Karlsruher Institut für Technologie

FUSION
KIT - EURATOM
ASSOCIATION

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

FUSION FOR ENERGY

Development of high performance materials for nuclear fusion power plants

Michael Rieth

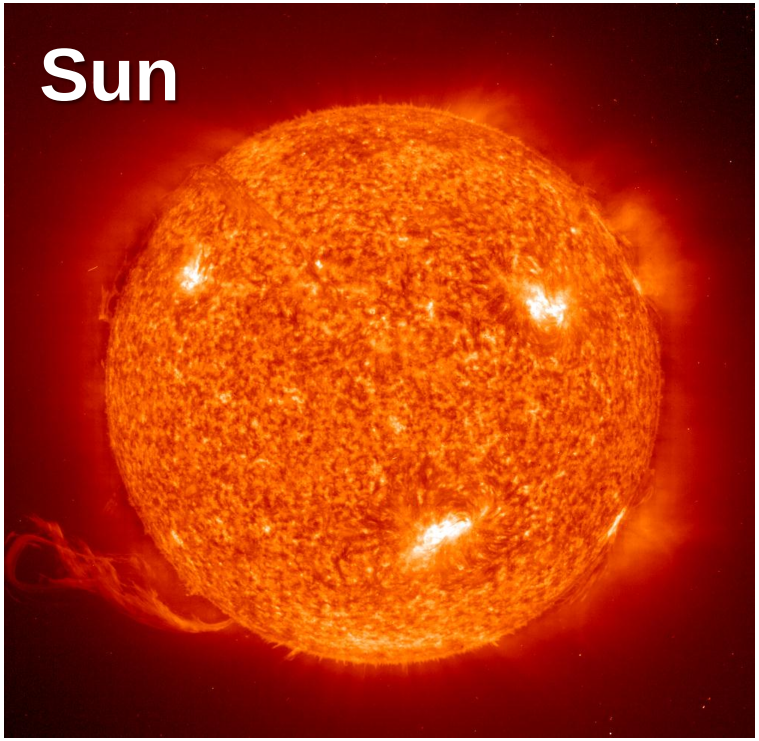
KARLSRUHE INSTITUE OF TECHNOLOGY, INSTITUTE FOR APPLIED MATERIALS – Applied Material Physics (KIT, IAM-AWP)

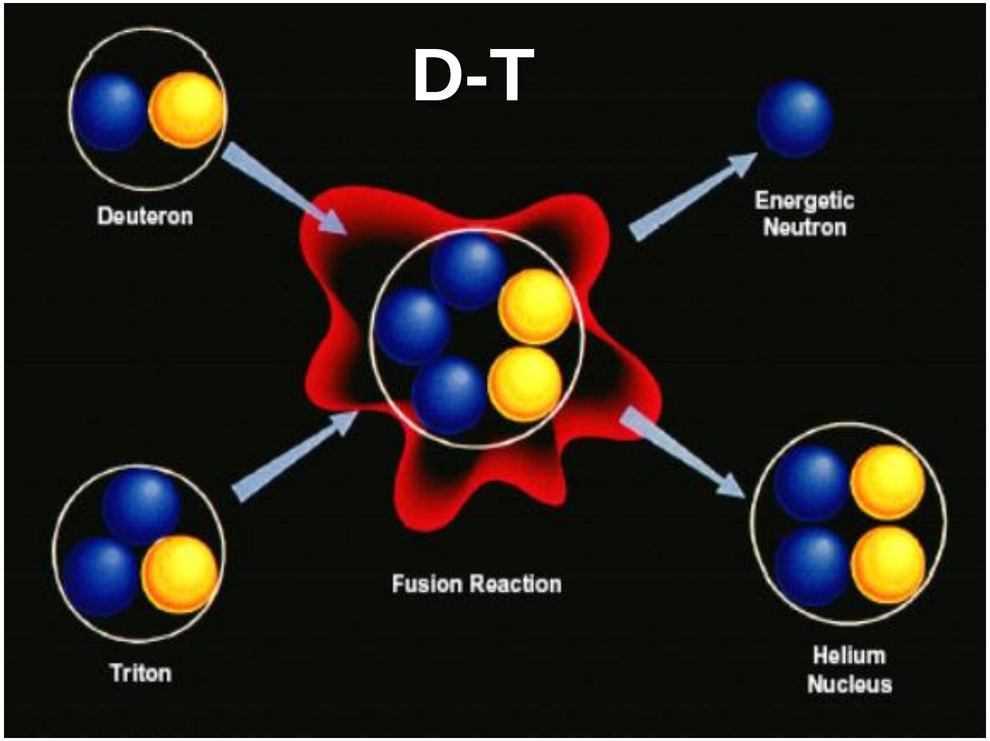
Contents

Karlsruher Institut für Technologie

- Introduction to Nuclear Fusion
- High Heat Flux Components
- Divertor Designs
- Divertor Material Problems
- High Performace Steel Developments

