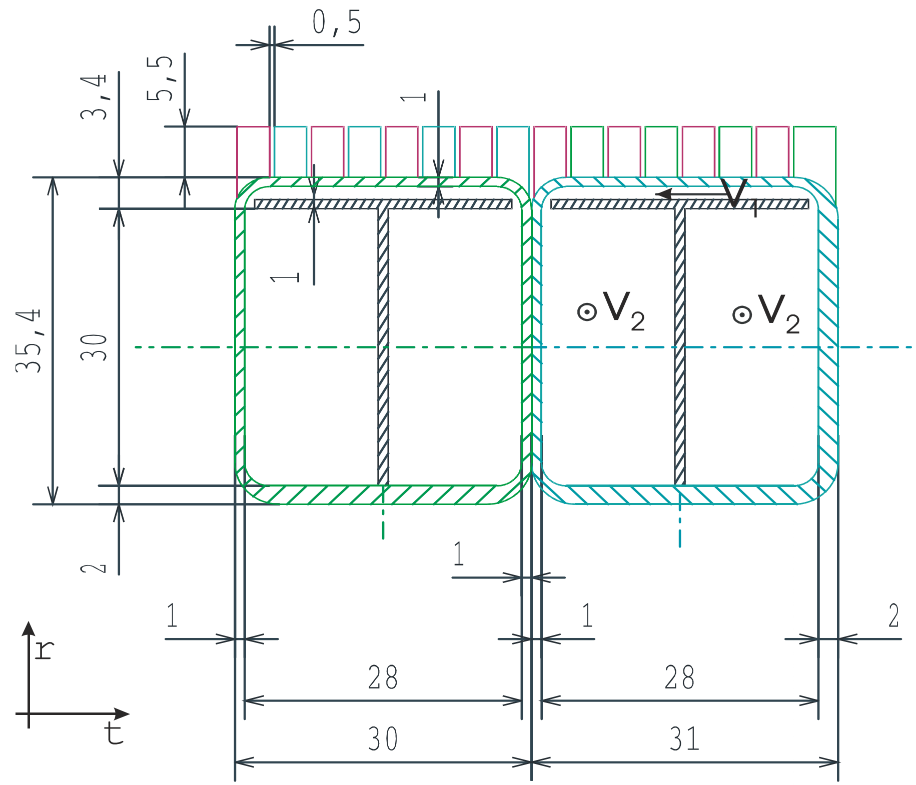
→ K. Noborio, Y. Yamamoto, Y. Takeuchi, T. Hinoki, S. Konishi, 2008



→ A. R. Raffray, L. El-Guebaly, S. Malang, I. Sviatoslavsky, M. S. Tillack, X. Wang, ARIES-AT, 2000



→ Followed up by: A. Li Puma, L. Giancarli, H. Golfier, Y. Poitevin, J. Szczepanski, 2003

SiC_f/SiC & Lead-Lithium

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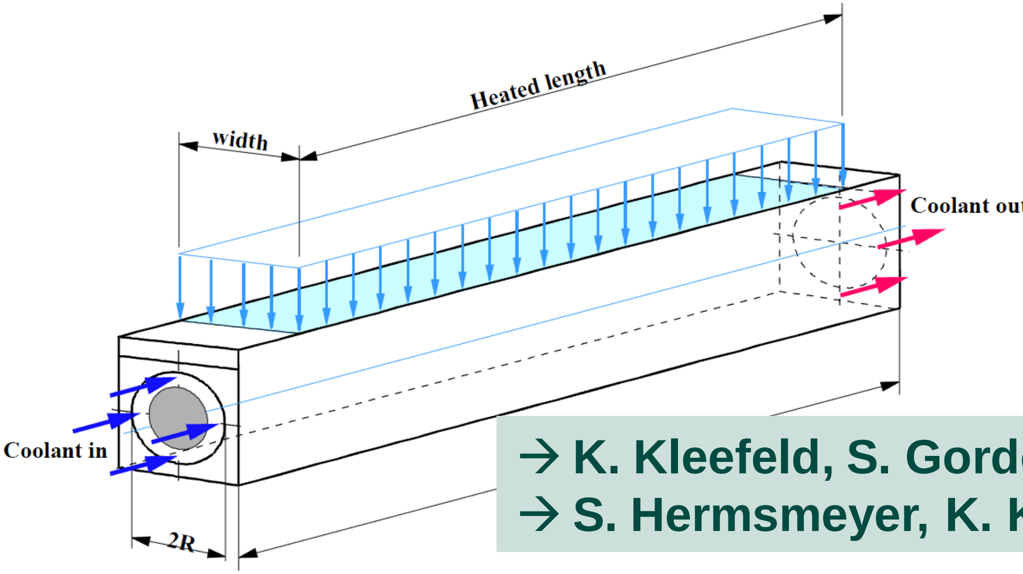
Theory

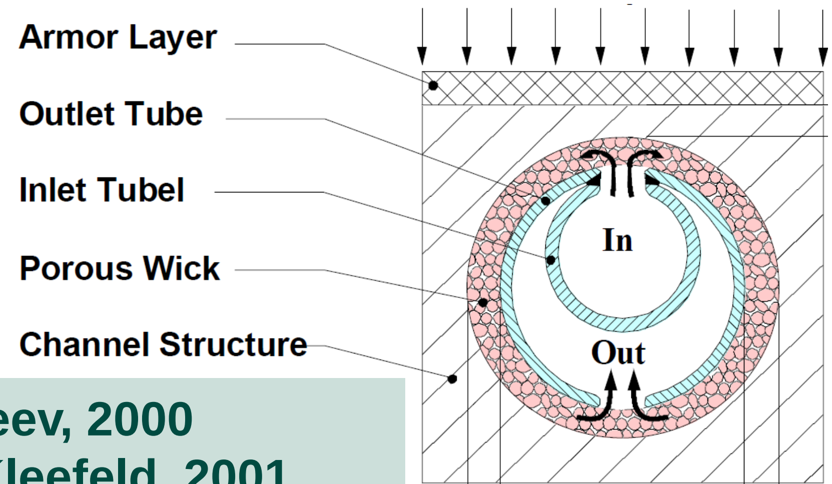
- Heat flux max. 5 MW/m^2
- Inlet temperature 600 °C
- Flow velocity 1-1.5 m/s

Drawbacks

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

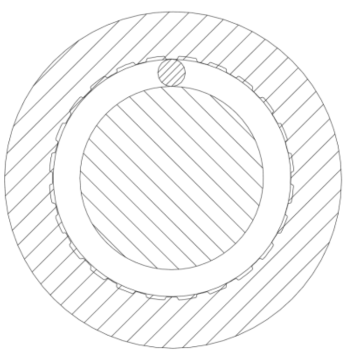
Tungsten & Helium, 5 MW/m² Concepts

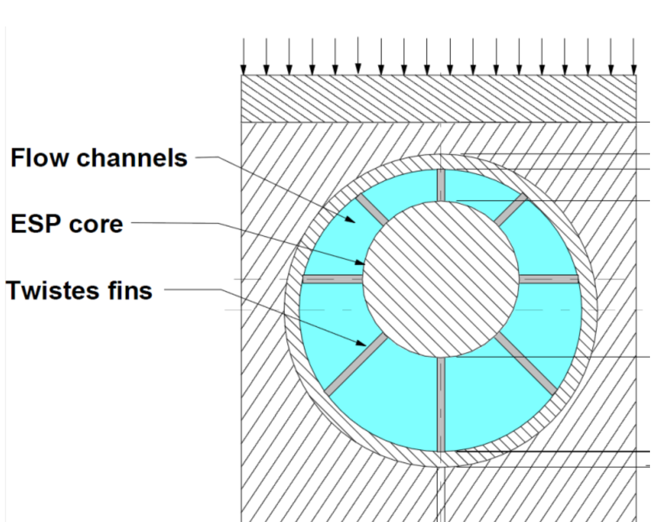


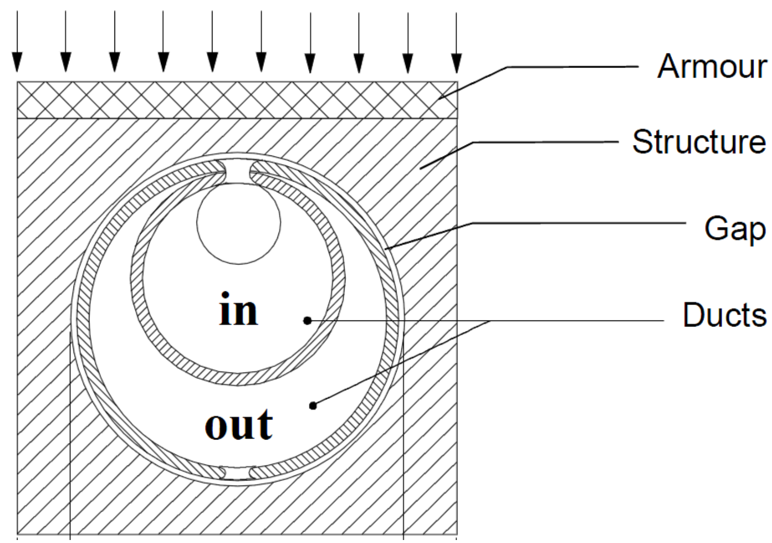


→ K. Kleefeld, S. Gordeev, 2000

→ S. Hermsmeyer, K. Kleefeld, 2001







Tungsten & Helium, 10 MW/m² Concepts

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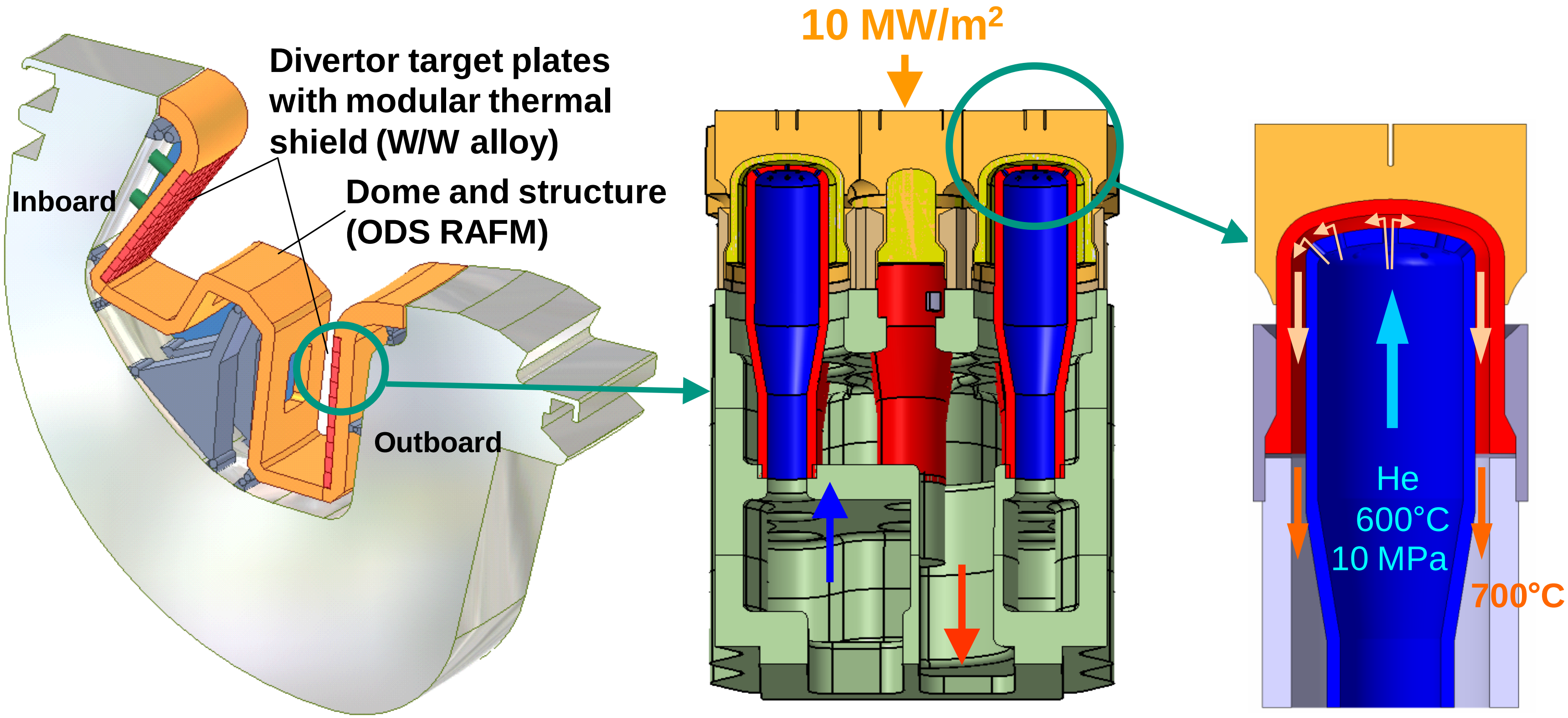


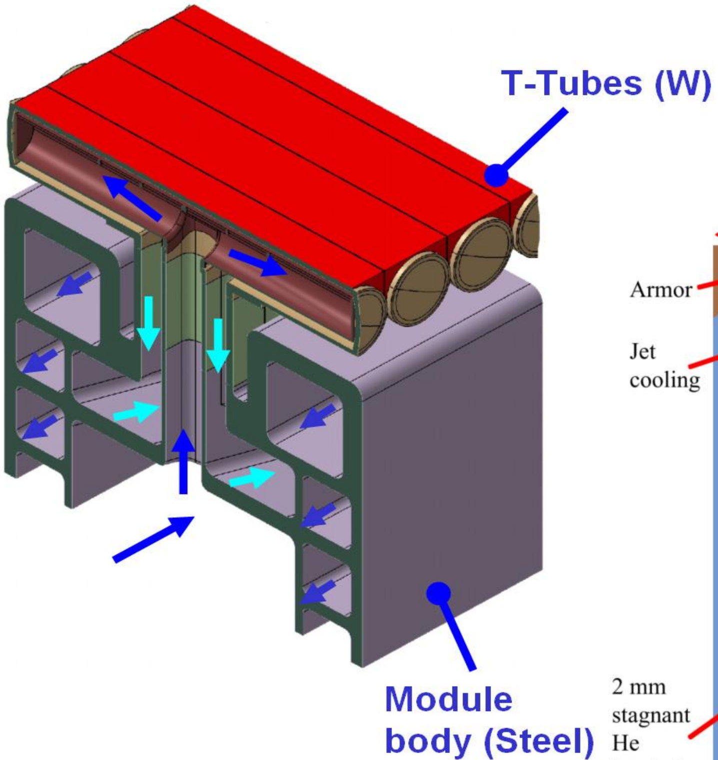
Divertor Cassette

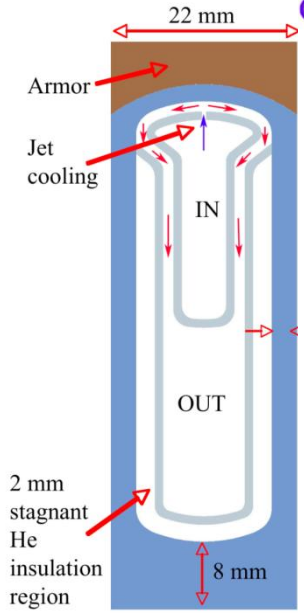
9-Finger Module

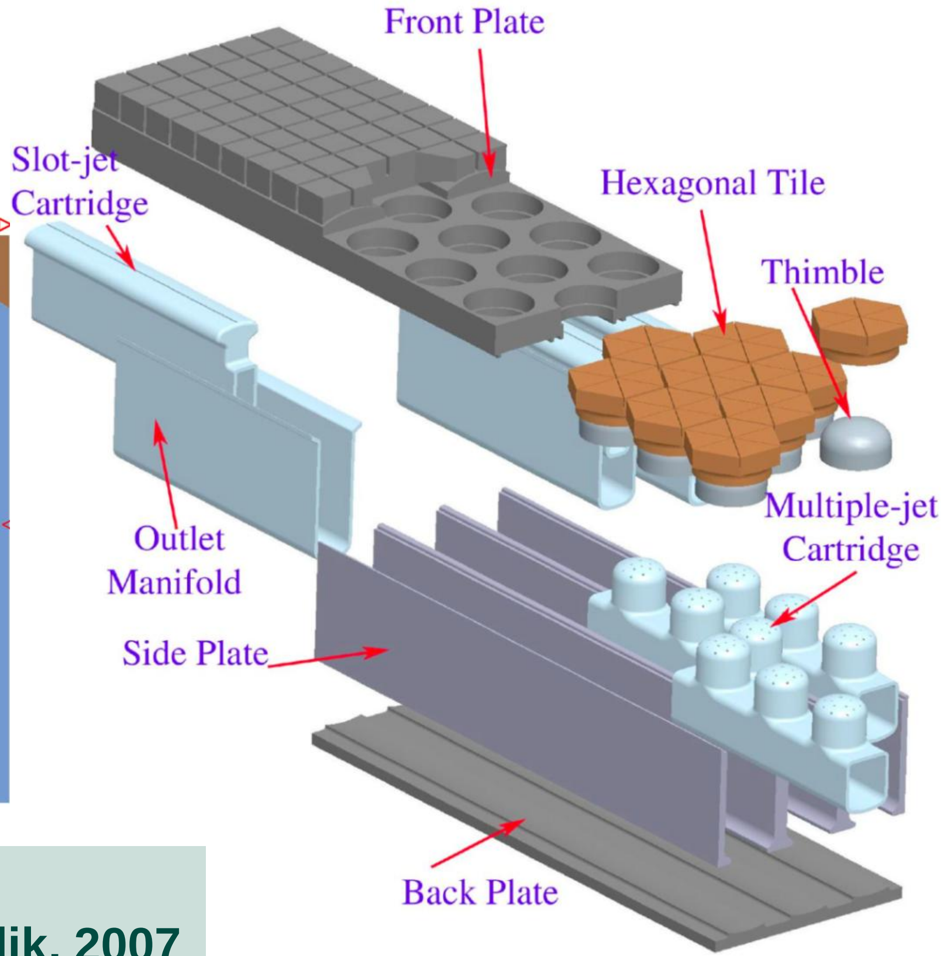
Finger

→ **P. Norajitra et al., 2003-2009**

Tungsten & Helium, 5-10 MW/m² Concepts







→ S. Hermsmeyer, S. Malang, 2002
→ T. Ihli, A. R. Raffrey, S. I. Abdel-Khalik, 2007
→ A. R. Raffrey, S. Malang et al., 2008