Nuclear Fusion





Gravity confined

T = 15 Mio. °C

$E_t = 3.7 \times 10^{17}$ GW

→ $\rho_E = 30$ W / m³

Magnetic confinement

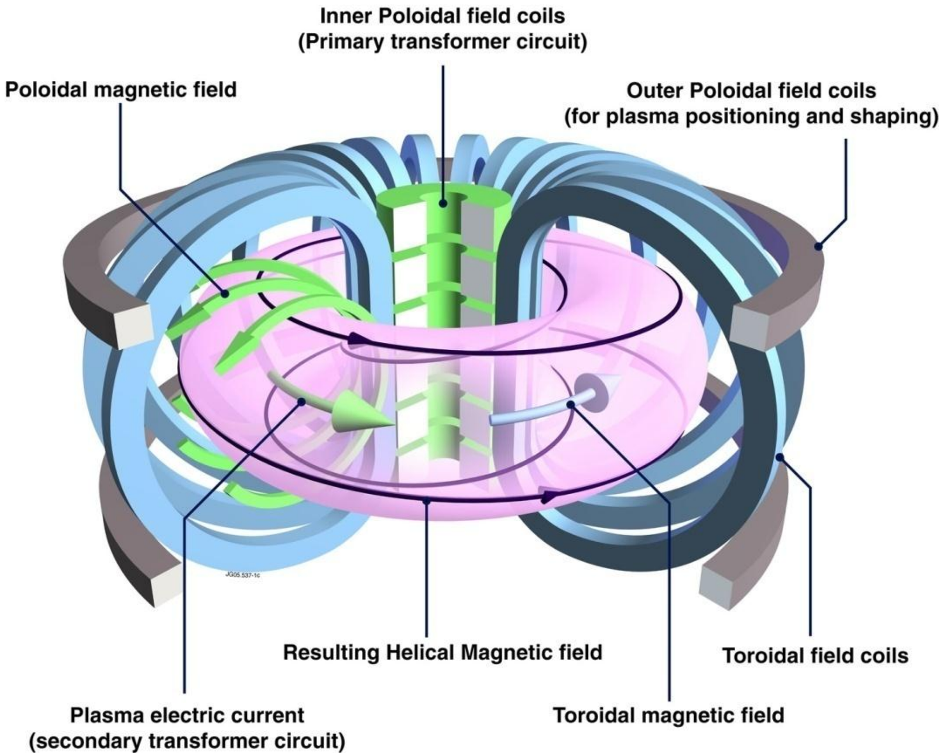
$E_t \sim 3.5$ GW

$\rho_E \sim 4$ MW / m³

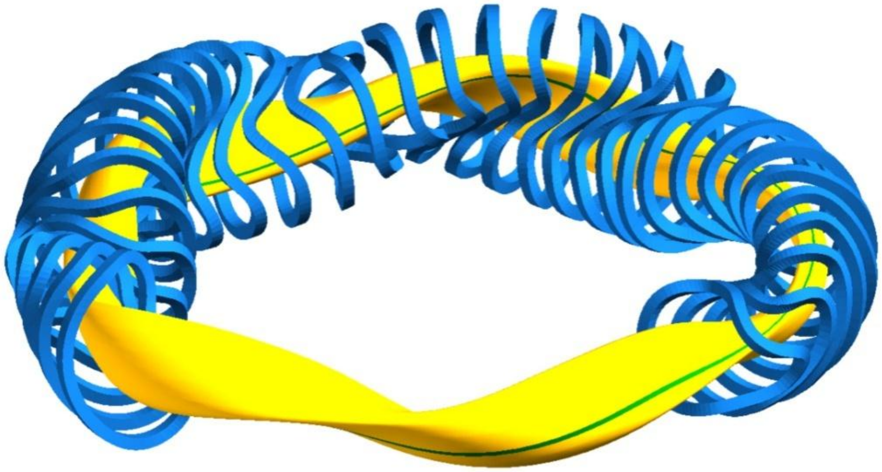
→ T = 100 Mio. °C

Magnetic Confinement

Tokamak

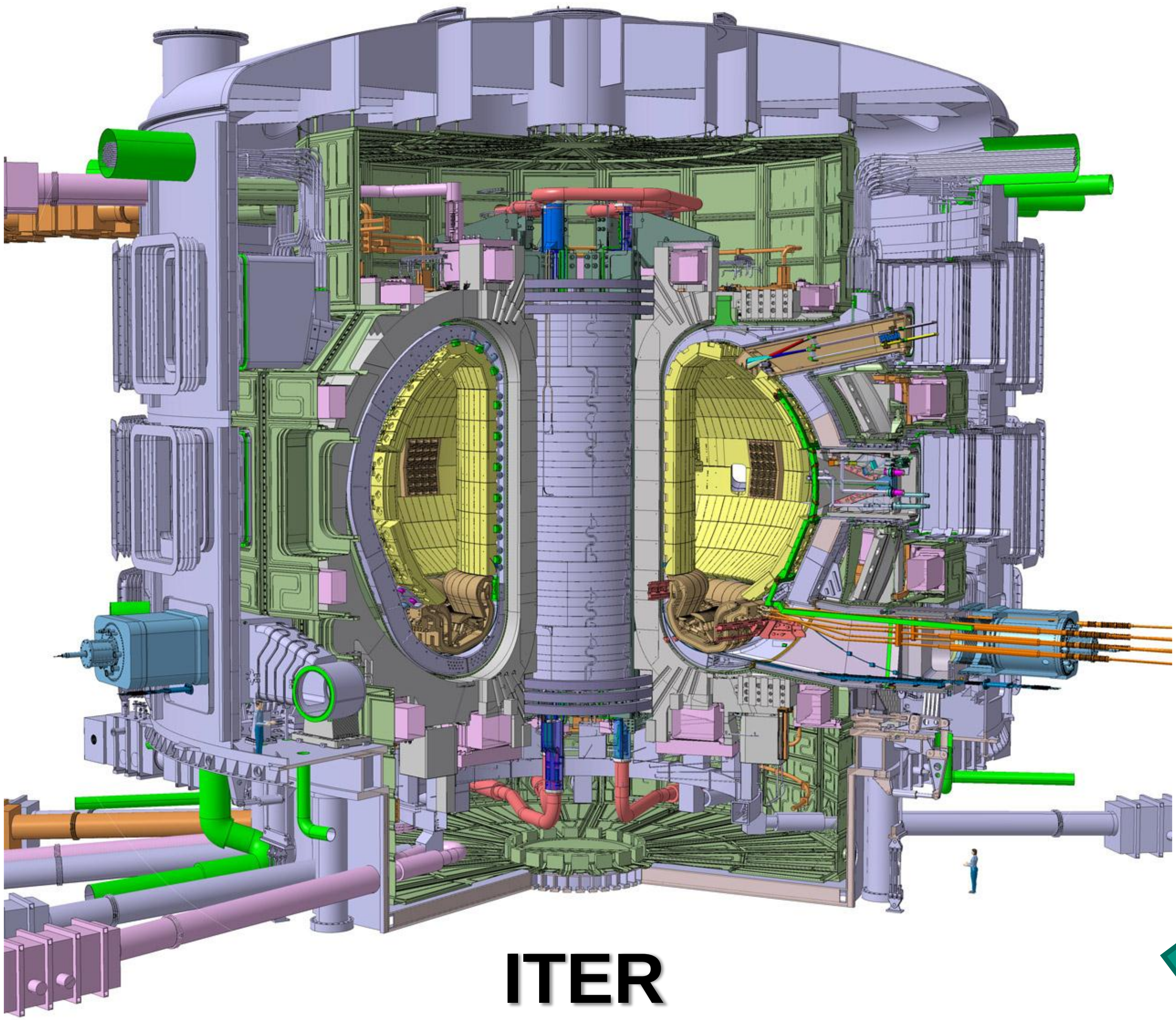


Stellarator



Research TOKAMAKs

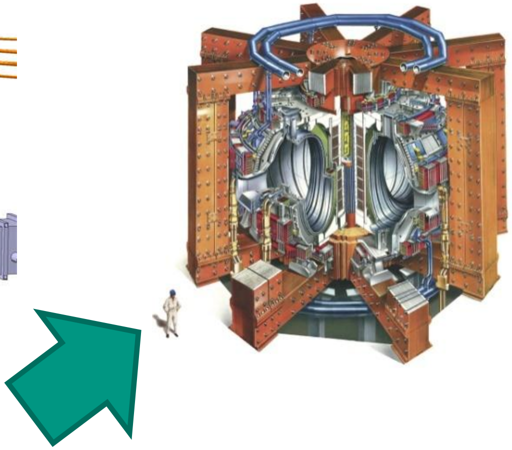
Karlsruher Institut für Technologie



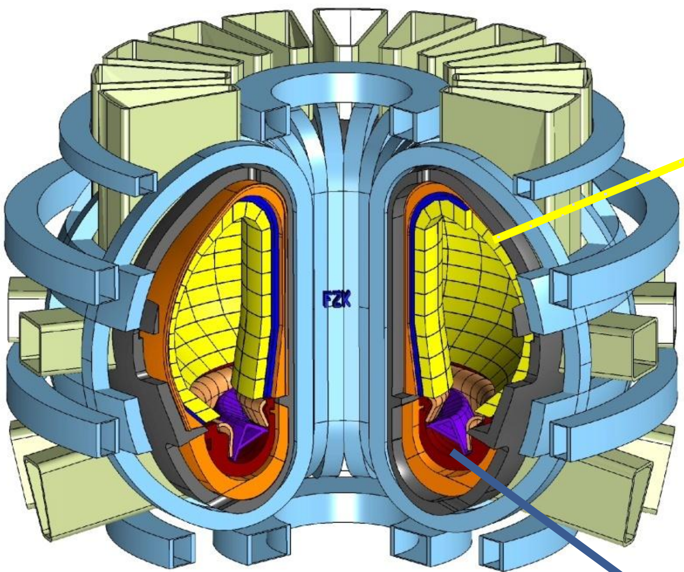
ITER

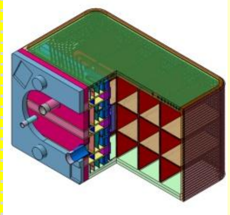
Nuclear fusion is relatively easy to accomplish. The trick is to gain energy out of it!

JET



High Heat Flux Components





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

DEMOnstration, PROTOtype & Power Reactor

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

Some Fusion Requirements

Karlsruher Institut für Technologie

Material

- Irradiation resistance (em-brittlement, swelling, trans-mutation)
- High temperature strength
- Thermal conductivity
- Low activation
- Oxidation

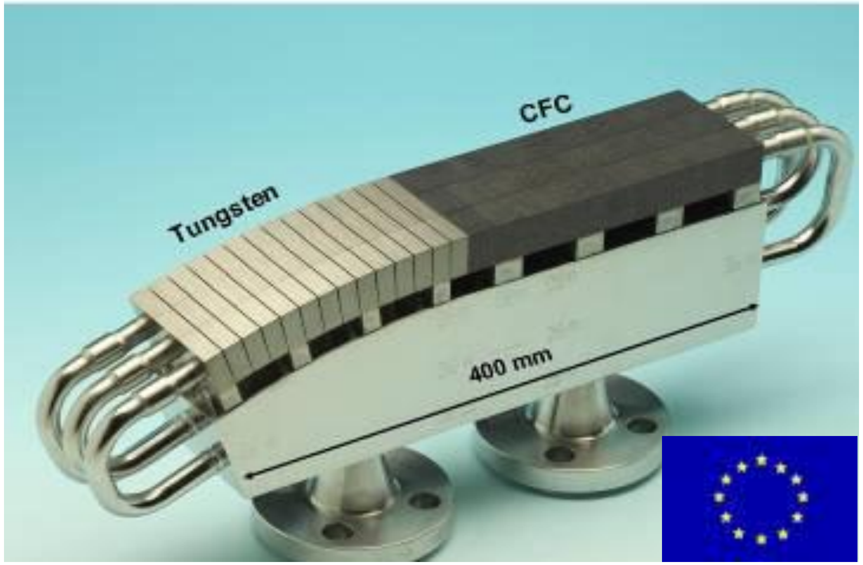
- *No* Mo, Ta, Zr, SiC, Ni, …
- 9% Cr steels
- Vanadium (e.g. V-Cr-Ti)
- Tungsten materials

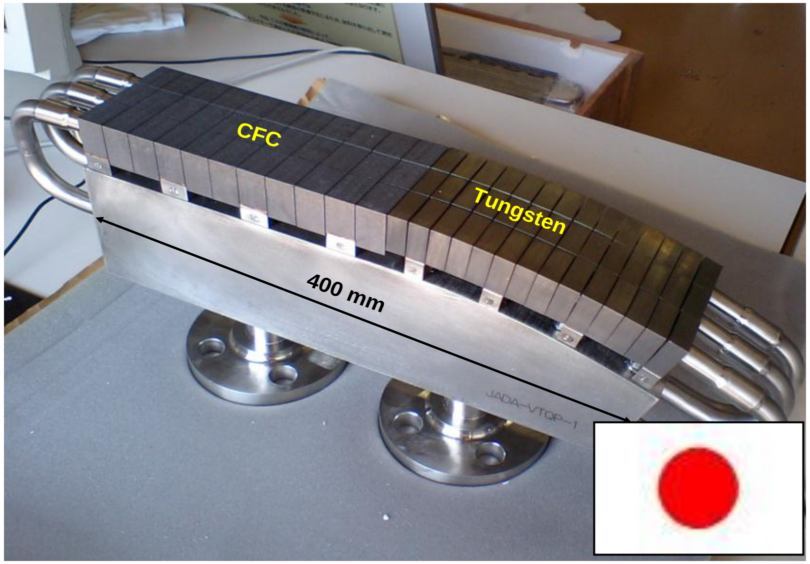
Technology

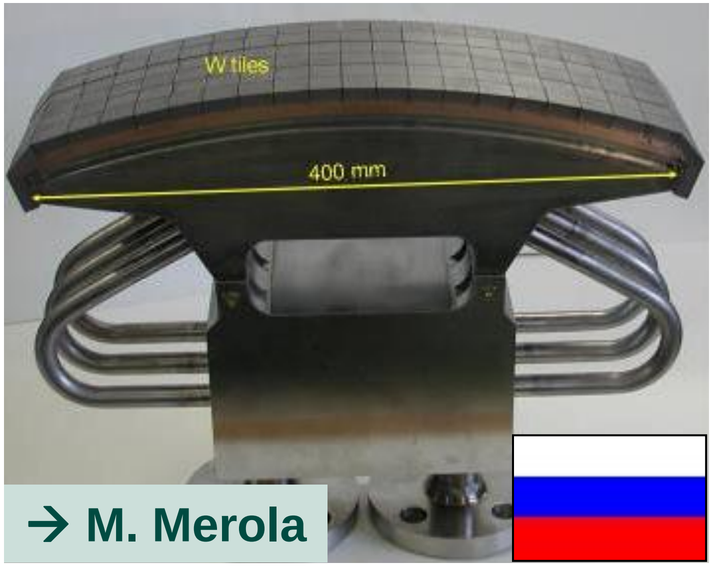
- Coolant compatibility
- Heat flux
- Neutron flux
- Safety
- Maintainability
- Rentability

- *No* water cooling (Temp.)
- *No* liquid metal (Magnetics)
- Gas → Helium
- Design → Temperature limits

ITER Divertor Concept (Cu & H_2O)



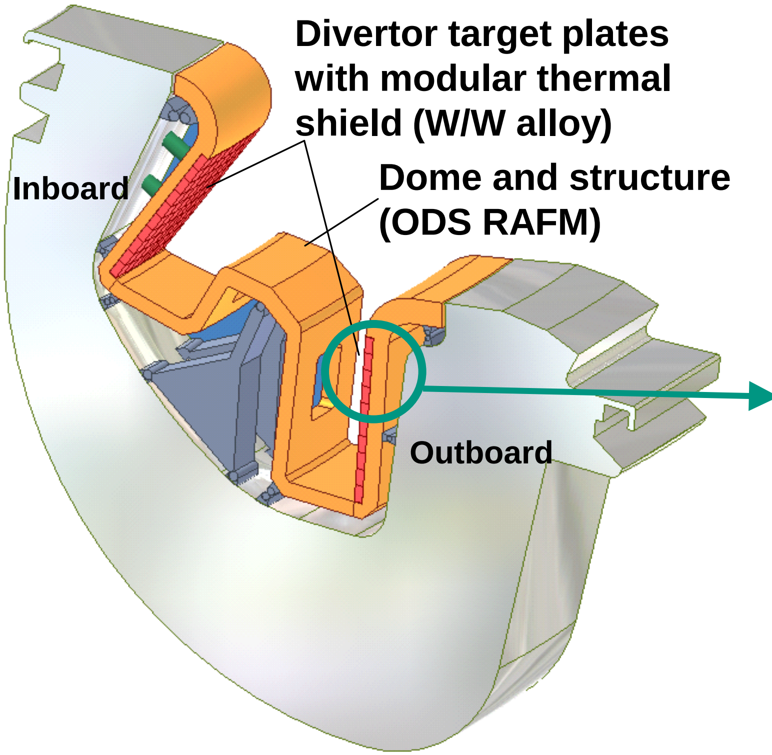


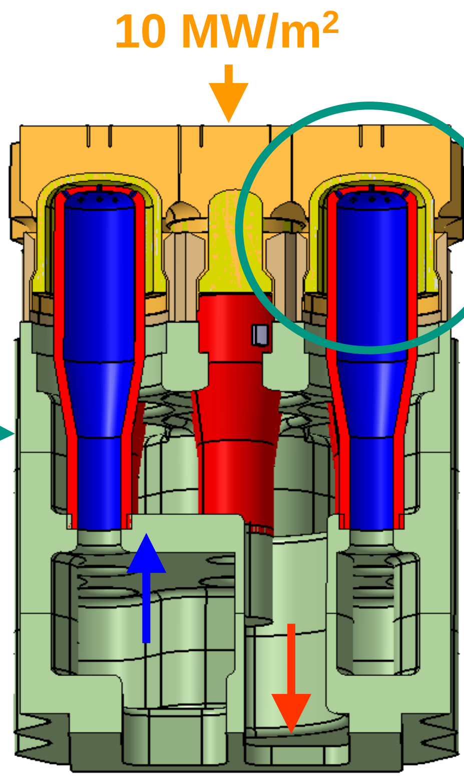


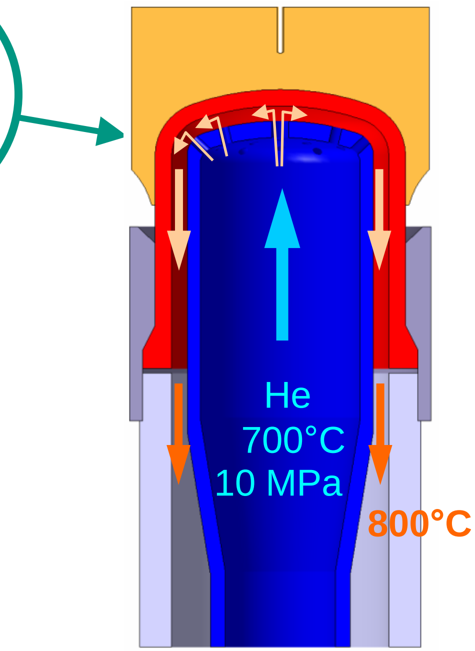
→ M. Merola

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

Tungsten & Helium, 10 MW/m² Concepts







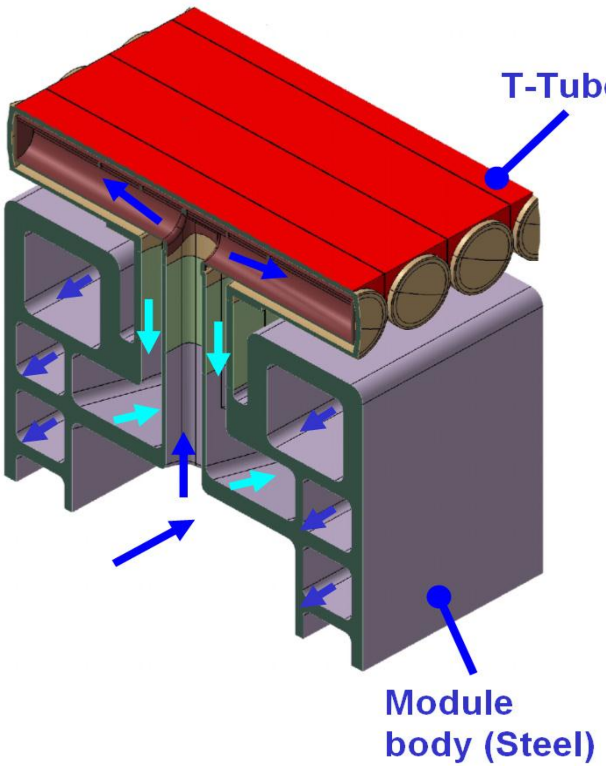
Divertor Cassette

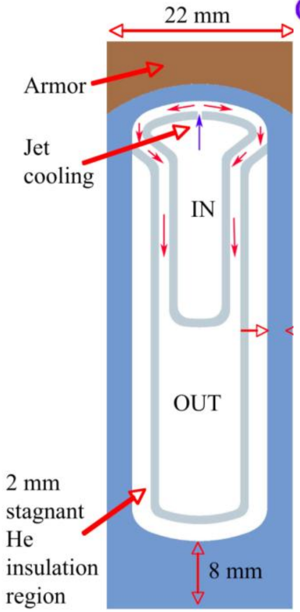
9-Finger Module

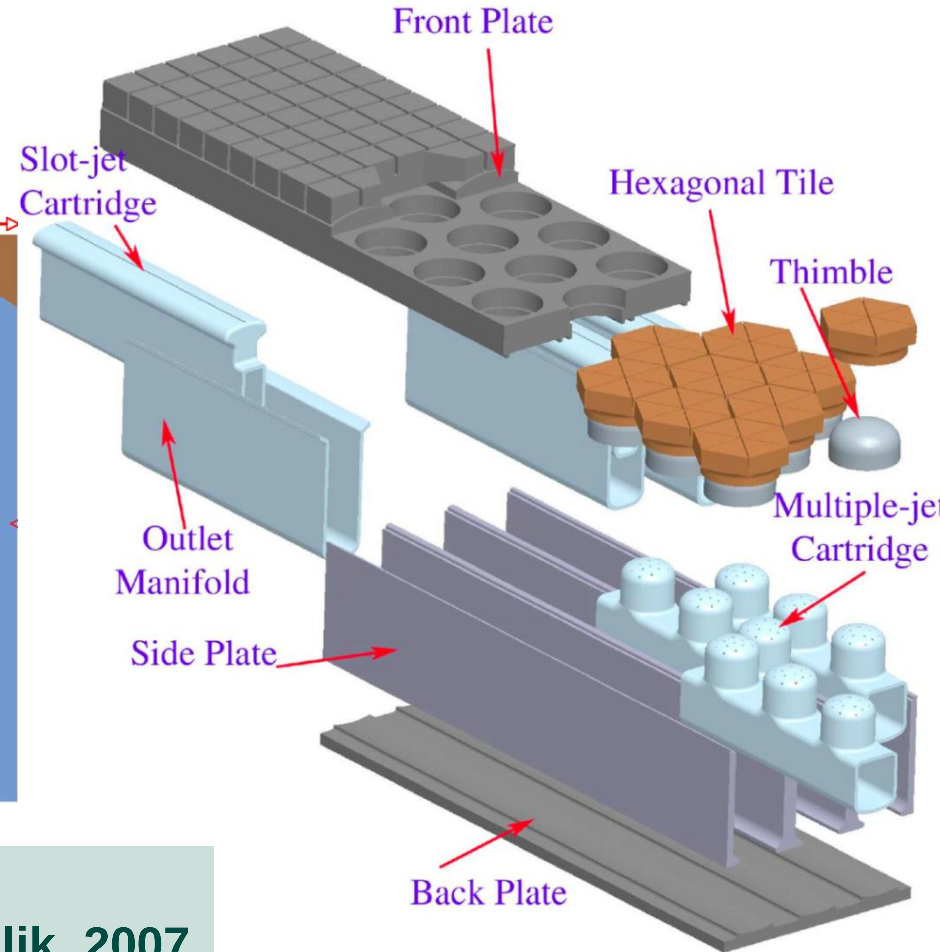
Finger

→ 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

Divertor Armor Material Problems

Karlsruher Institut für Technologie

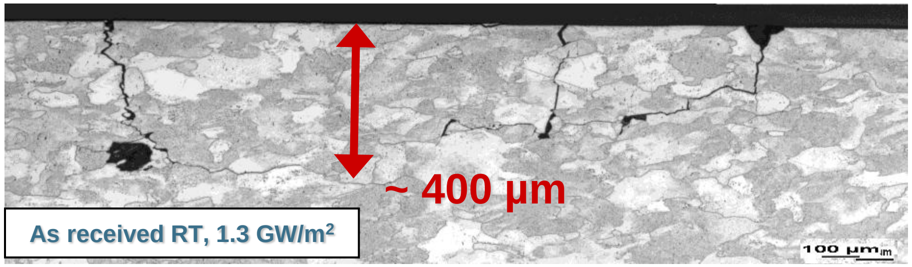
Typical Important Questions in this Field

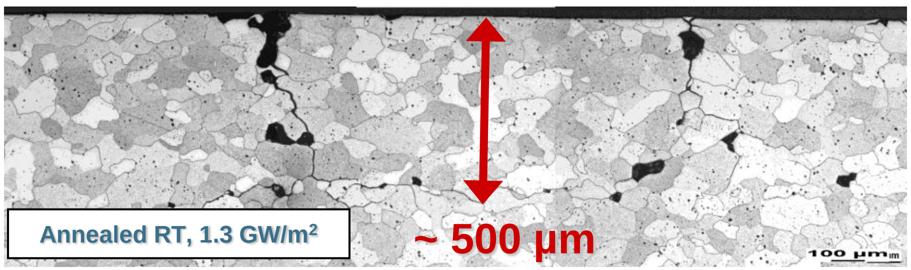
- What is the optimized microstructure for fusion relevant thermo-mechanical load conditions?
- How high is the real sputtering rate when surface morphology changes come into play?
- Is it possible to increase the crack resistivity?
- What are possible solutions for the oxidation problem?

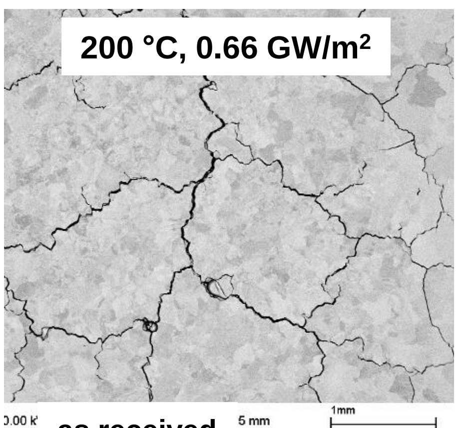
Tungsten Armor Materials: High Heat Flux Tests