Tungsten & Helium, 10 MW/m² Concepts

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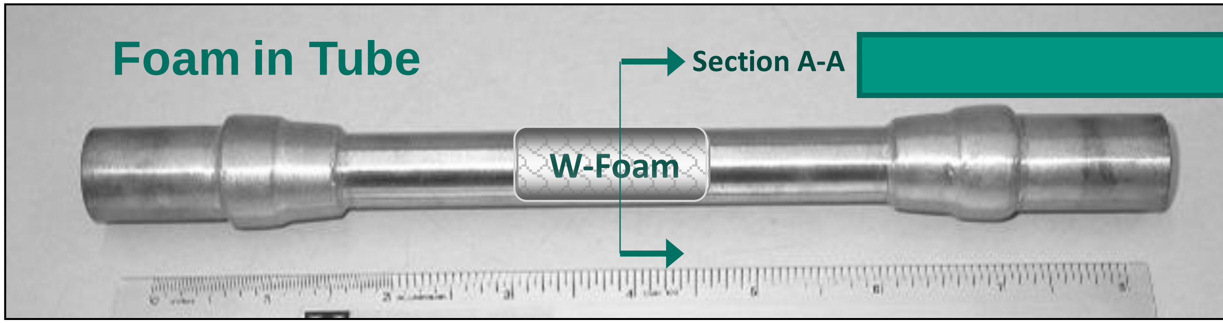

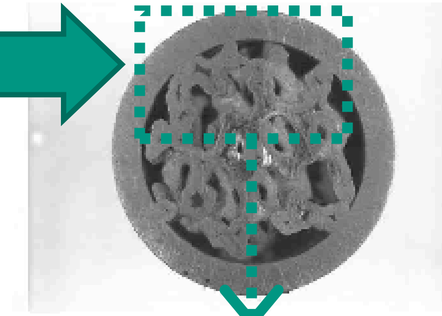

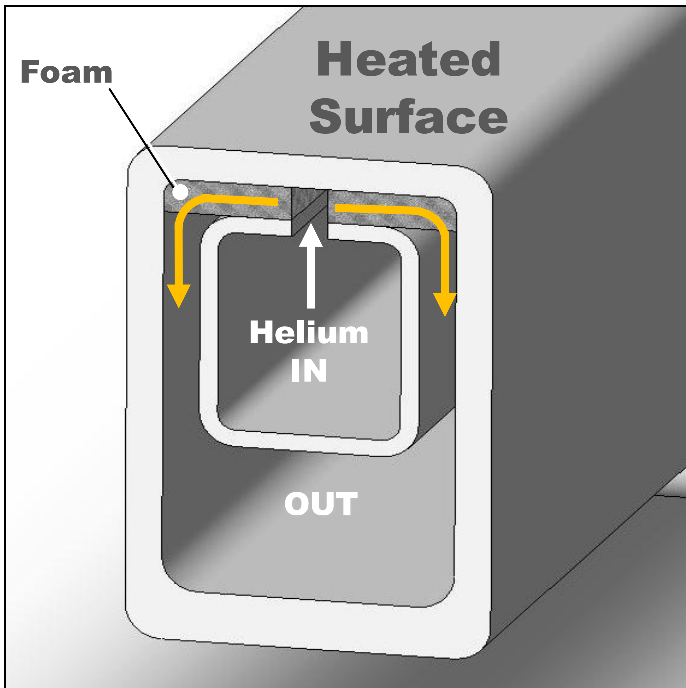

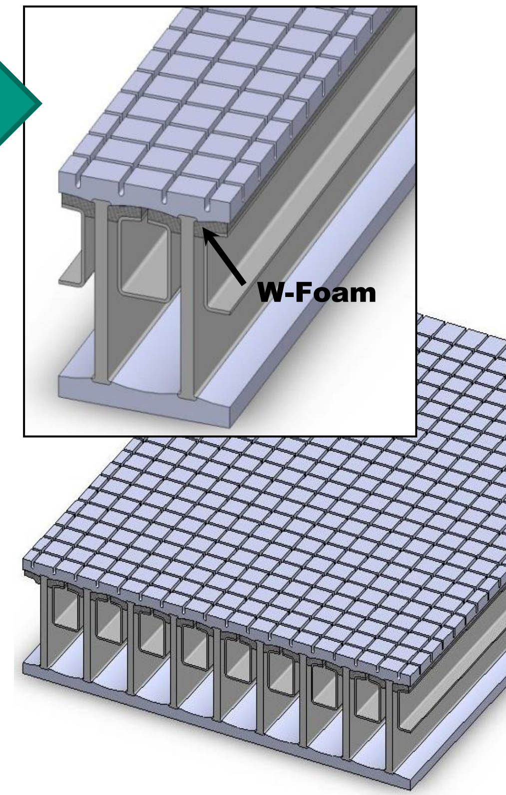

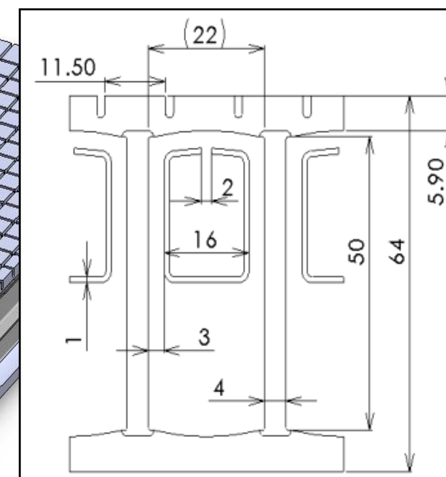

→ S. Sharafat et al., 2005-2009

Tungsten & Helium

Facts	Drawbacks
■ Heat flux 5-10 MW/m^2 ■ Various concepts available (proof for finger module) ■ Flexible operation temperatures	■ Brittleness (fracture behaviour) of tungsten (even without irradiation) ■ Unsolved fabrication issues (e.g. brazing for irrad. conditions)

Ranking of Divertor Concepts

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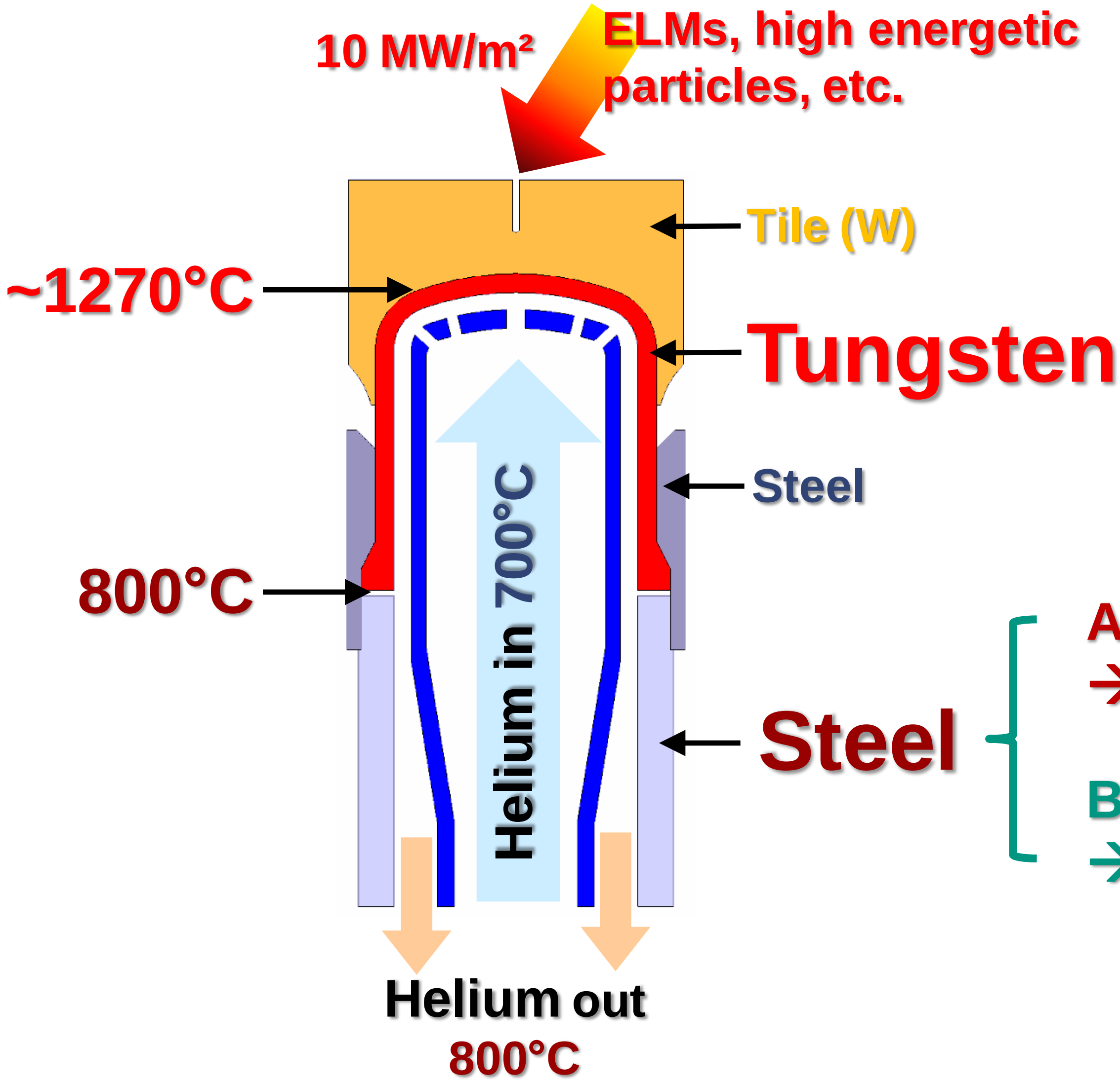
Feasibility (even for reduced heat flux of 5 MW/m²)

- Copper (CuCrZr) **no go!**
- Vanadium (V-4Cr-4Ti, …) **not likely!?**
- Low Activation Steel (Eurofer) **not likely!?**
  → coolant? concept? …
- SiC_f/SiC **no go!?** **→ long-term option, R&D needed**
- Tungsten (W, WL10, …) **Not yet! But …**
  → solution for ductility problem needed!

He Cooled Divertor Dilemma



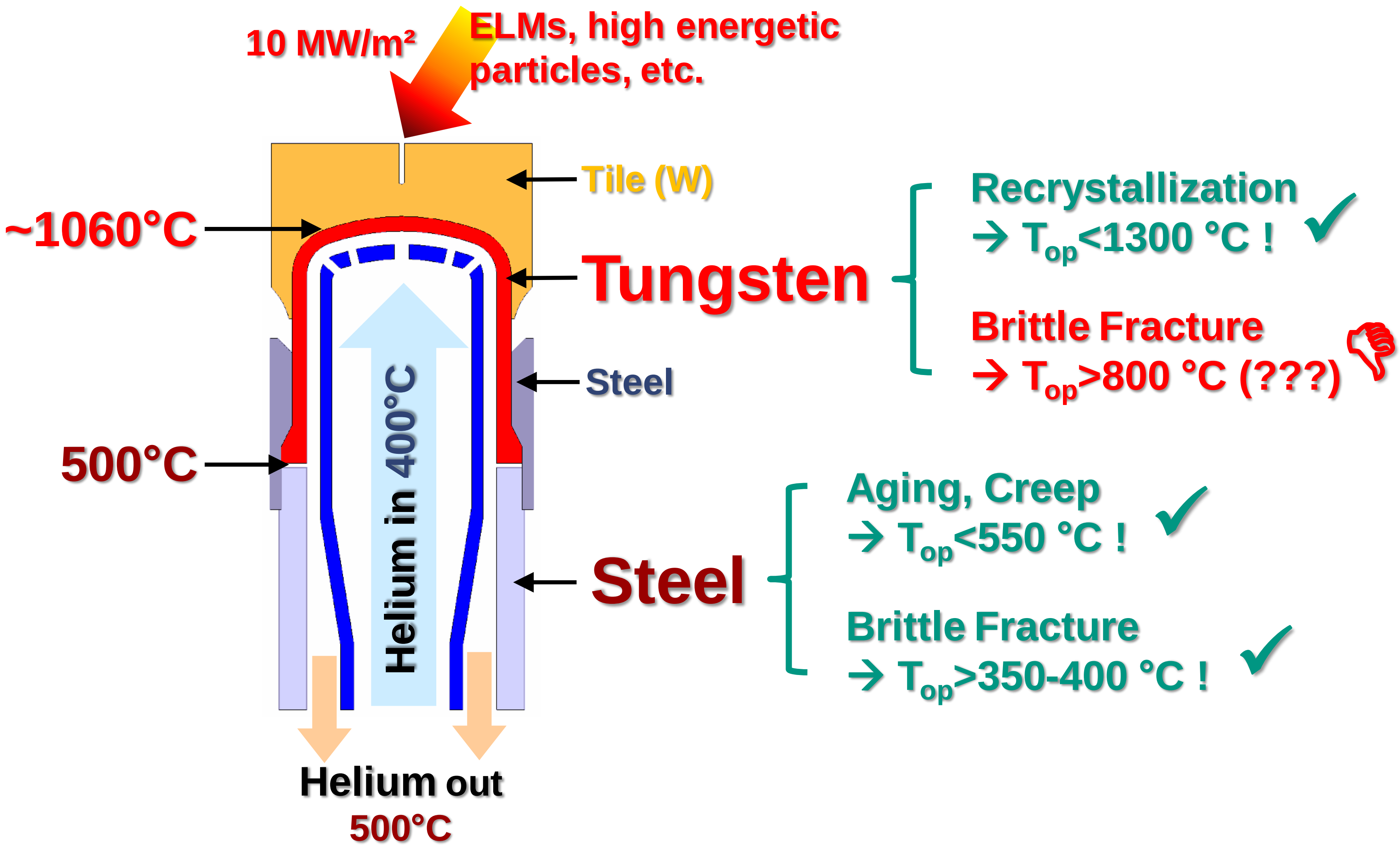
Tungsten

- 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 ! ✓

He Cooled Divertor Dilemma



Main Criteria for Structure Divertor Material

Heat Flux (10 MW/m²)

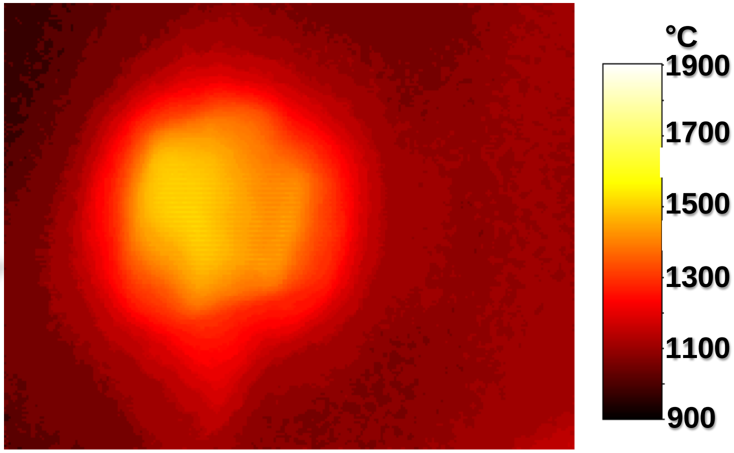
- Very Effective Cooling Strategy
- Thermal Conductivity
- High Operation Temperature

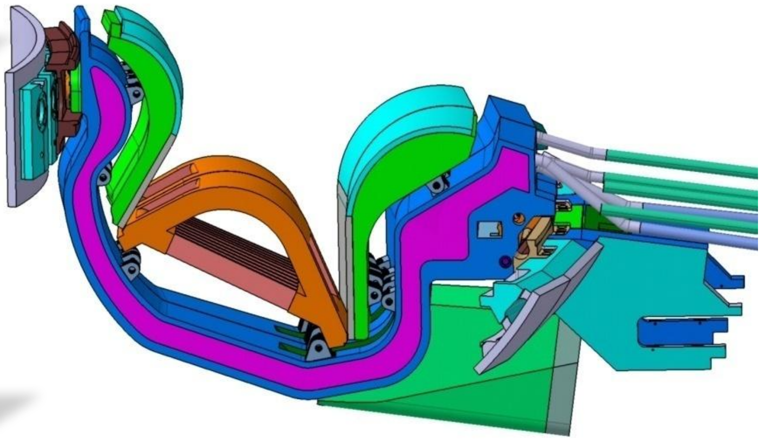
Neutron Dose (min. 30 dpa)

- Irradiation Damage
- Activation (Transmutation?)