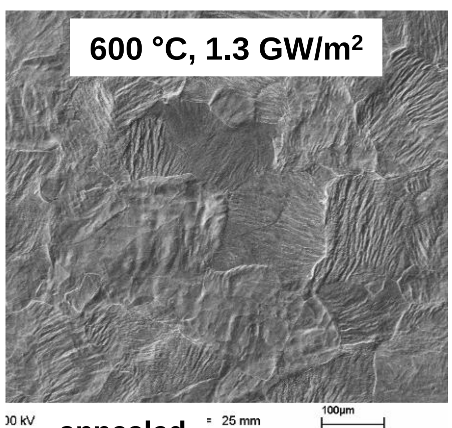
Karlsruher Institut für Technologie

Electron Beam



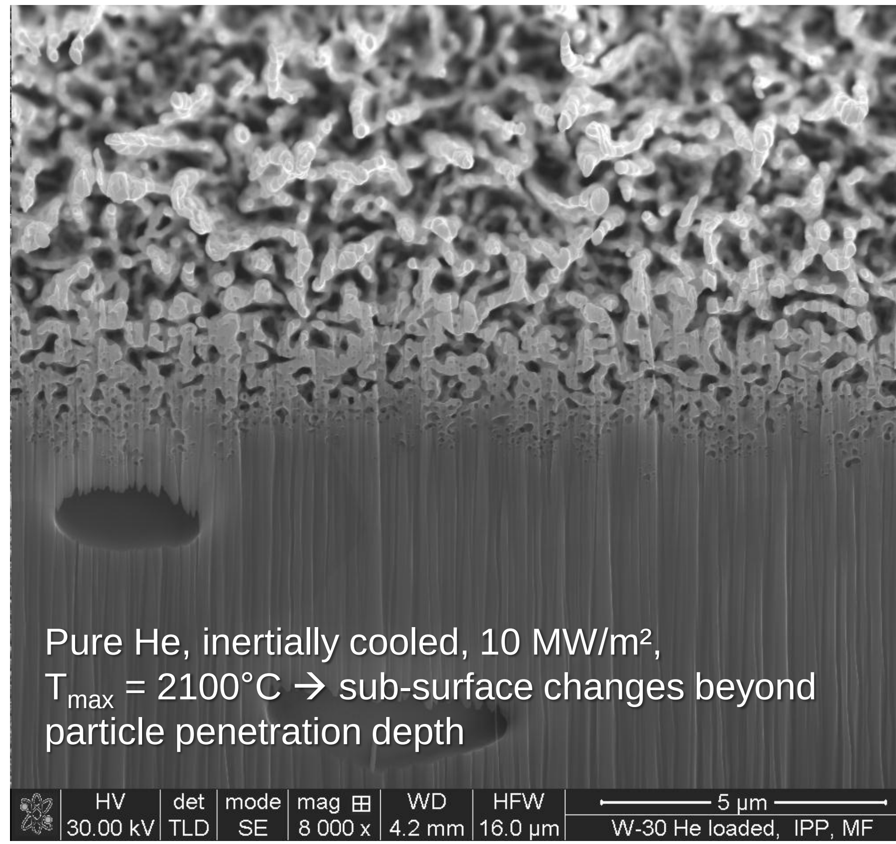






→ G. Pintsuk, J. Linke, et al., FZJ

Hydrogen/Helium Ion Beam

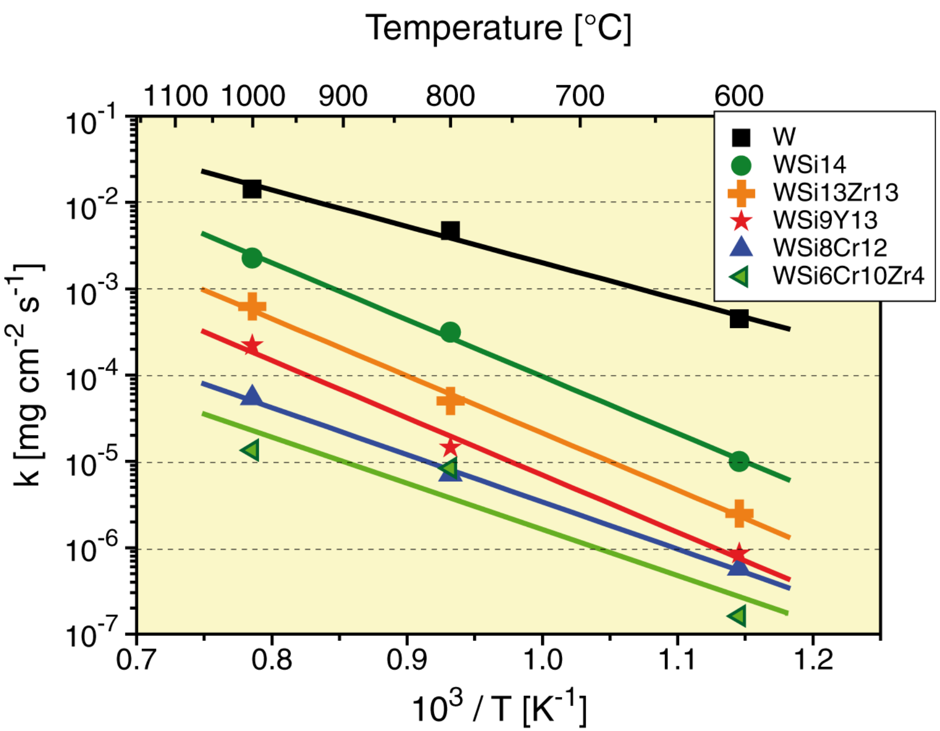


→ H. Maier, H. Greuner, M. Rasinski, Ch. Linsmeier, IPP

Oxidation Test Results

Karlsruher Institut für Technologie

Arrhenius plot of oxidation rates of tungsten and tungsten alloys



Alloy	W	Si	Cr	Zr
WSi8Cr12	46	30	24	-
WSi3Cr10Zr5	56	13	24	7

Composition in at.%

Linear oxidation rates of W-Si-Cr and quaternary alloys comparable.

Oxidation resistance can be increased by factor 100…1000

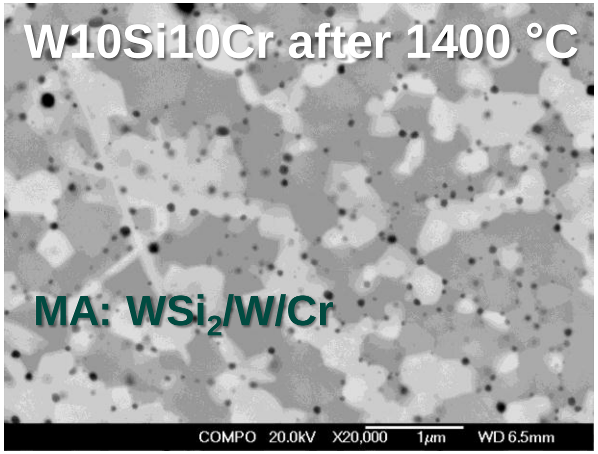
Oxidation rate (k) has been calculated from weight increase versus time, linear fit.

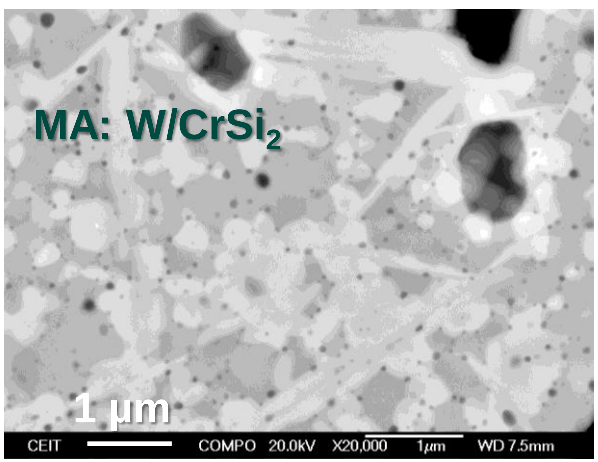
F. Koch, IPP

Oxidation Resistant Tungsten Armor Materials

Karlsruher Institut für Technologie

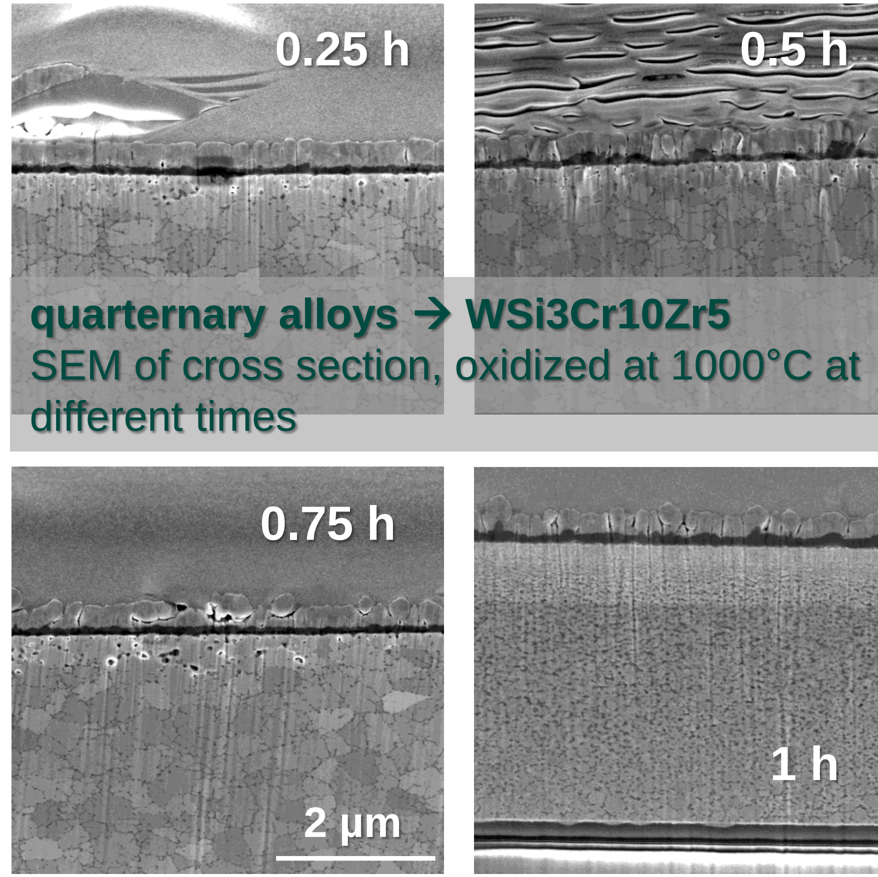
W-Si-Cr Protection Bulk Materials





→ C. García-Rosales, P. López, N. Ordás, CEIT

Self Passivating Thin Films



quarternary alloys → WSi3Cr10Zr5

SEM of cross section, oxidized at 1000°C at different times

→ F. Koch, C. Lenser, M. Rasinski, M. Balden, Ch. Linsmeier, IPP

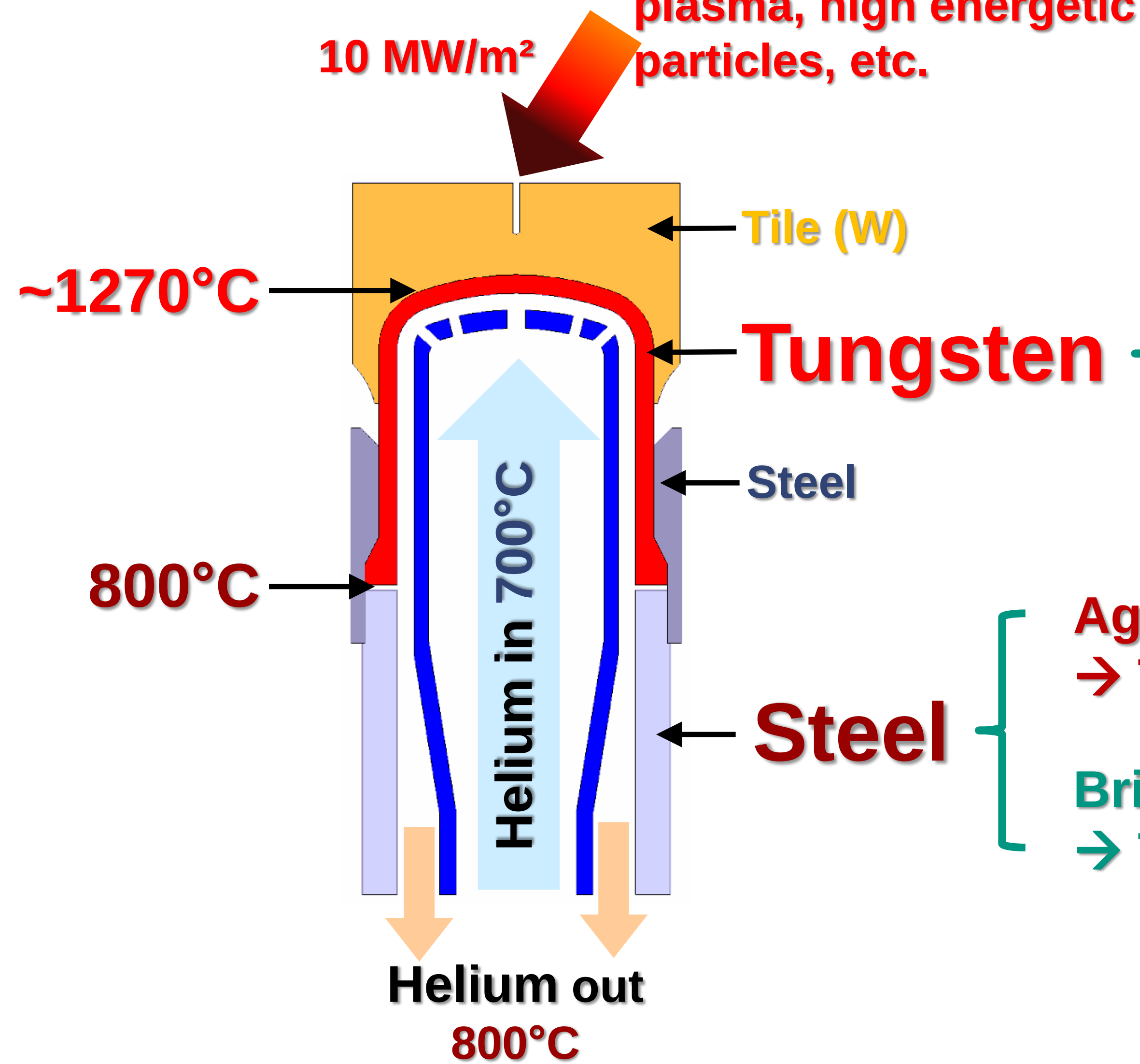
Structural Tungsten Material Problems

Karlsruher Institut für Technologie

Typical Important Questions in this Field

- Can the ductile-to-brittle transition temperature (DBTT) be significantly decreased?
- Can we live with a pronounced anisotropic micro-structure or is it necessary to produce isotropic structured materials?
- Is it possible to reach a reasonable compromise between strength, ductility, and heat conductivity?

He Cooled Divertor Dilemma



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

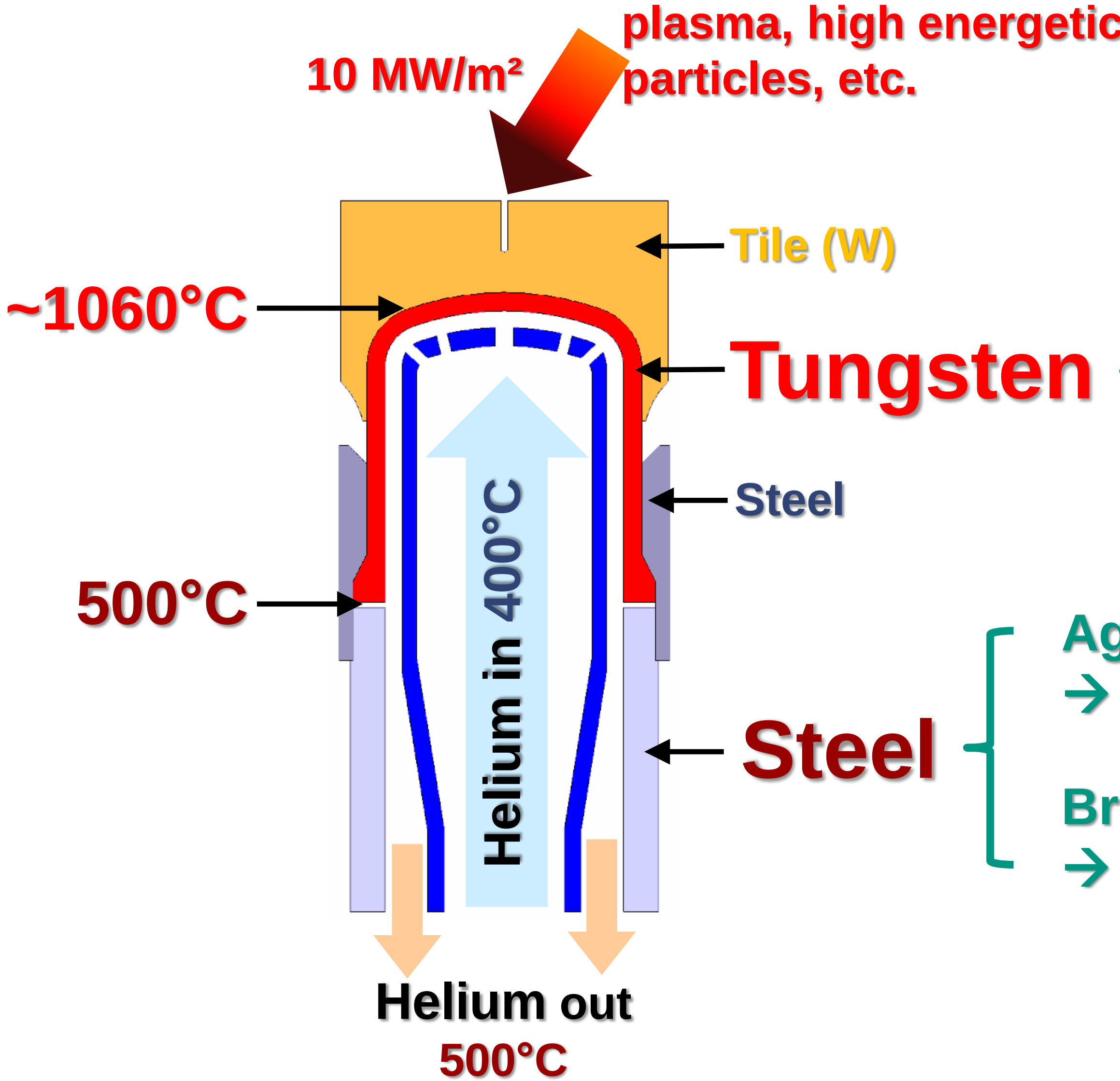
Steel:
- Aging, Creep → T_{op}<550 °C !
- Brittle Fracture → T_{op}>350-400 °C ! ✓

2nd BRAGFOST Symposium
2011, Podsdam, Germany

M. Rieth: Development of high performance materials for nuclear fusion power plants

Institute for Applied Materials (IAM-AWP)

He Cooled Divertor Dilemma



Tungsten

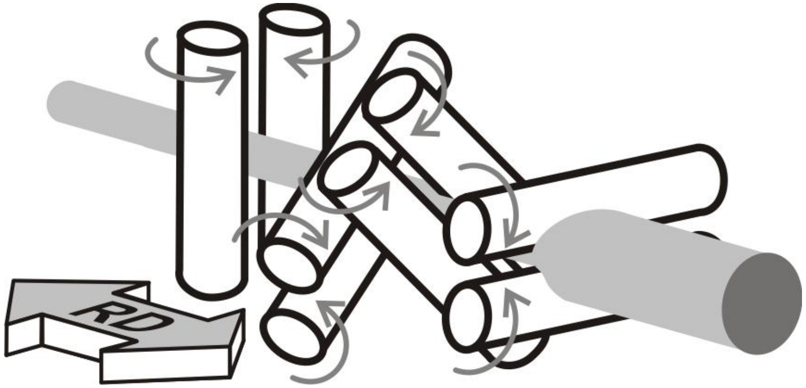
- Recrystallization → T_{op}<1300 °C ! ✓
- Brittle Fracture → T_{op}>800 °C (???)

Steel

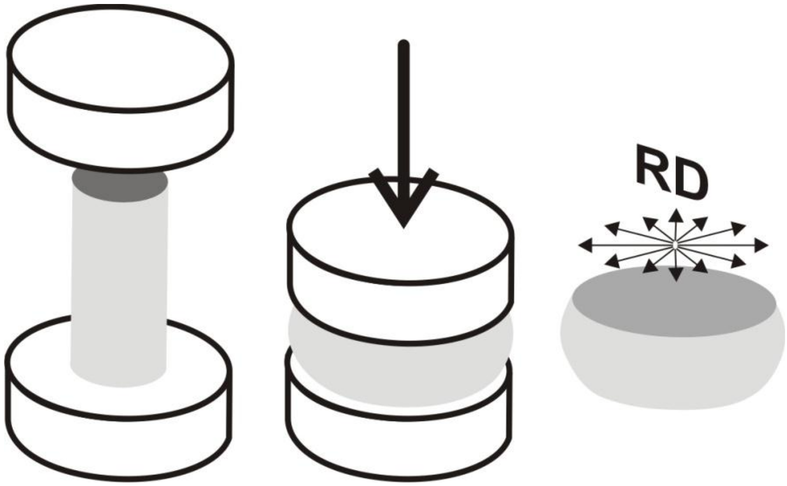
- Aging, Creep → T_{op}<550 °C ! ✓
- Brittle Fracture → T_{op}>350-400 °C ! ✓