Other Criteria

- Fabrication/Joining
- Tritium Inventory
- Availability/Cost





Why Tungsten? → Element Selection

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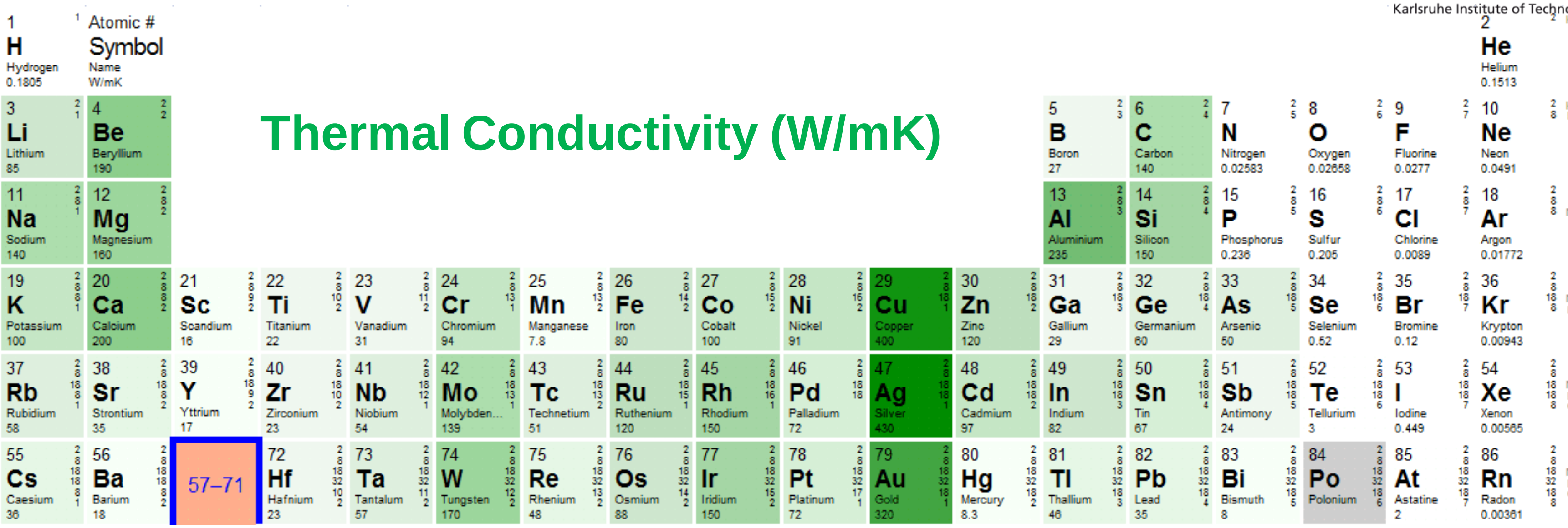

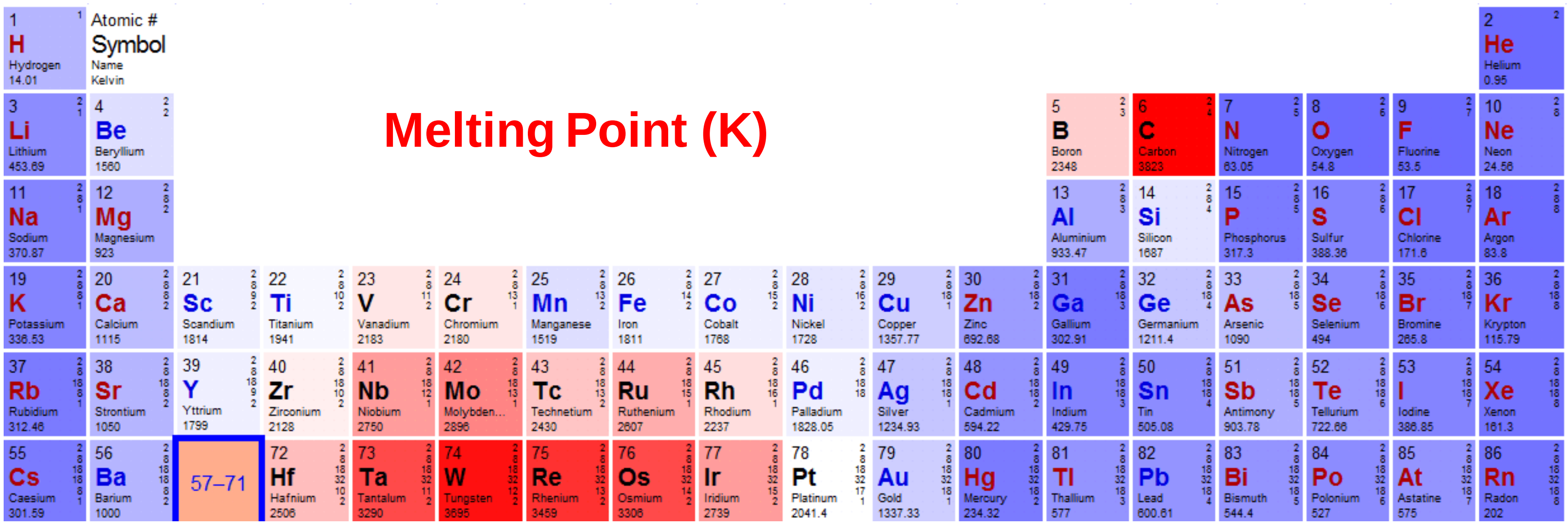

HHFC Base Material

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Melting Point >2000 K
Thermal Conductivity >50 W/mK

24 Cr Chromium 2180 (2 8 13 1)
6 C Carbon 3823 (2 4)
41 Nb Niobium 2750 (2 8 18 12 1)
42 Mo Molybden… 2896 (2 8 18 13 1)
43 Tc Technetium 2430 (2 8 18 13 2)
44 Ru Ruthenium 2607 (2 8 18 15 1)
45 Rh Rhodium 2237 (2 8 18 16 1)
73 Ta Tantalum 3290 (2 8 18 32 11 2)
74 W Tungsten 3695 (2 8 18 32 12 2)
75 Re Rhenium 3459 (2 8 18 32 13 2)
76 Os Osmium 3306 (2 8 18 32 14 2)
77 Ir Iridium 2739 (2 8 18 32 15 2)
78 Pt Platinum 2041.4 (2 8 18 32 17 1)

\+

Availability, Cost

24 Cr Chromium 2180 (2 8 13 1)
6 C Carbon 3823 (2 4)
41 Nb Niobium 2750 (2 8 18 12 1)
42 Mo Molybden… 2896 (2 8 18 13 1)
74 W Tungsten 3695 (2 8 18 32 12 2)

\+

Low/Medium Activation

24 Cr Chromium 2180 (2 8 13 1)
6 C Carbon 3823 (2 4)
74 W Tungsten 3695 (2 8 18 32 12 2)

\+

Irradiation

24 Cr Chromium 2180 (2 8 13 1)
74 W Tungsten 3695 (2 8 18 32 12 2)

\+

e.g. T_{RC}

74 W Tungsten 3695 (2 8 18 32 12 2)

HHFC Alloying Elements (up to 1%)

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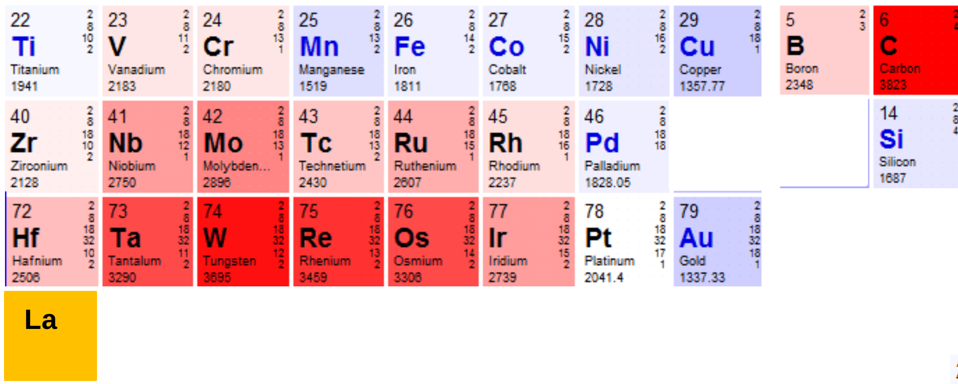
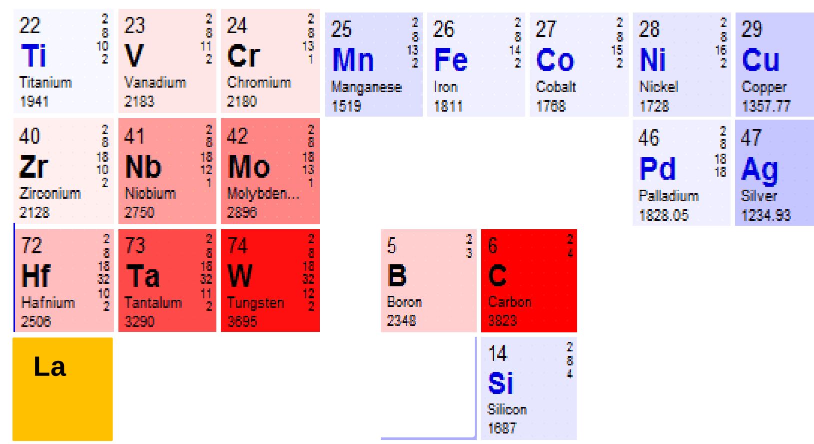
Melting Point >1300 K
Thermal Conductivity >20 W/mK



+ Availability, Cost



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HHF Alloying Elements (up to 1%)

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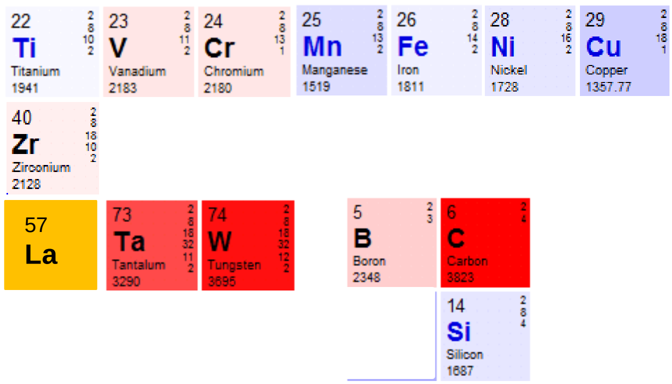
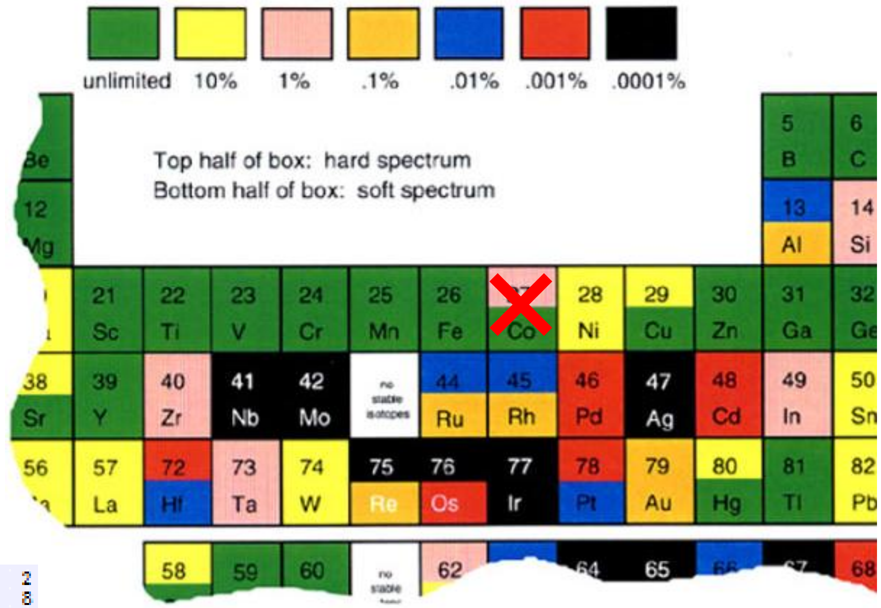
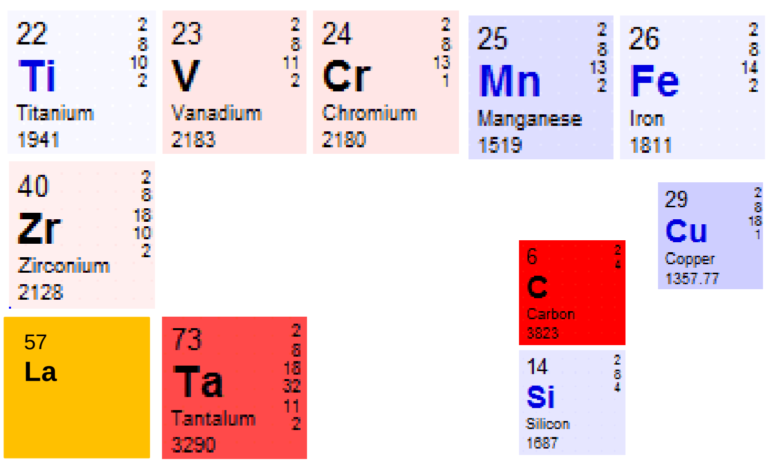
+ Activation

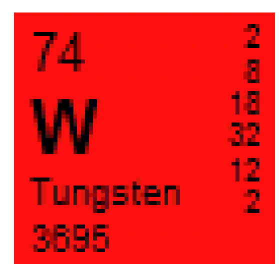




→ Class C Waste Disposal, ORNL

+ Irradiation

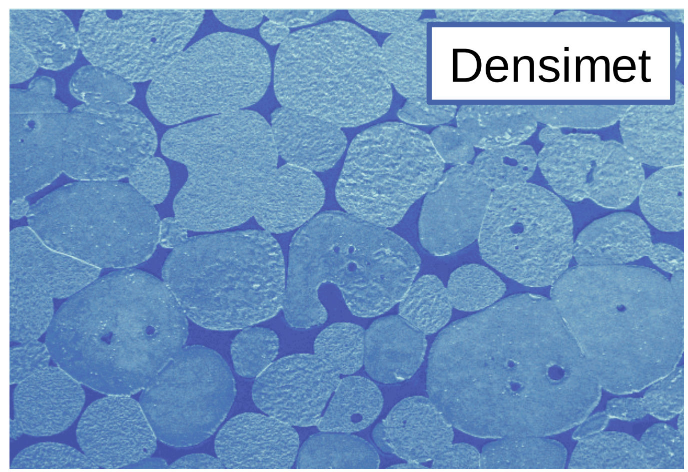




What can be done with these elements?

Pure Tungsten

- **Grain Stabilized Tungsten**
  - **Potassium Doping**
    - e.g. WVM
    - → Bulb Wire
  - **Oxide Particles**
    - La_2O_3 (e.g. WL10)
    - ZrO_2
    - CeO_2
    - (ThO_2)
    - (HfC)
- **Tungsten Compounds**
  - W-(Ni)-Fe (Densimet)
  - W-Cu (Elmet)
  - (W-Ag)
- **Tungsten Alloys**
  - W-V
  - W-Ta
  - (W-Mo)



Tungsten Material Production Routes

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Sintering & Forming

+ Mass Production
+ Density

-/+ Specific, aniso-tropic micro-structure

Powder-Metallurgy

Mechanical Alloying & HIP

+ Fine Particles
+ Homogenous Microstructure

- Small Quantities
- Porosity
- Brittleness?