Fabrication of Half-finished Products

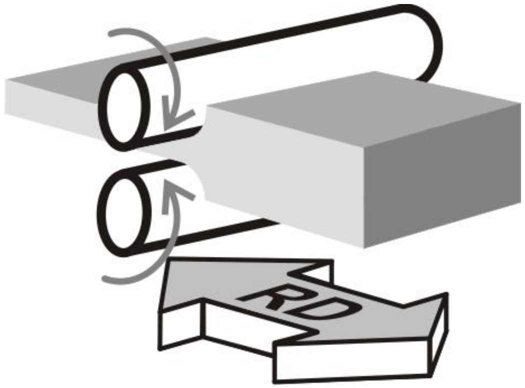
Rolling/Swagging Rods



Forging Round Blanks

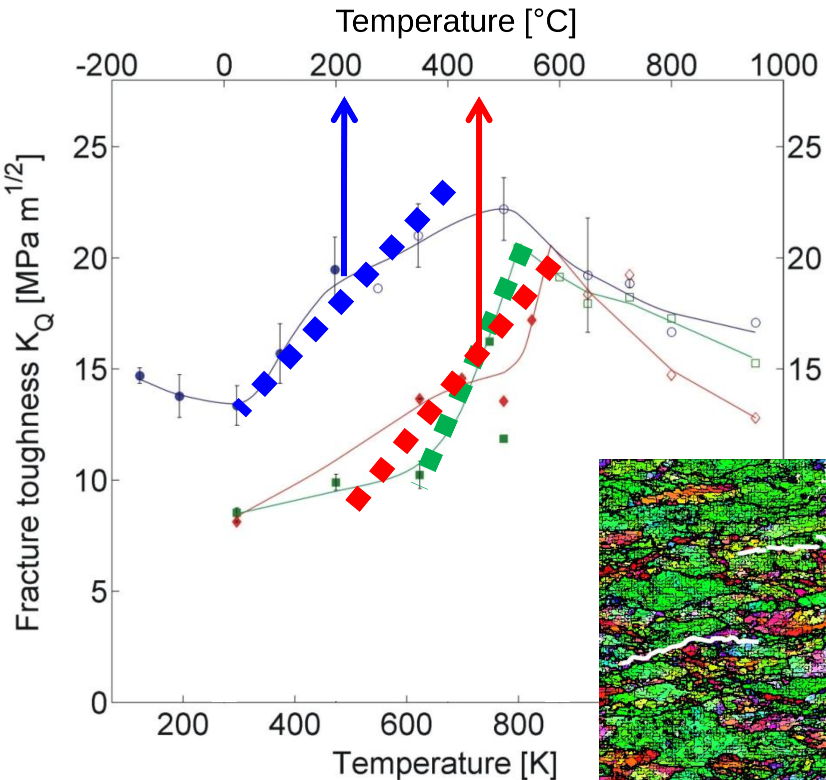


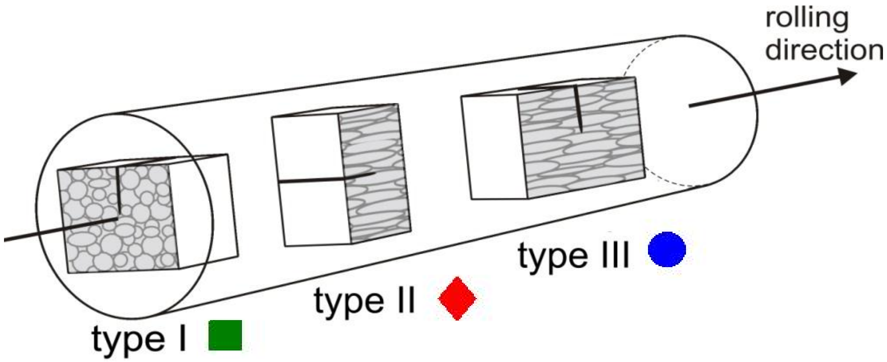
Rolling Plates

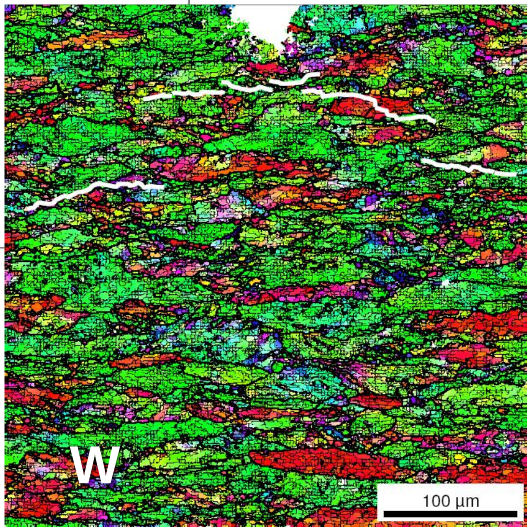


Structural Tungsten Materials: DBTT

Anisotropic Microstructure of Commercially Produced Tungsten Materials





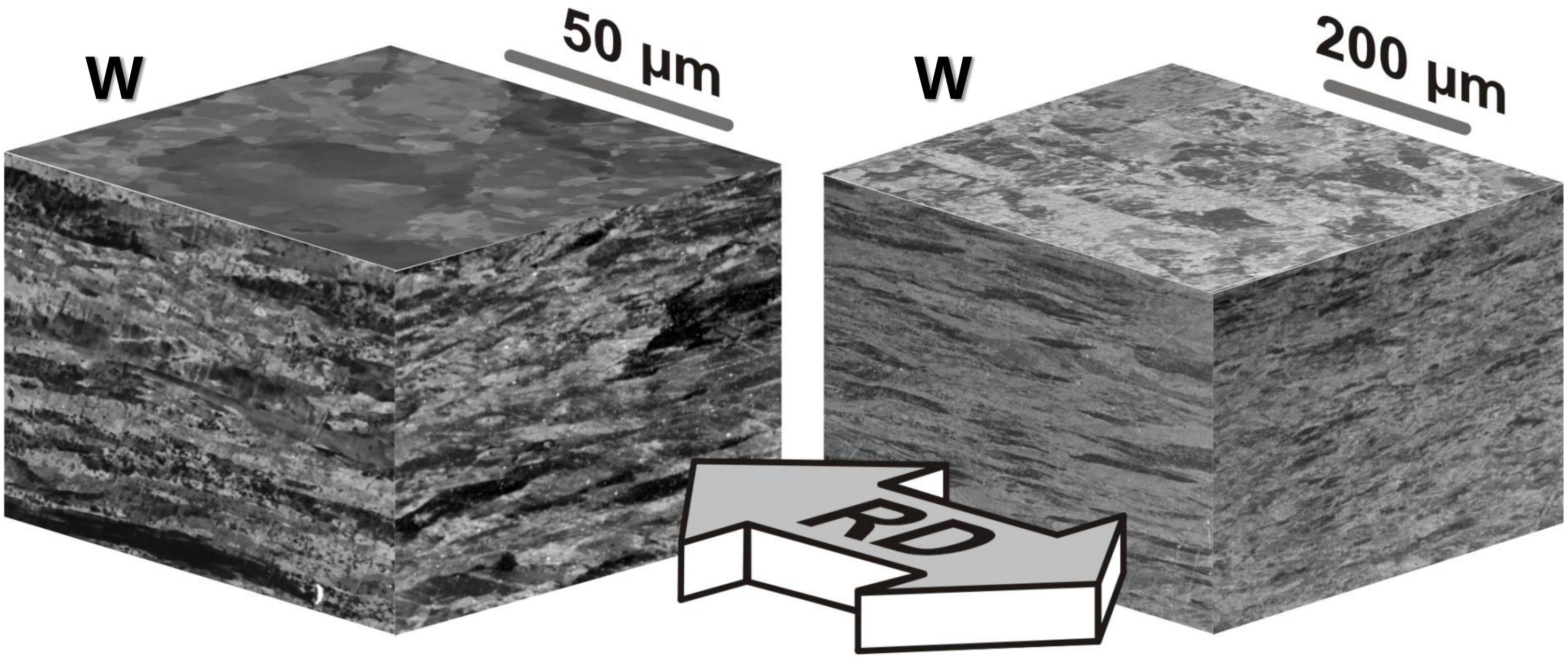


- strong anisotropy of fracture toughness and DBTT (T_{BDT})
- type I and II: inter-crystalline fracture
- type III: trans-crystalline fracture