Injection Molding & Sintering/HIP

+ Mass Production
+ Nearly Finished Products
+ Homogenous Microstructure

- Porosity
- Severe Brittleness

(S)Melting & Forming

+ Real Alloying

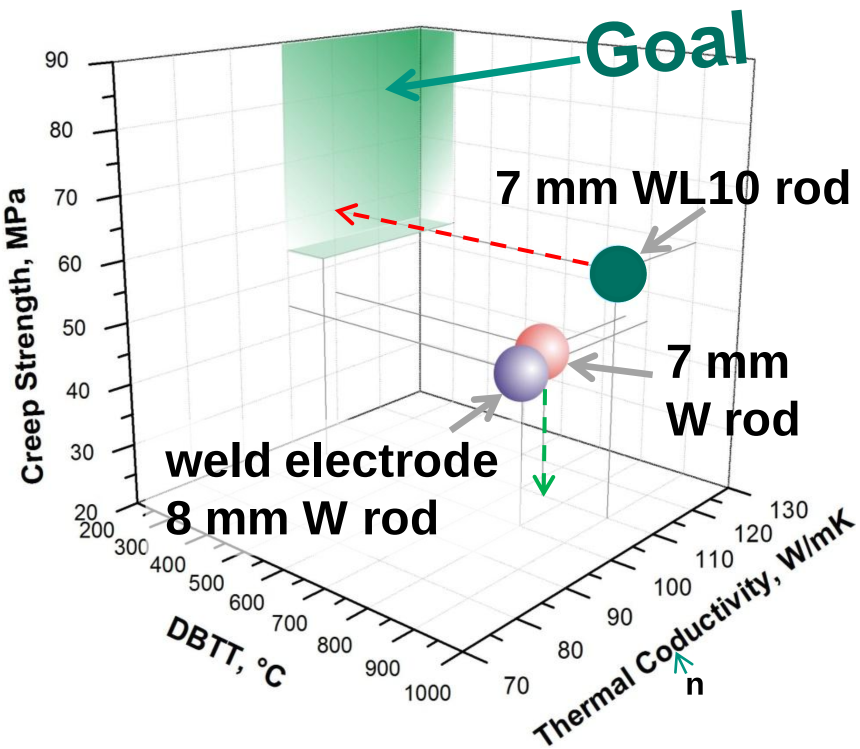
(-) sometimes expensive (→ EB, Arc, Vacuum, ...)

Where are we today?

Important Design Criteria

Thermal Conductivity	100 W/mK @ 1200 °C
Creep Strength	55 MPa, 20 kh @ 1200 °C
DBTT unnotched	300 °C, un-irradiated
Recrystallization Temperature	1300 °C, for 20 kh

Present Situation



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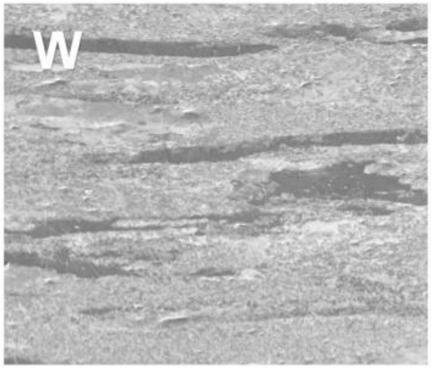
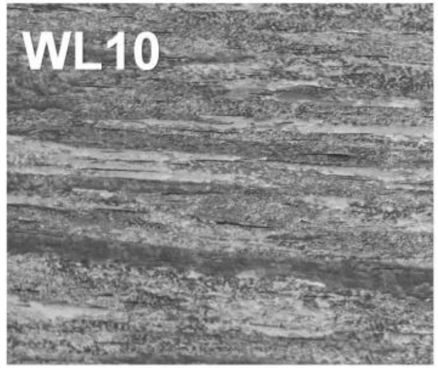
W-Materials, Rolling Texture

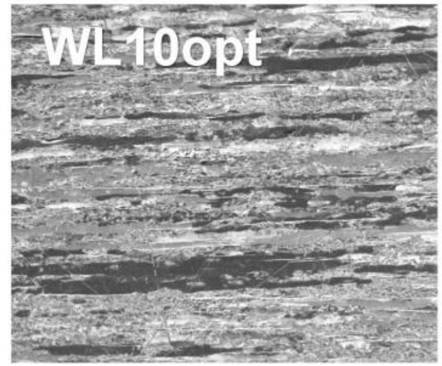
RODS



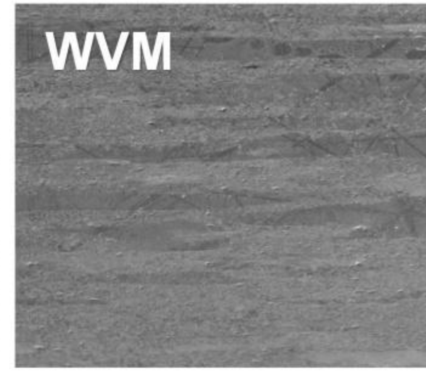
Ø6,9 mm	91%	Rolling



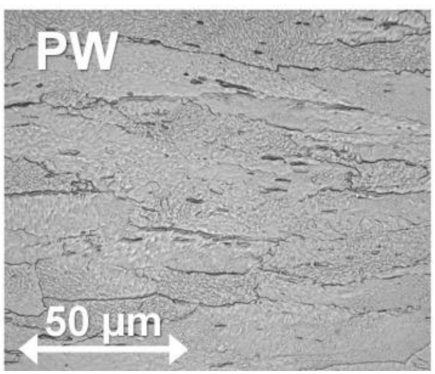
Ø6,9 mm	91%	Rolling



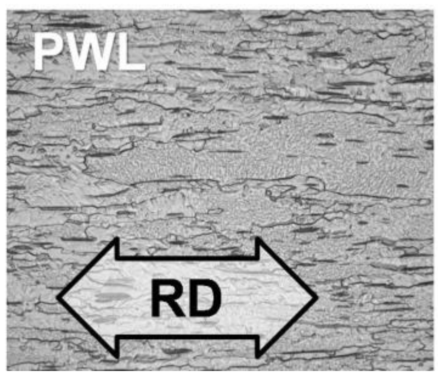
Ø6,9 mm	94%	Swaging



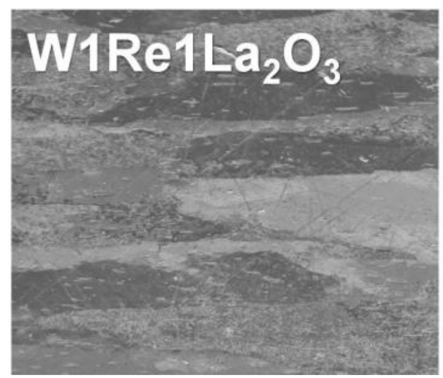
Ø16 mm	91%	Rolling



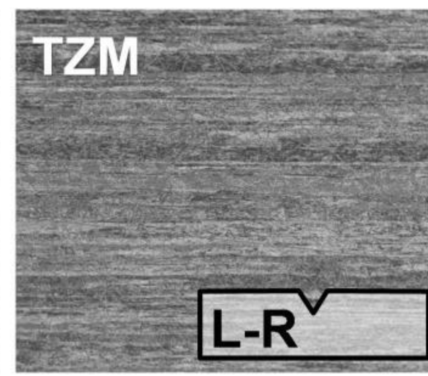
Ø20 mm	93%	Swaging



Ø20 mm	93%	Swaging



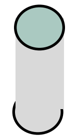
Ø10 mm	81%	Rolling

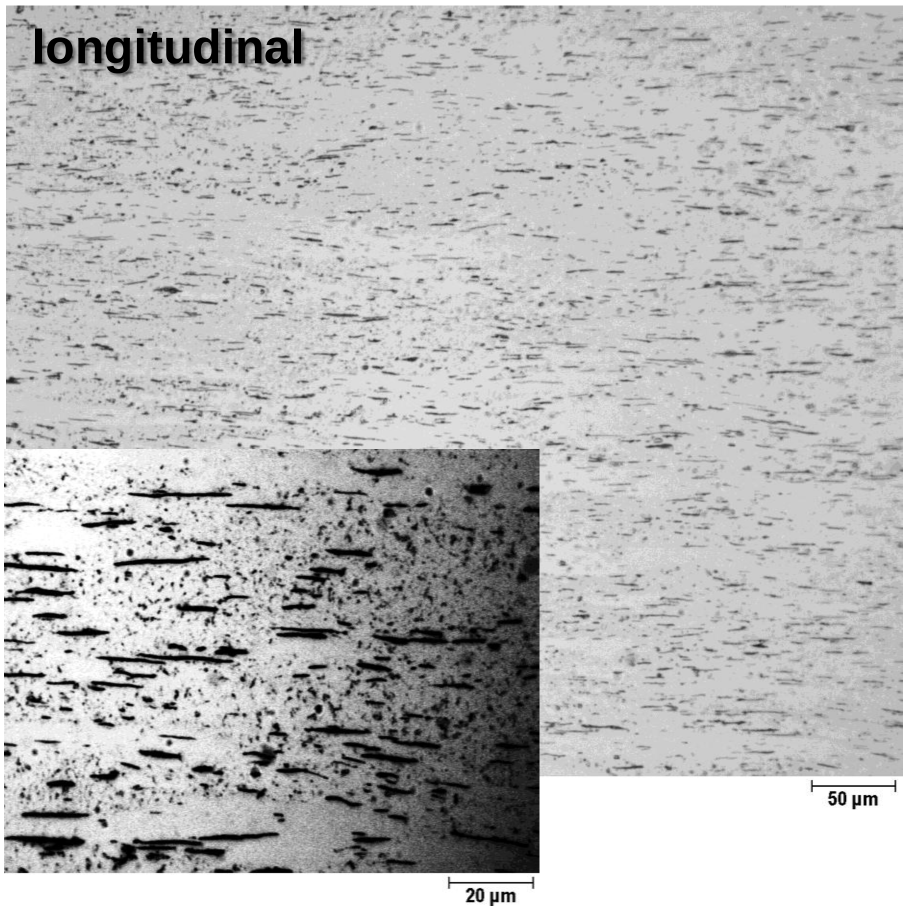


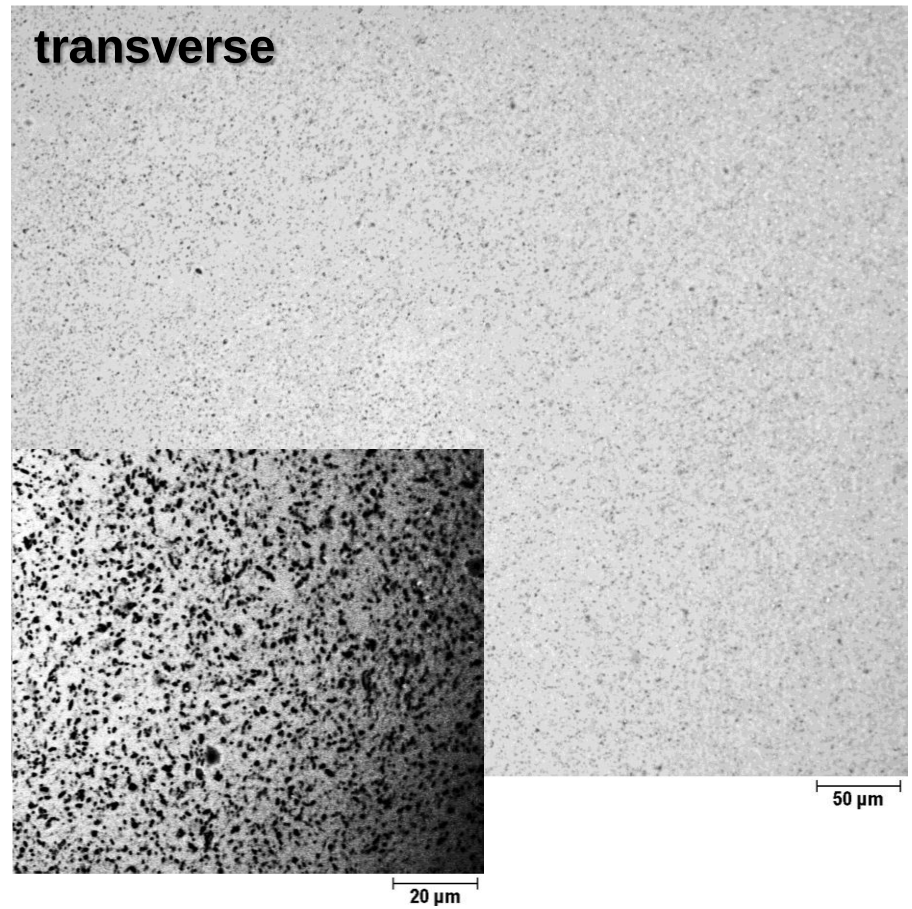
Ø7 mm	91%	Sw+Rol

Microstructure

WL10 Rod, Ø7 mm

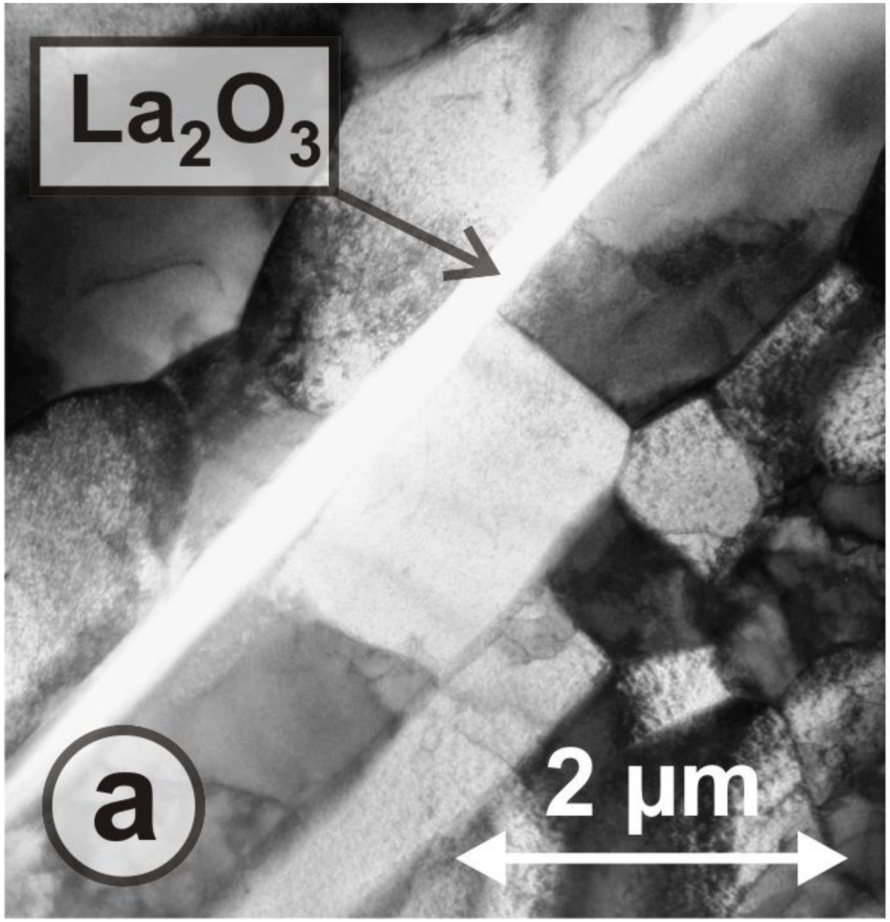




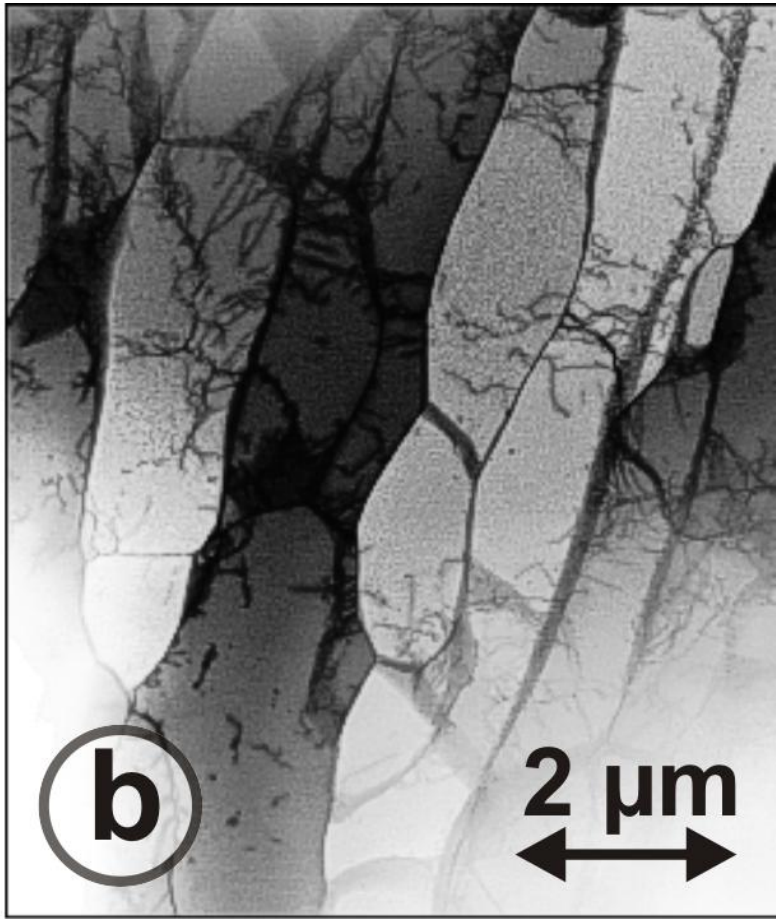


Microstructure in the condition as delivered (by TEM)

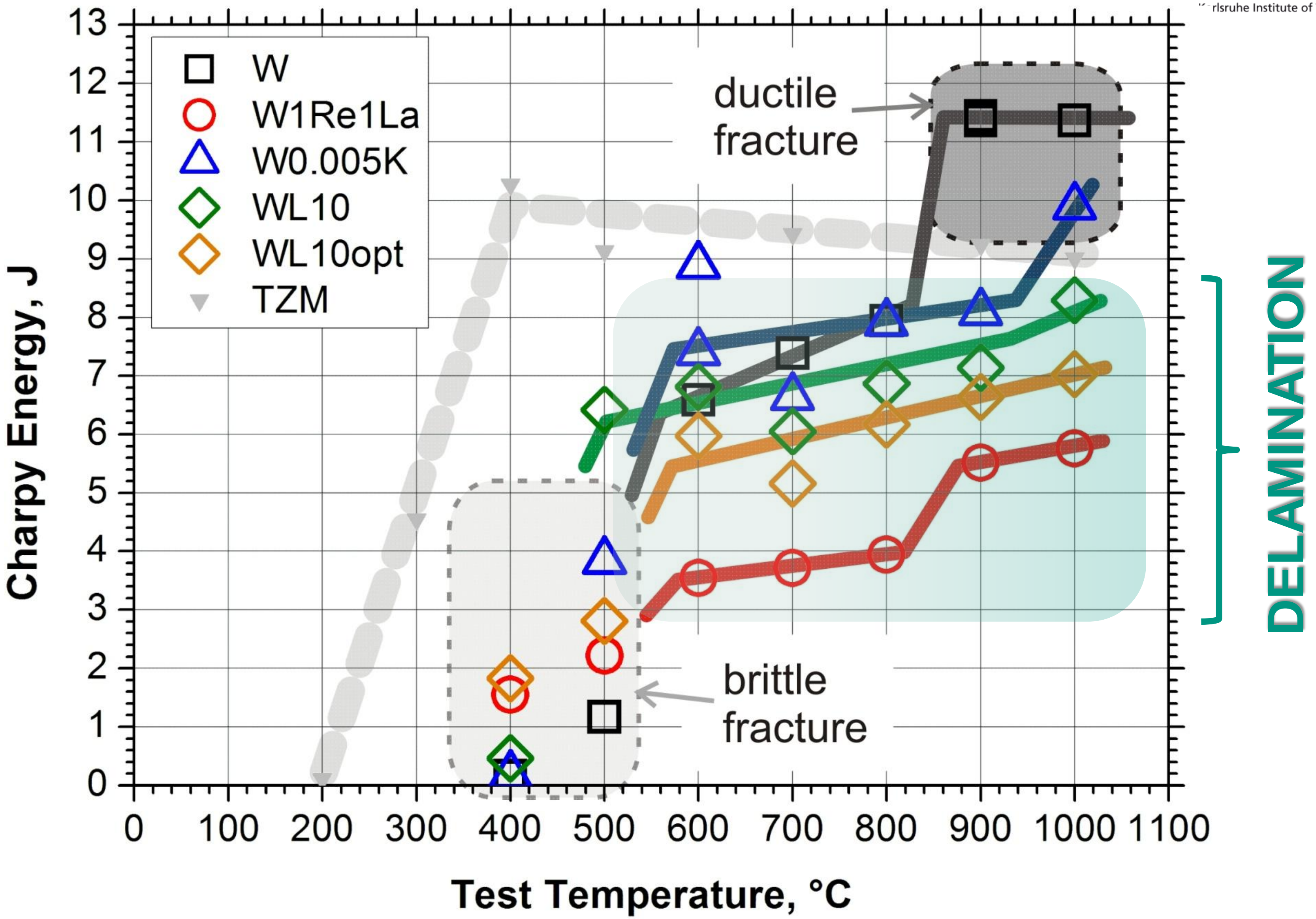
WL10 Rod, Ø7 mm



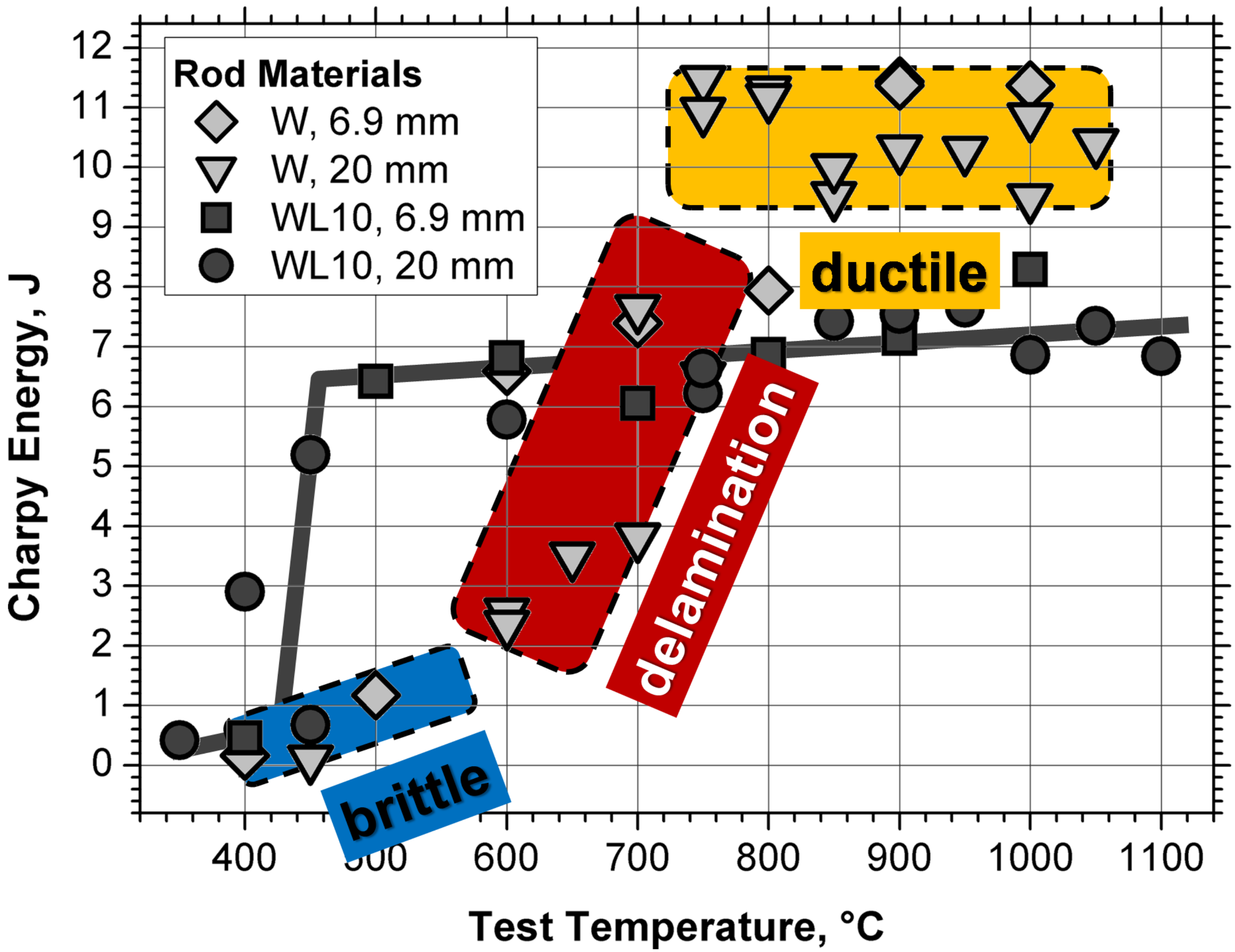
W Rod, Ø7 mm



Rods: Fracture Characteristics



Rods: Fracture Characteristics



Transition of Fracture Modes

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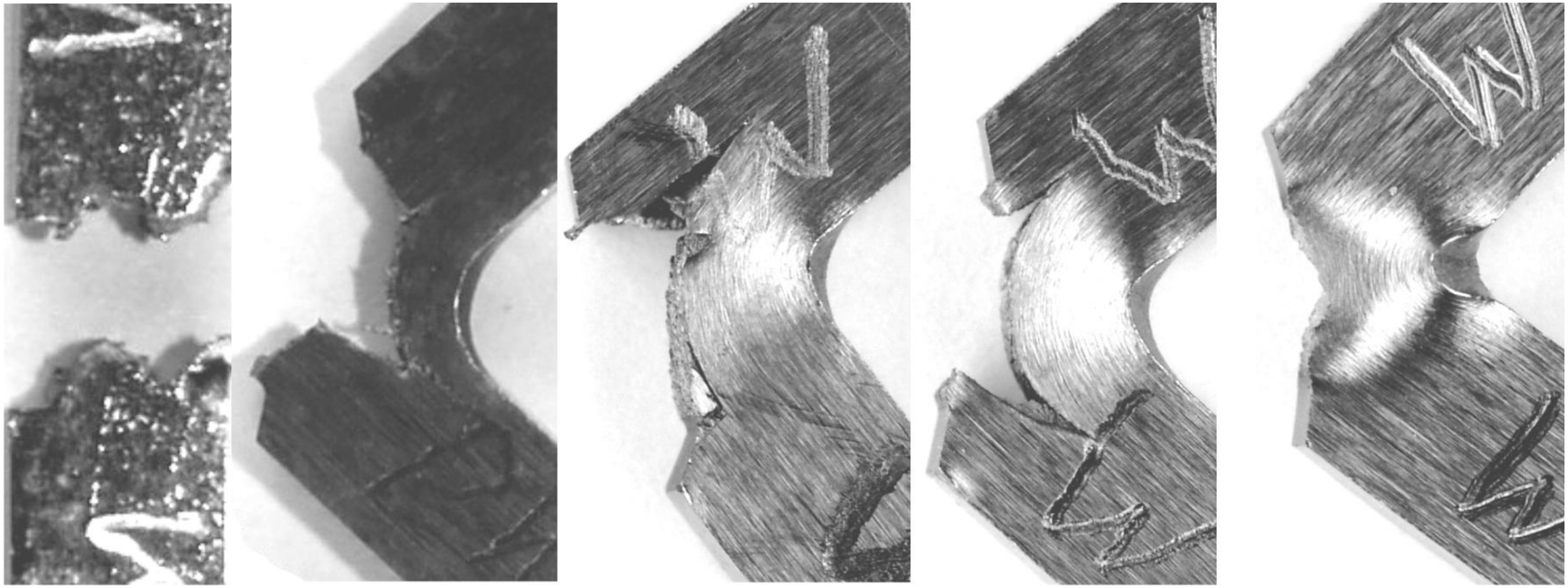
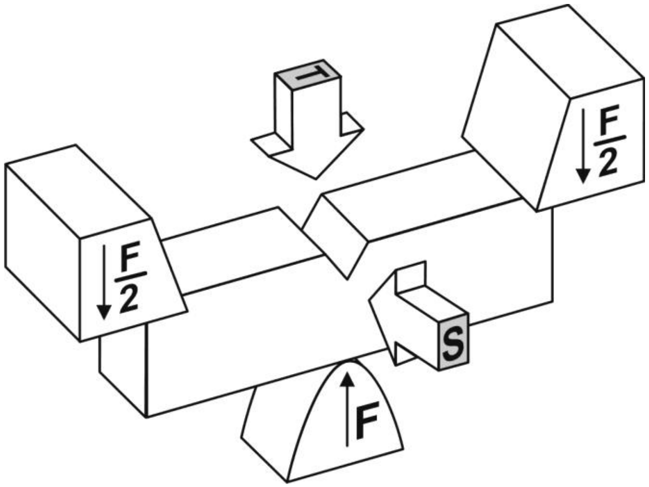
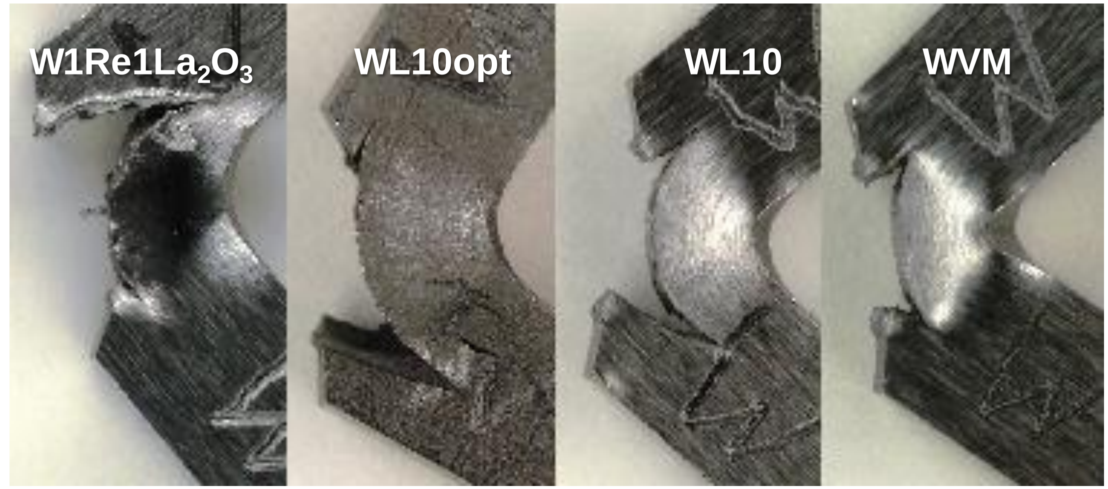
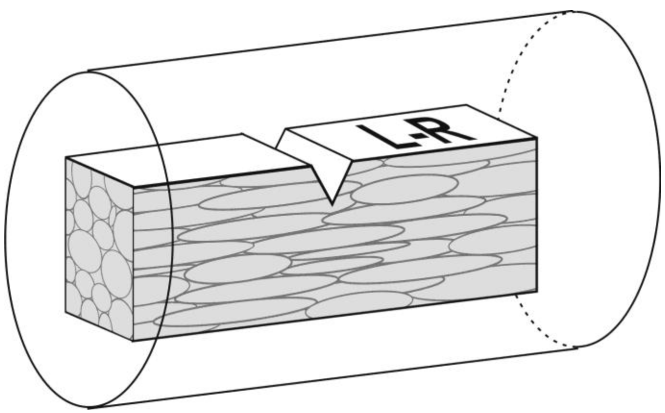
brittle → delamination → ductile