→ **D. Rupp et al., KIT**

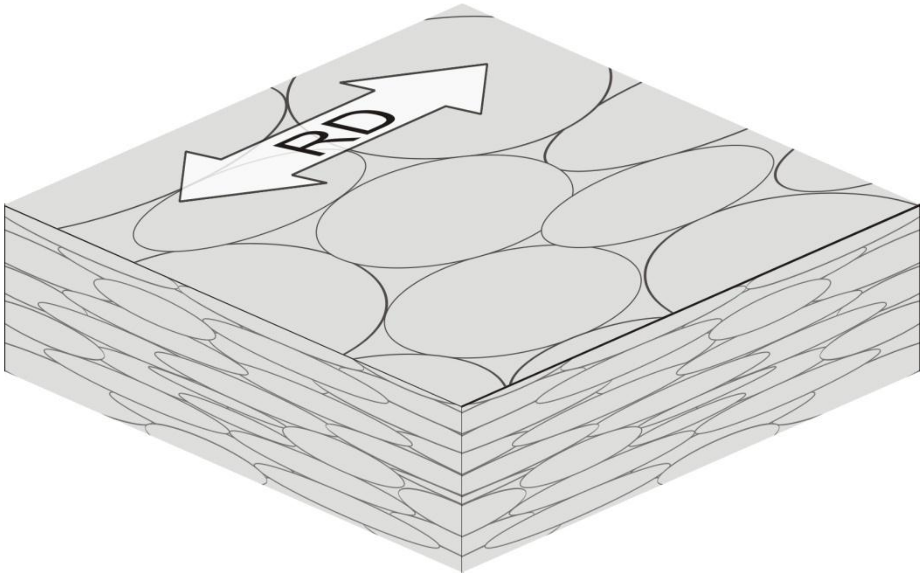
Microstructure Anisotropy

Plates/Round Blanks: SEM / FIB channeling effect

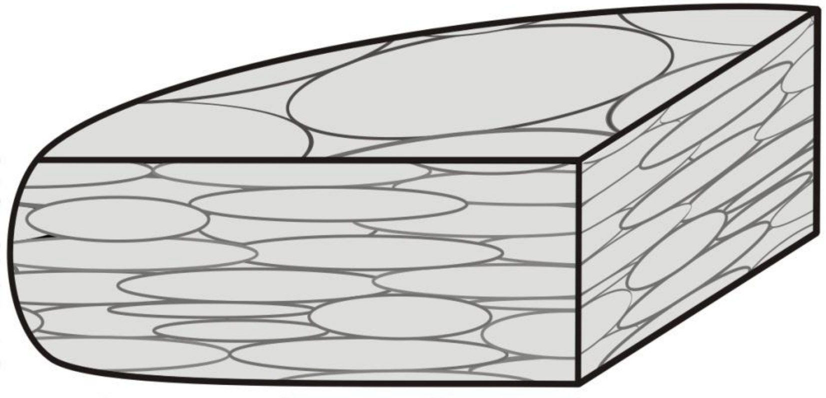


Microstructure Anisotropy

Plates

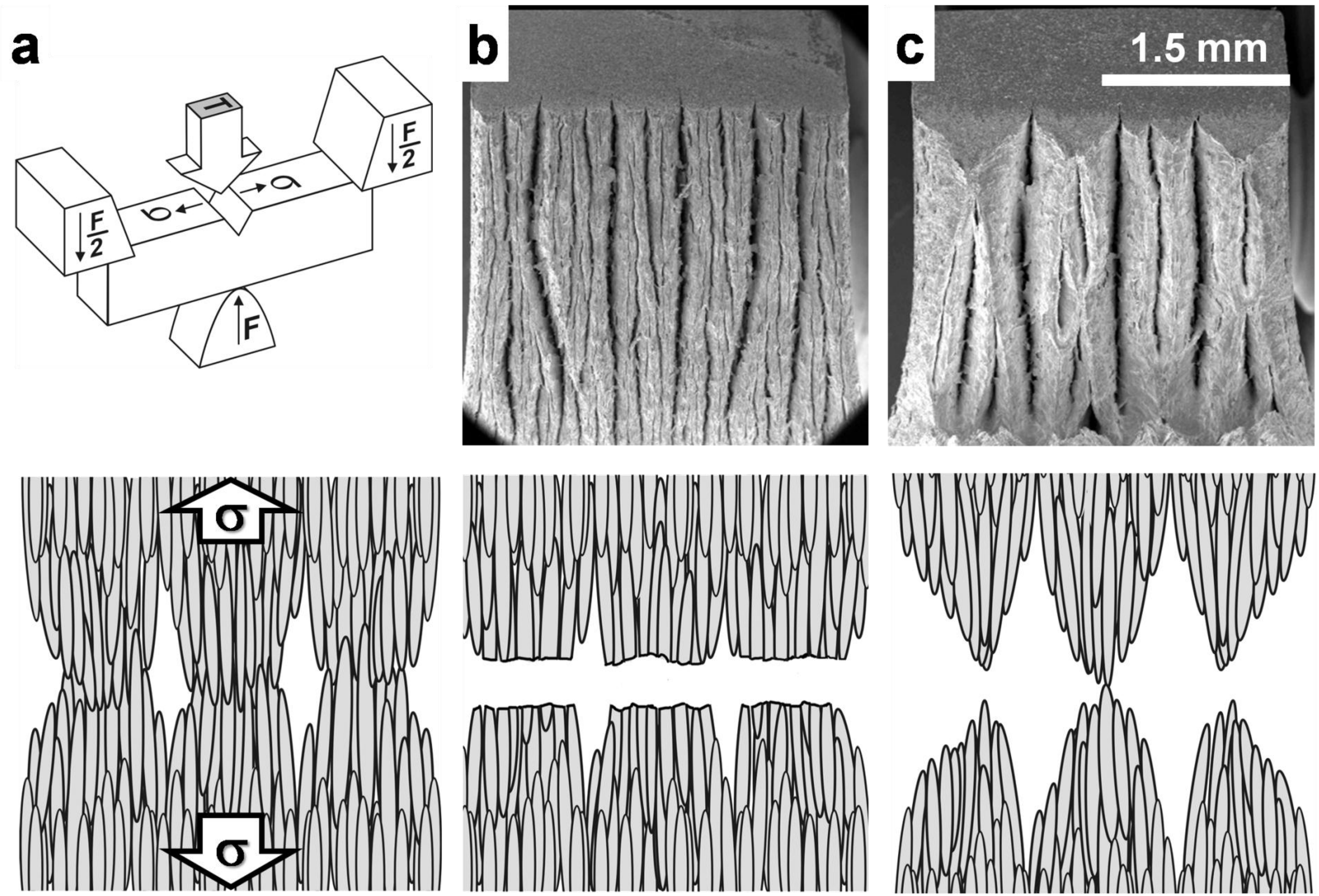


Round Blanks

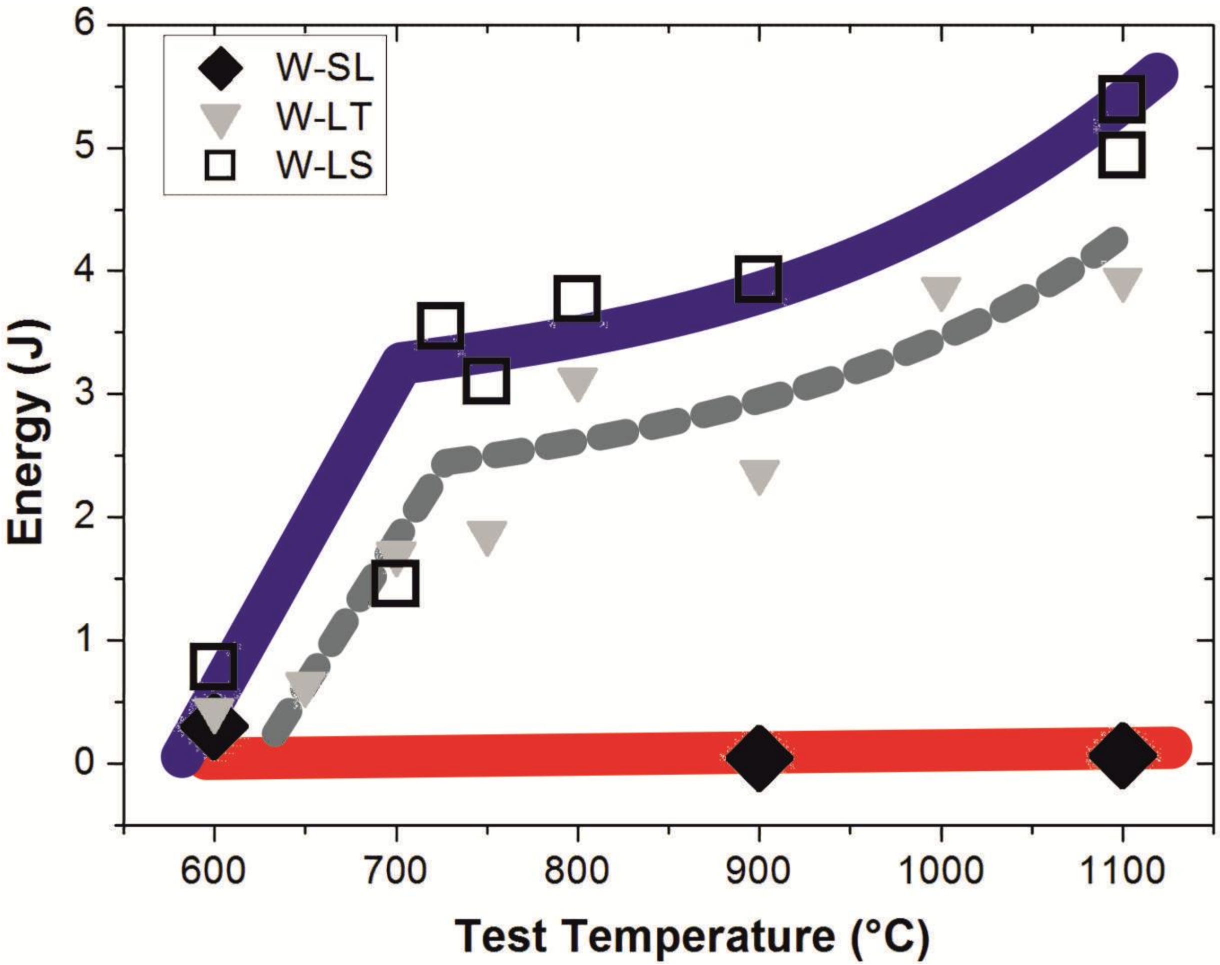


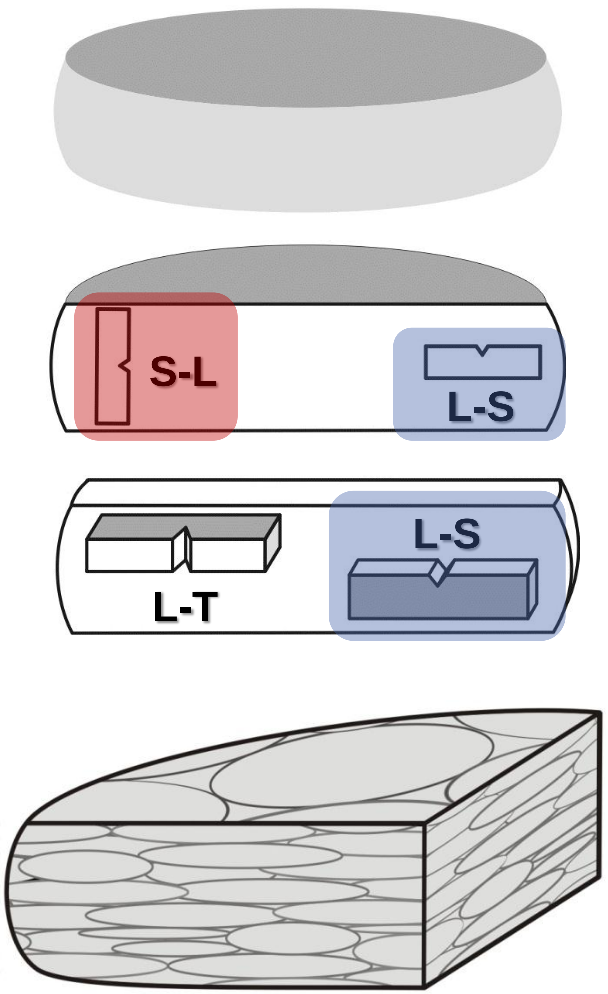
Stack of „Pancakes“

Delamination Fracture in Plates: L-T

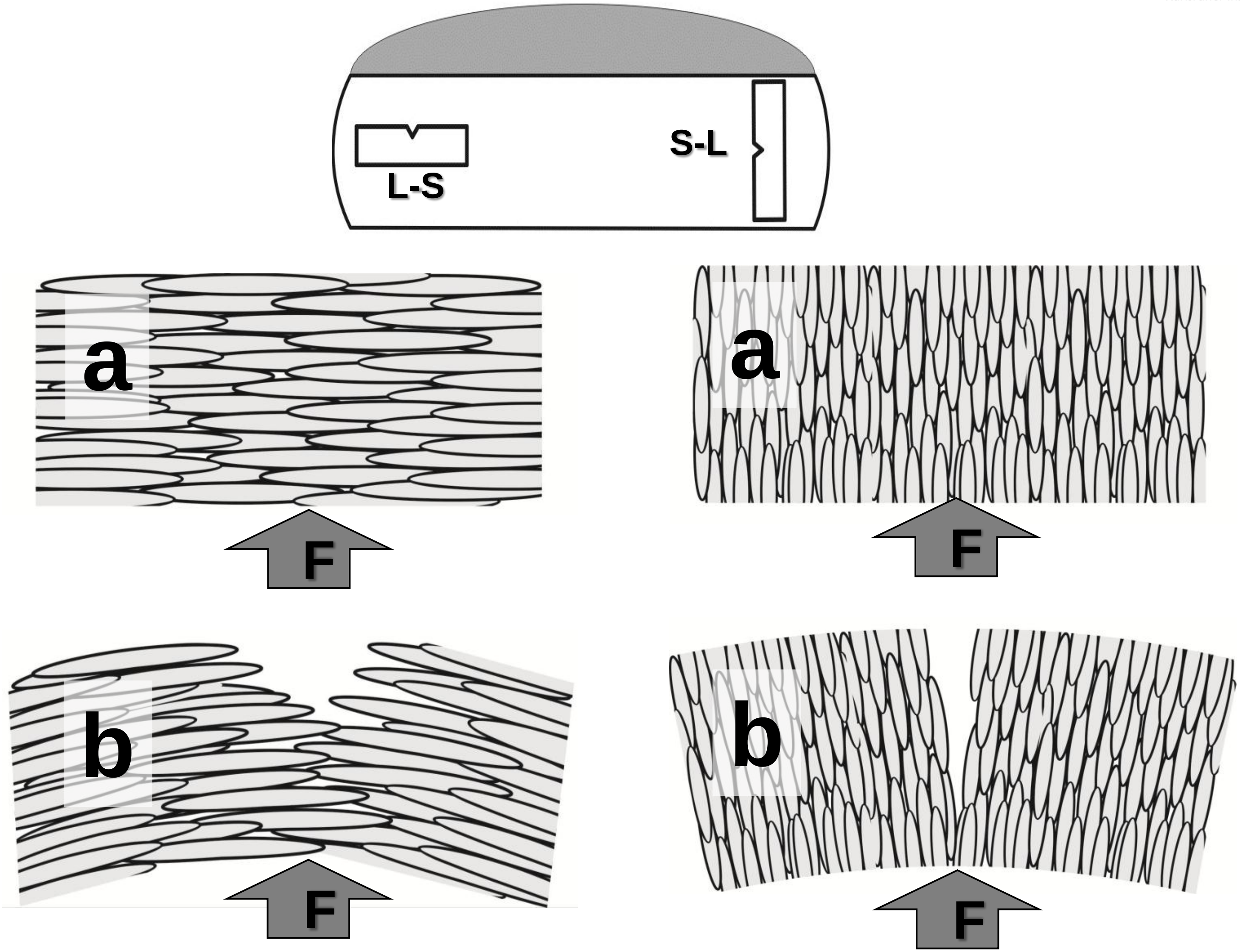


Round Blanks in L-S and S-L Orientation



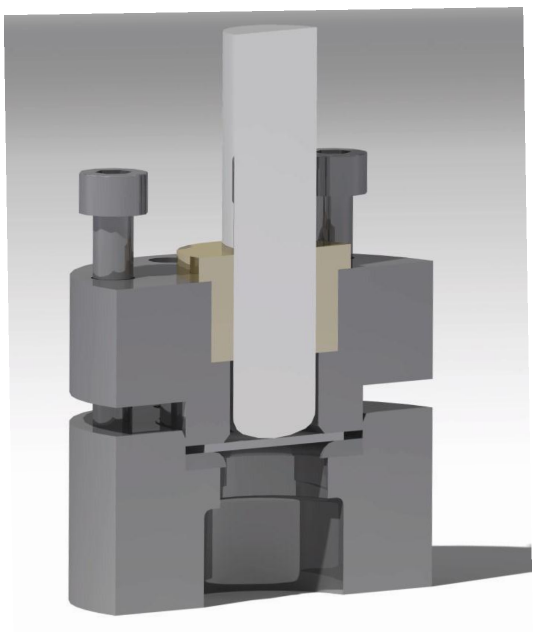


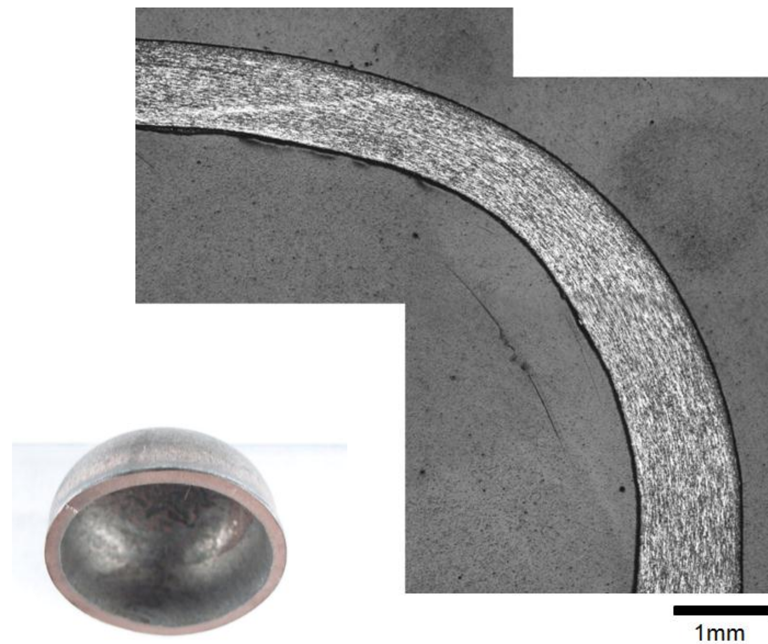
Fracture Mode in L-S and S-L Orientation