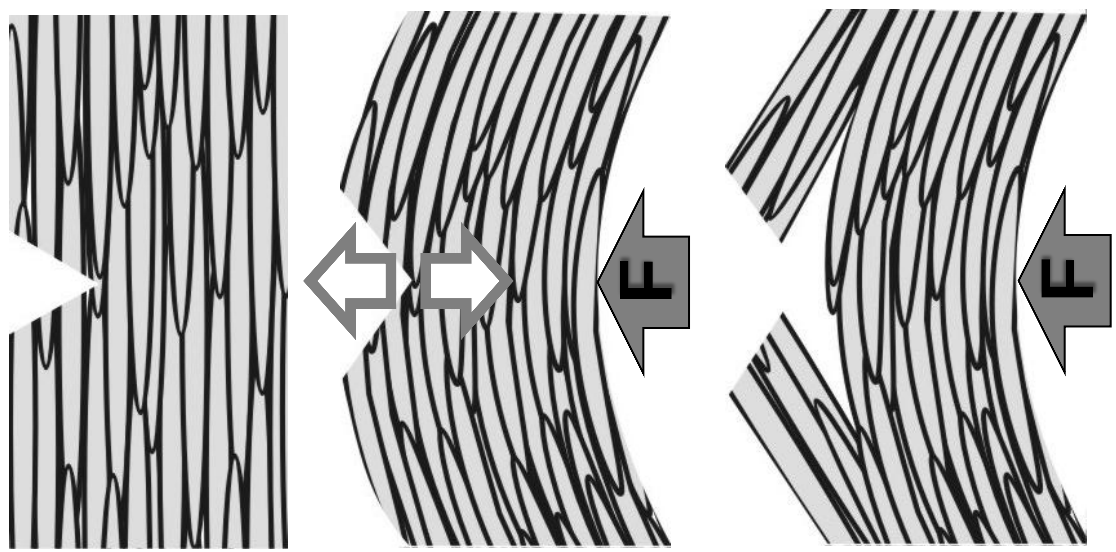


Delamination Fracture in Rods

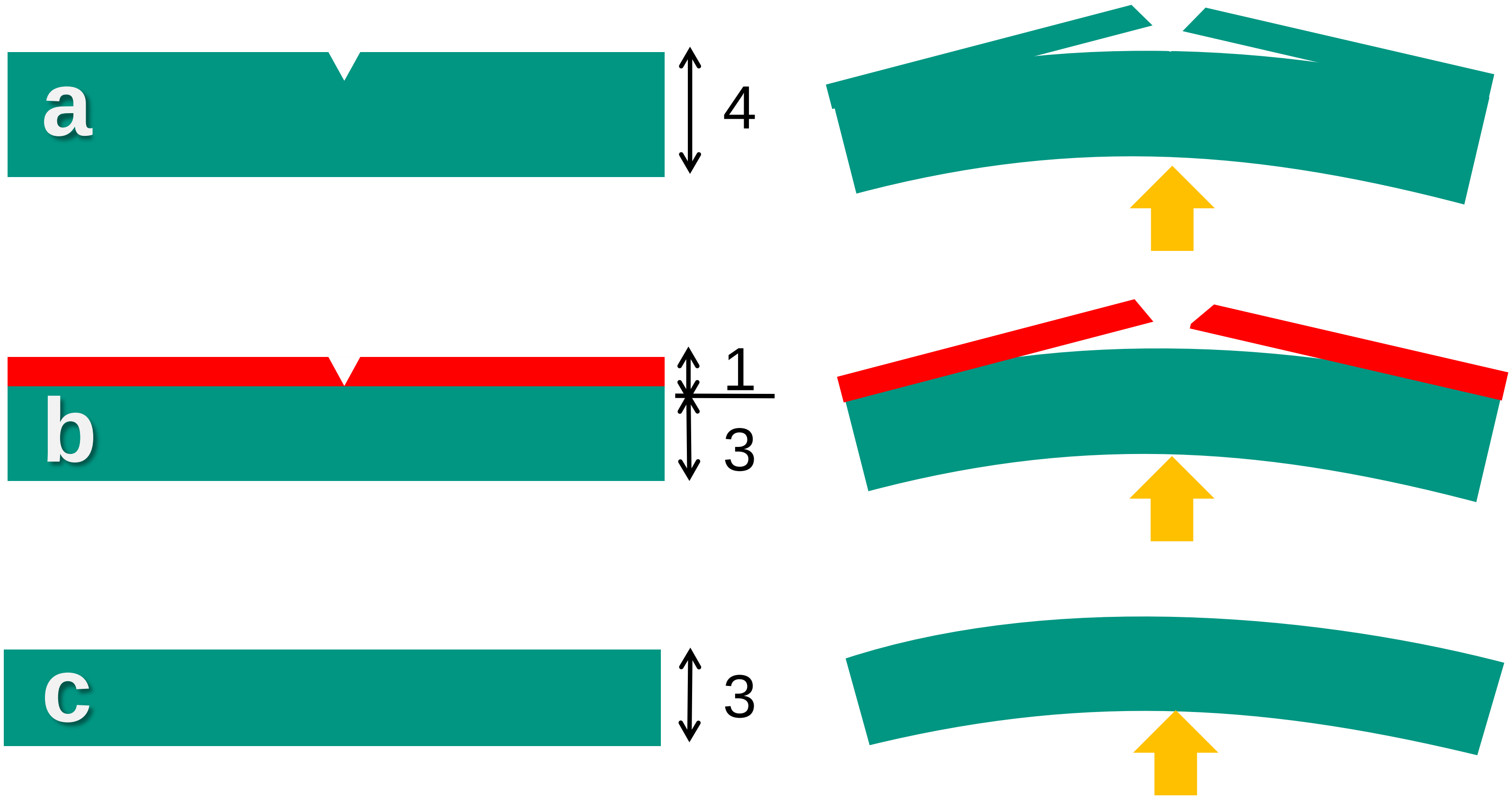








Delamination, Simple Analogy



Prediction: *Delamination will disappear with flat surfaces!*

Surface Fabrication and Notch Effect

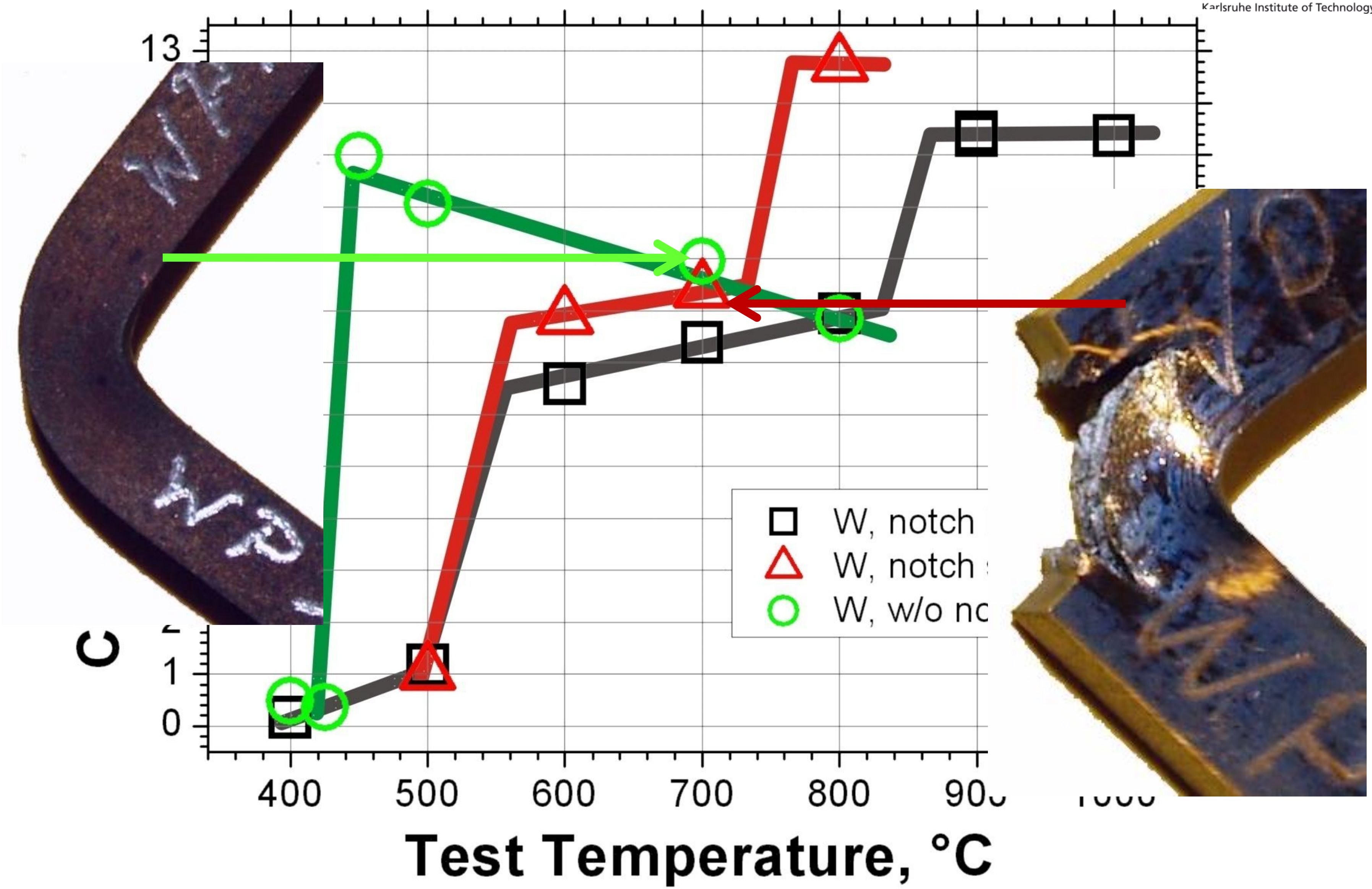


Plate Materials

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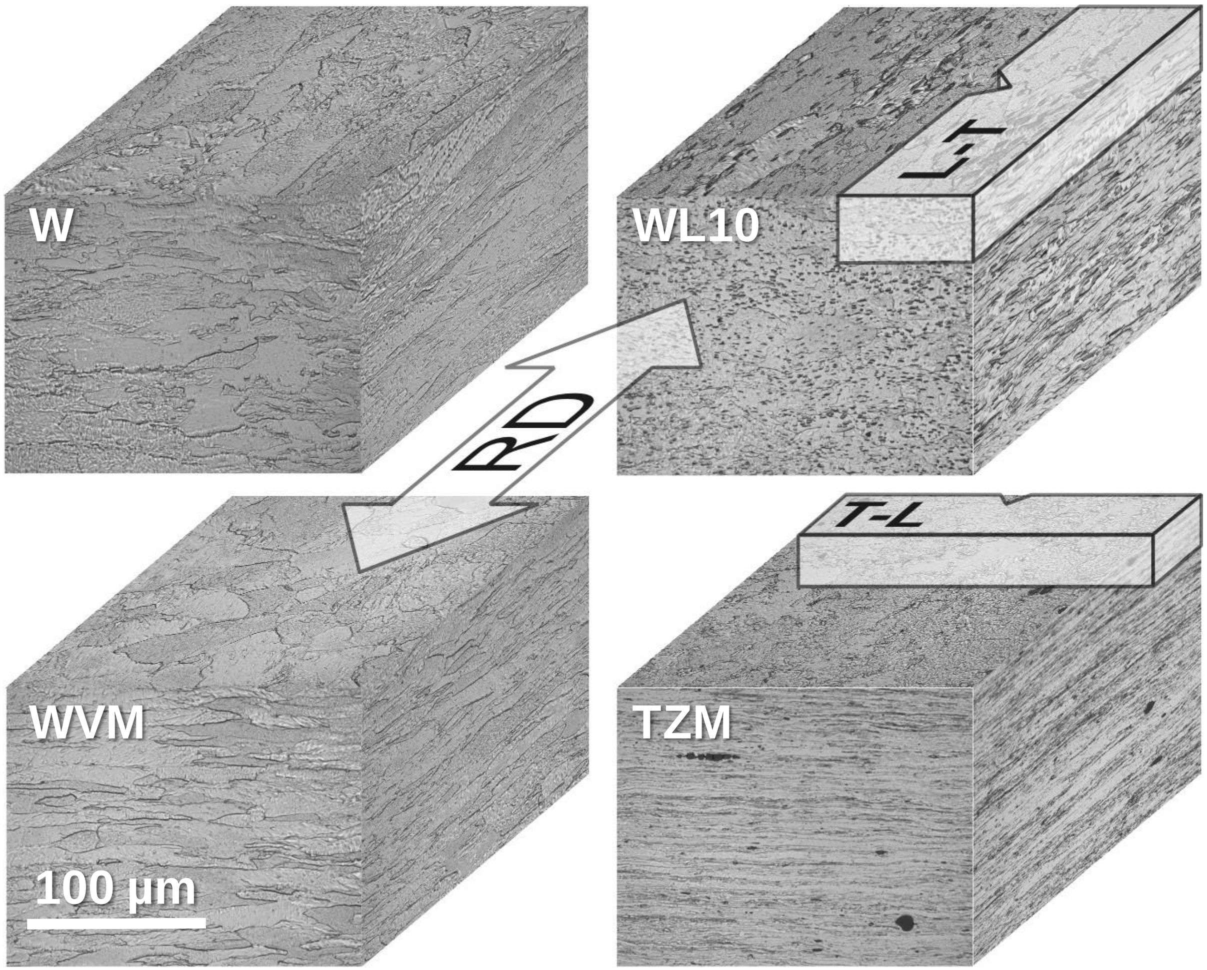
thickness 3.6 mm	91%

thickness 3.6 mm	91%



thickness 4 mm	90%

thickness 3.6 mm	91%

Plate Microstructure

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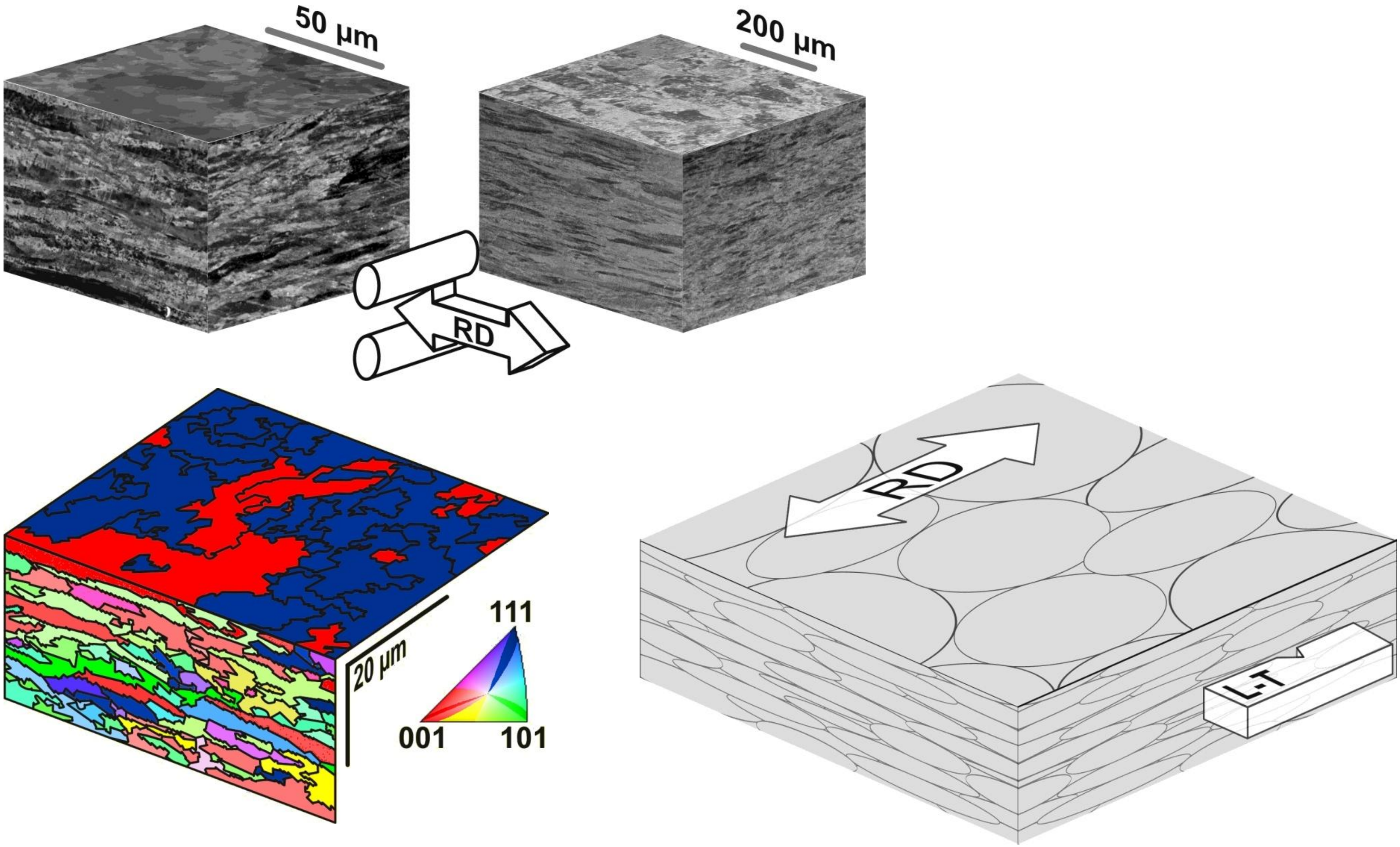
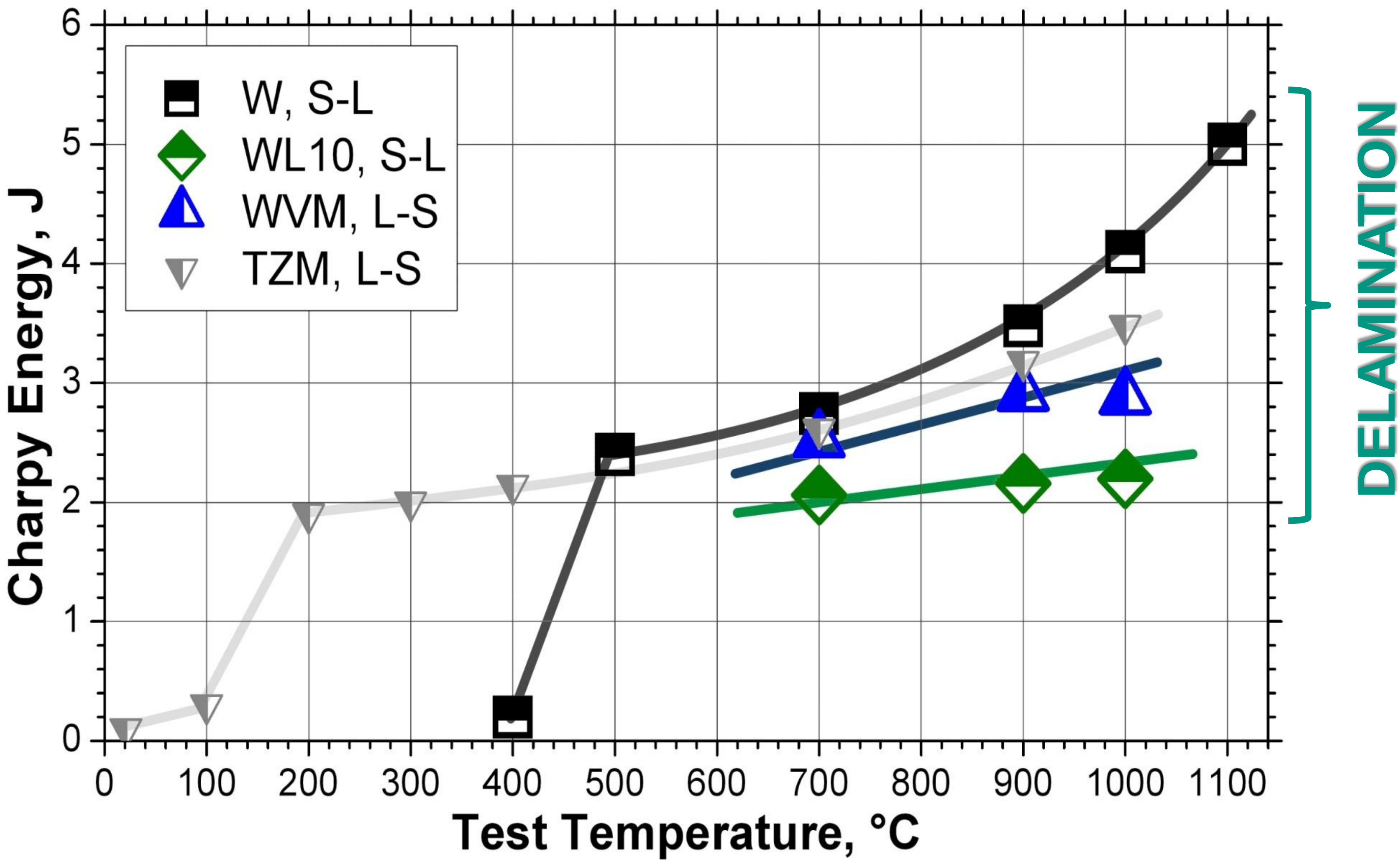


Charpy Tests, Plate Materials



Fracture: W & WL10, plates

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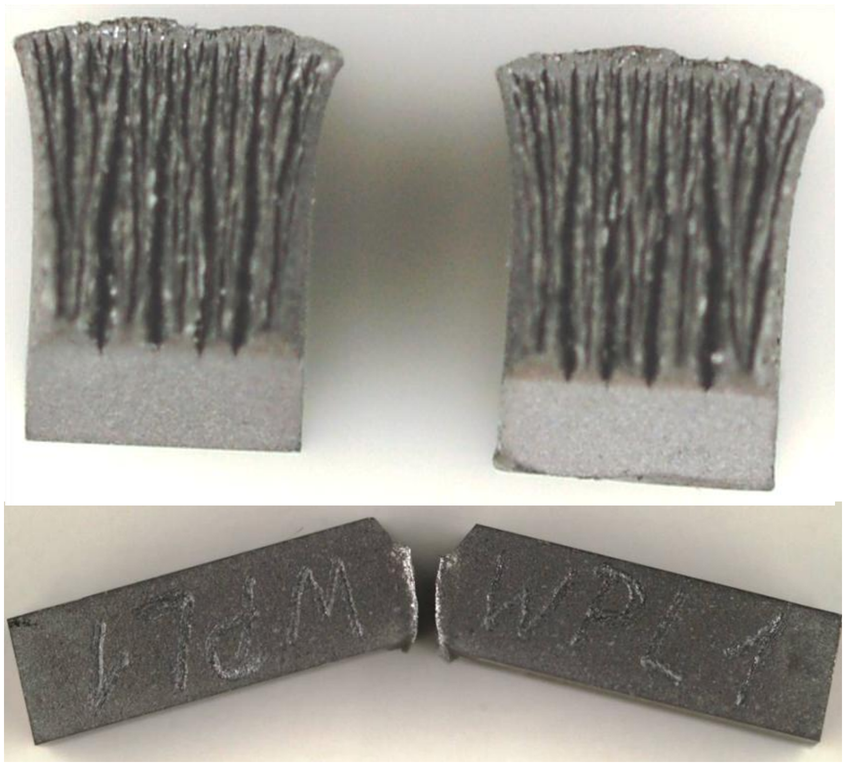
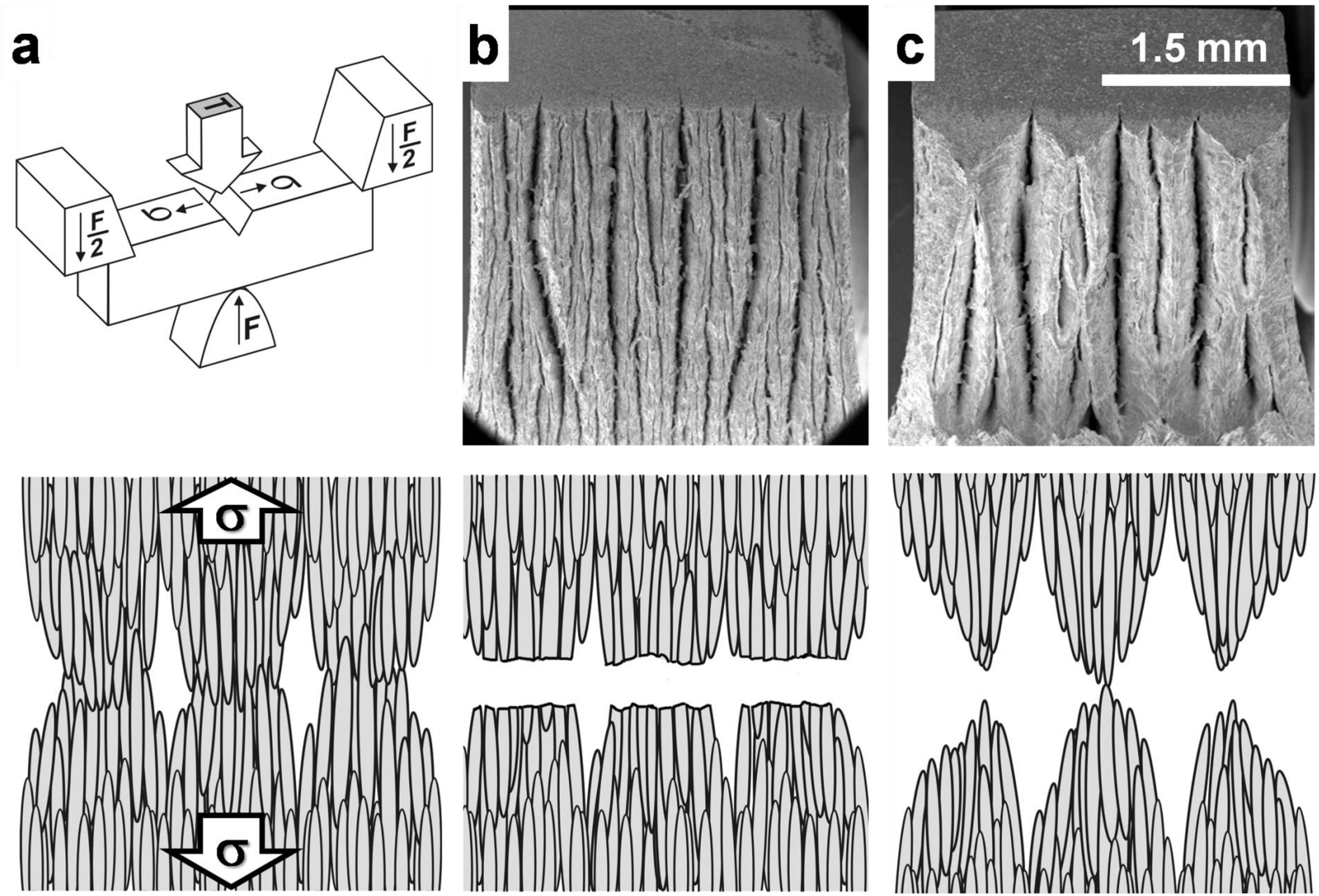
W



WL10

Tested at 1000 °C !!!

Delamination Fracture in Plates



Important Conclusions for HHFCs

- **Plates delaminate at all temperatures**
- **High deformation degree improves D-Delam.-TT**
- **Oxide particles (and K doping) promote delamination**
- **Microcracks (by EDM) promote delamination**
- **Notches, edges, grooves, etc. promote delamination**

In other words:

- **Use highly deformed W rod material**
- **Produce parts with flat surfaces by milling, sawing, turning (avoid EDM!)**

But how to fabricate divertor parts?

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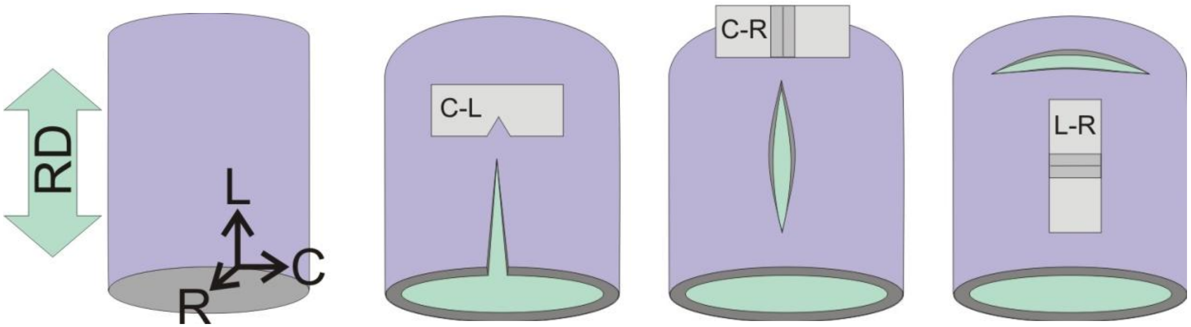
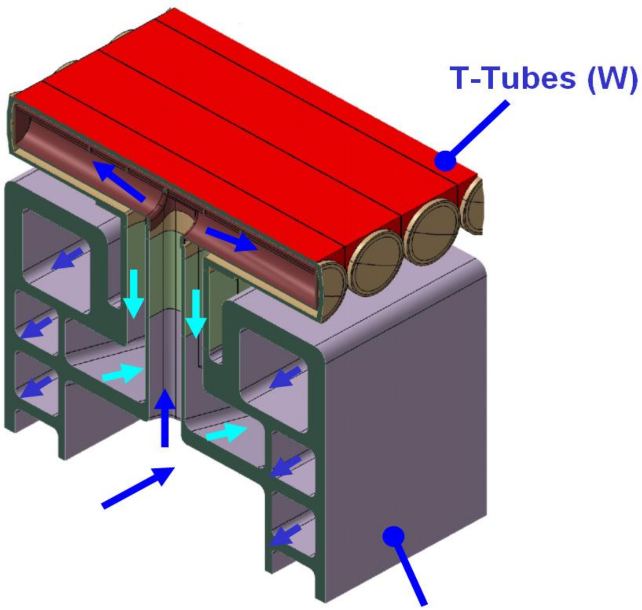
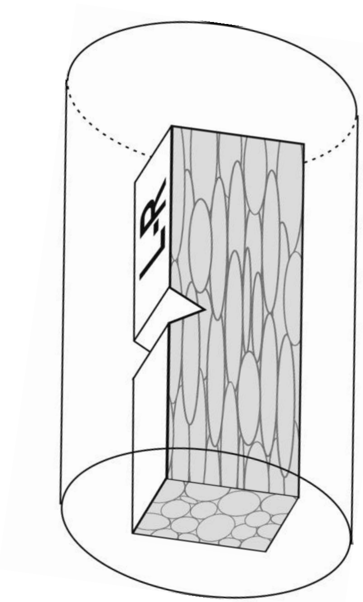
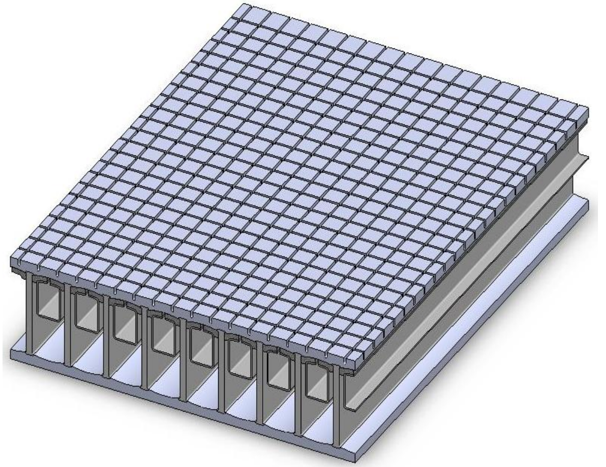


→ J. Reiser et al., FZK

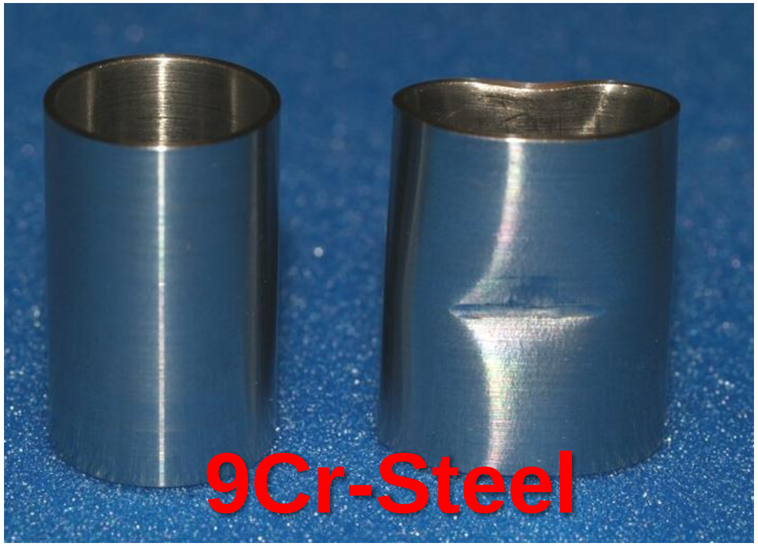






Problem of Microstructure Orientation

Pipe Impact Test



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, …)

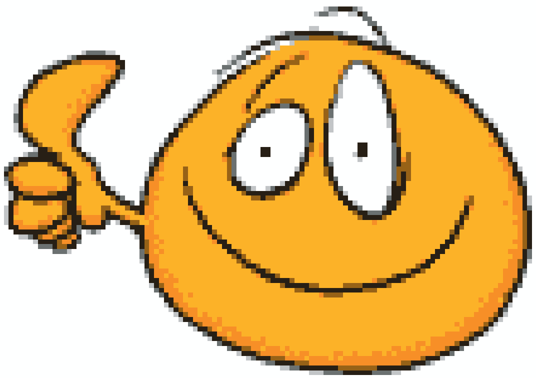
There is no structural divertor material (yet)

- Eurofer (heat conductivity, thermal expansion, 550°C limit, …)
- SiC_f/SiC (irradiation defects, He prod., joining, 5 MW/m² limit, …)
- Tungsten (ductility/irradiation, spec. fabrication issues)

Alternatives/Outlook

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

… and that's only one reason why fusion is so challenging!



THANKS

for your interest

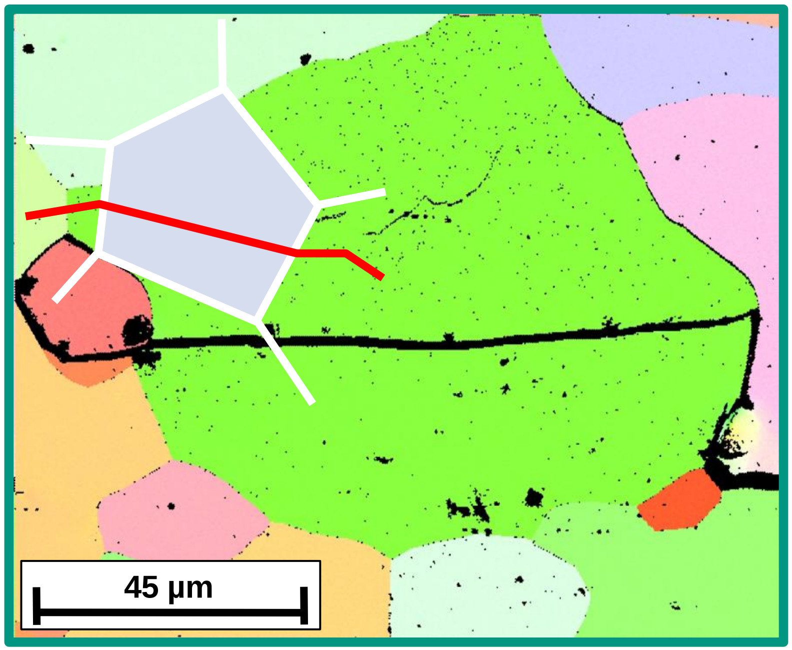
Additional Slides

Tungsten Problematic

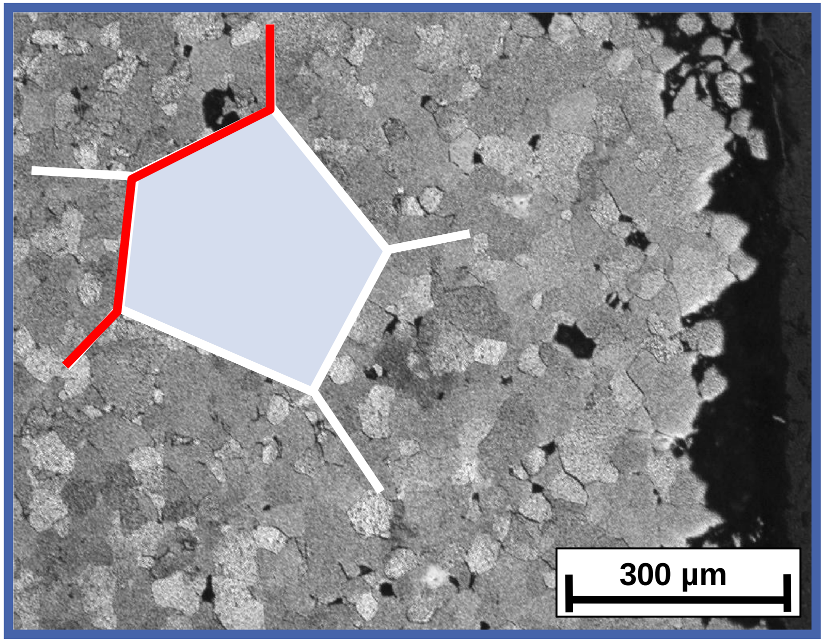
Question: **Is tungsten a brittle material?**

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

Trans-Crystalline



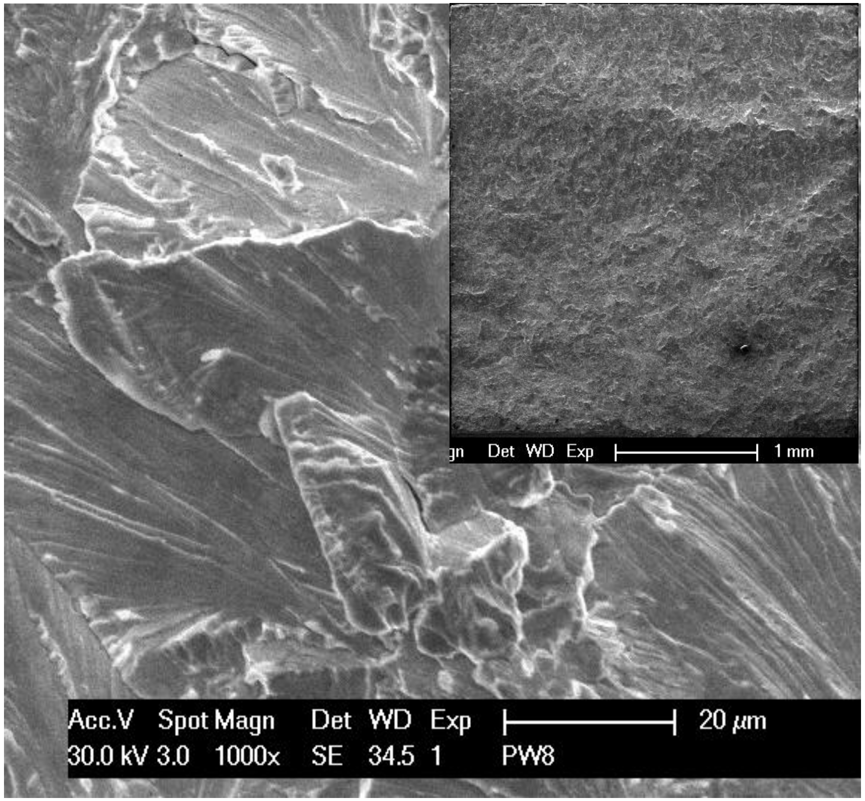
Inter-Crystalline



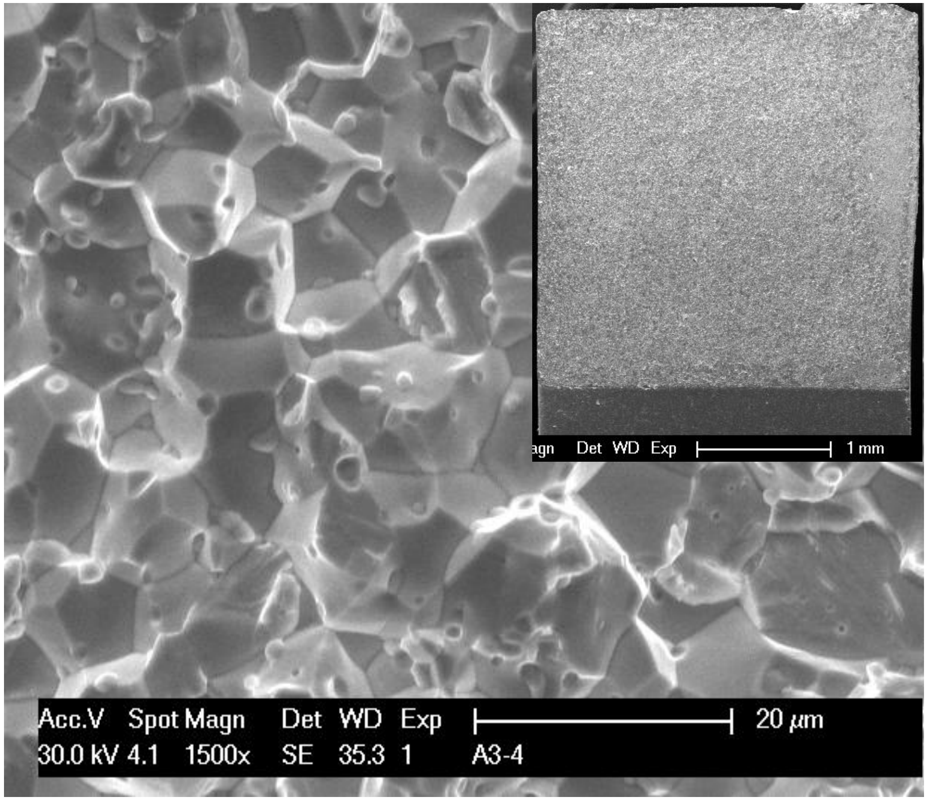
→ R. Pippan et al., ÖAW

Tungsten Problematic

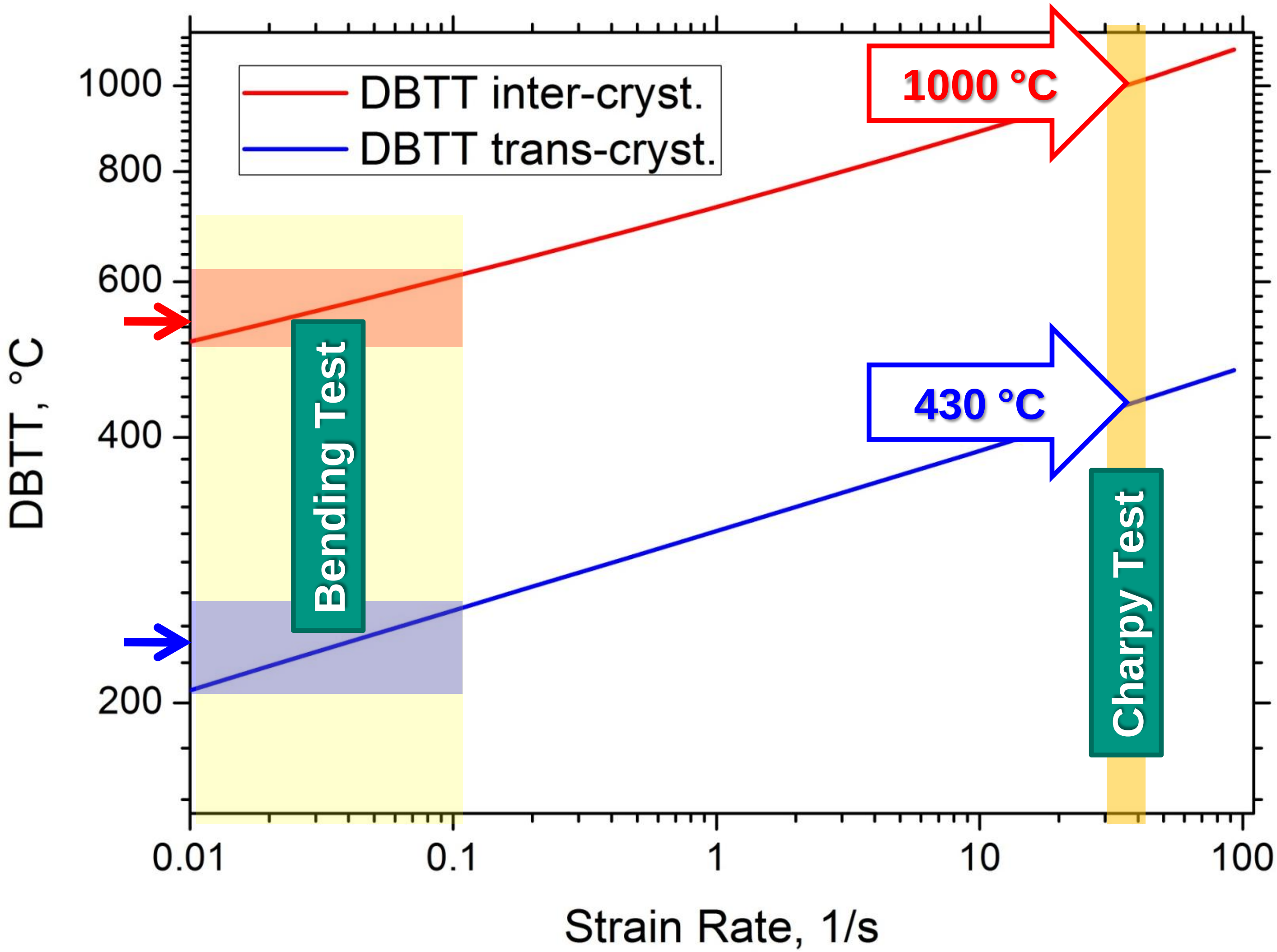
Trans-Crystalline



Inter-Granular

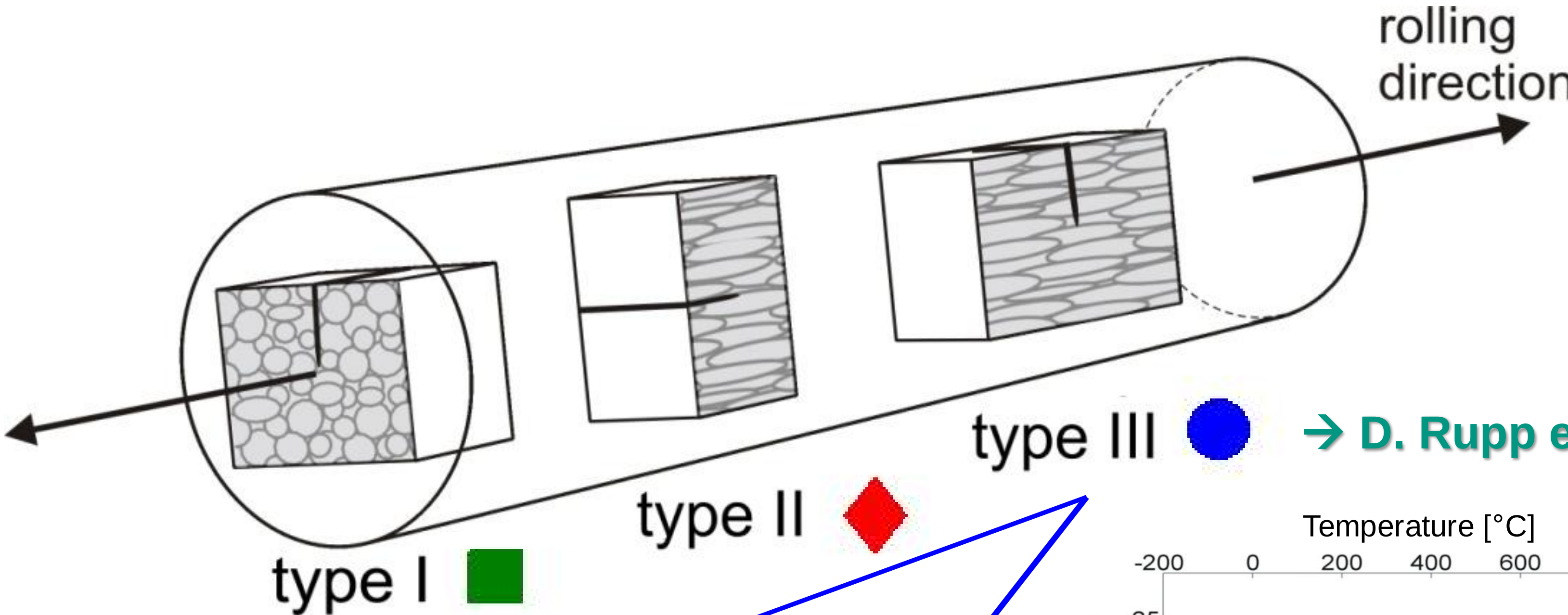


DBTT is Strain-Rate Dependent

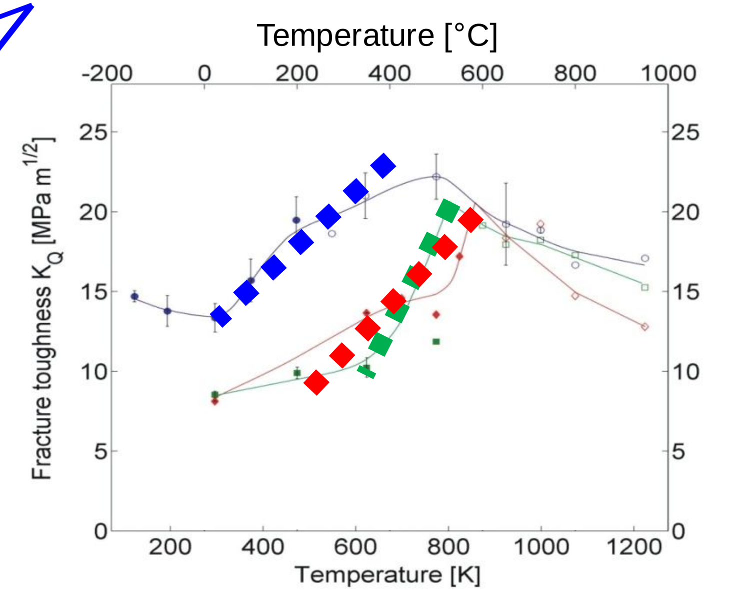


→ **S. Roberts, J. Murphy, D. Armstrong, Oxford**

Influence of the Grain Shape



→ **D. Rupp et al., FZK**



Notches Influence Grain Boundary Fracture