Conclusions

- W plates are ideally suited for deep drawing
- Composite materials are most probably the best choice



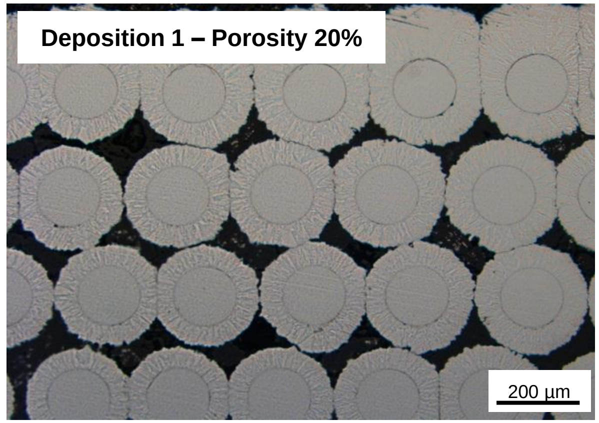


J. Reiser, S. Baumgärtner, KIT

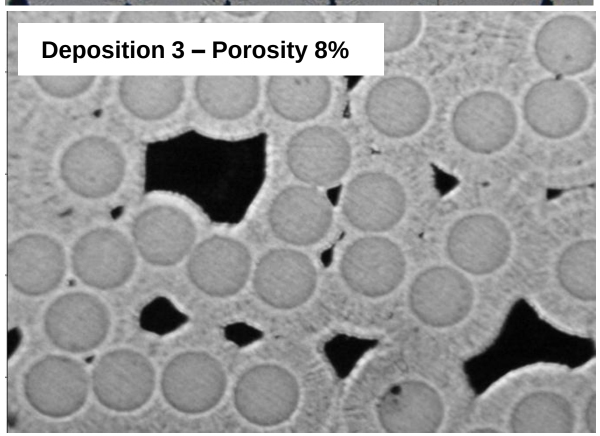
W Composite Materials Development

Fibre Reinforced Tungsten

Deposition 1: Porosity 20%; Interface WO_x; Uniform coating of all fibres (≈50 µm)



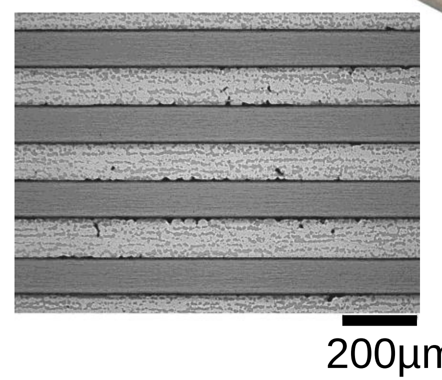
Deposition 3: „Moving Heater“ – Concept; Interface Er_2O_3 Porosity 8%; fibre pattern not maintained



J. Riesch, J.-H. You, IPP

Tungsten Foils

Sandwich of W-Foils



J. Reiser, KIT

Manufacturing Parts of Tungsten Materials

Karlsruher Institut für Technologie

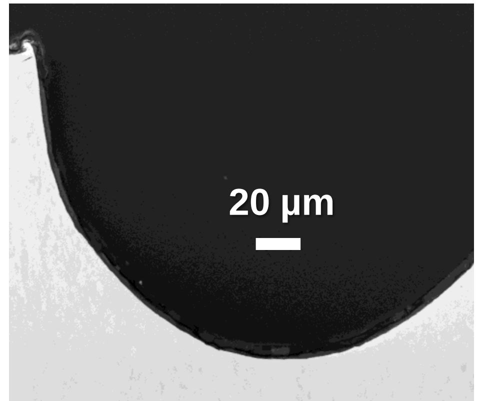
Typical Important Questions in this Field

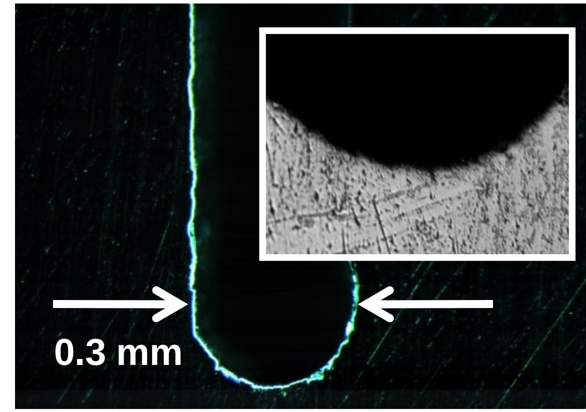
- How to avoid micro-cracks?
- What alternative fabrication process could be suitable?
- Are there applicable reduced activation brazing materials for W-W and W-steel joints?
- Can mass/series production processes be applied to tungsten parts?

Manufacturing Parts of Tungsten Materials

Karlsruher Institut für Technologie

Machining Crack-Free Tungsten Surfaces and Contours

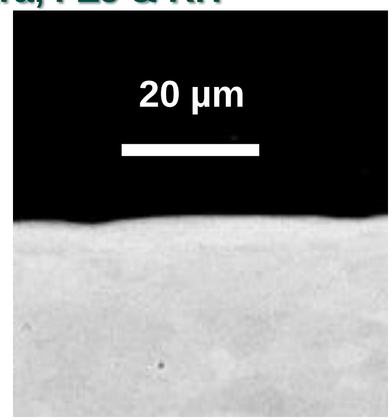




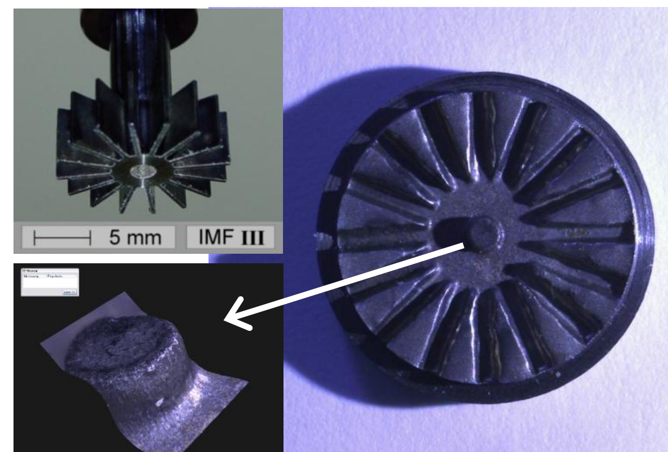
Turning **Cutting wheel**

→ G. Ritz, T. Hirai, J. Reiser, P. Norajitra, FZJ & KIT

Electro-chemical machining removes cracks & grooves



Milling (front and peripheral)

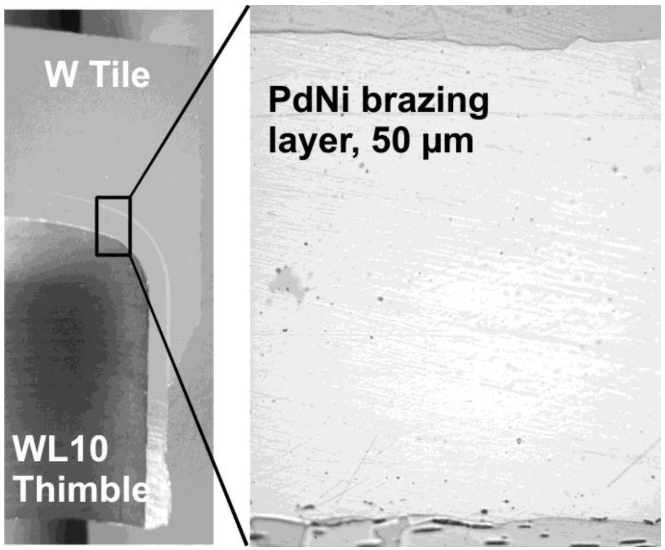


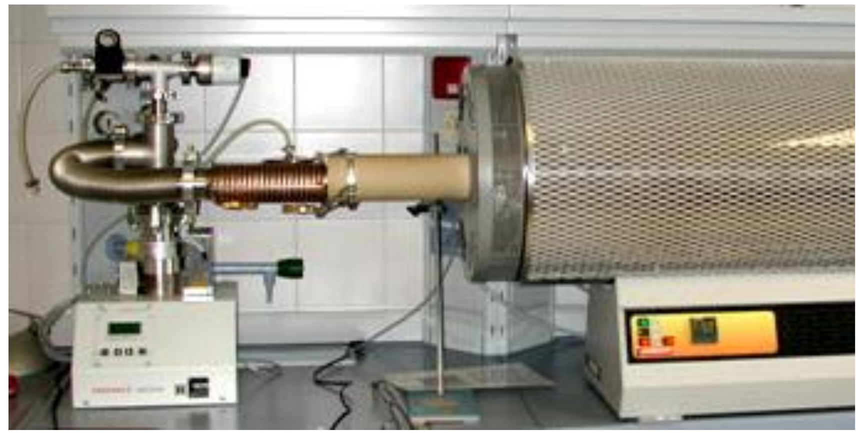
→ N. Holstein, W. Krauss, J. Konys, KIT

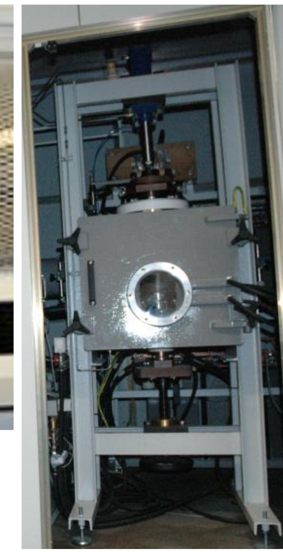
Manufacturing Parts of Tungsten Materials

Karlsruher Institut für Technologie

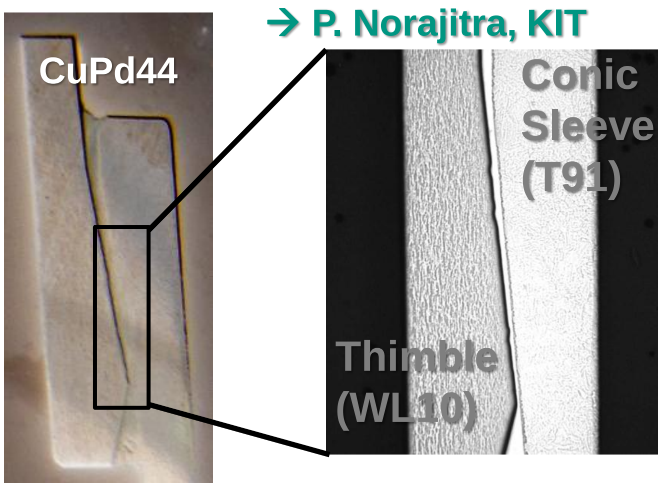
Joining W-W & W-Steel



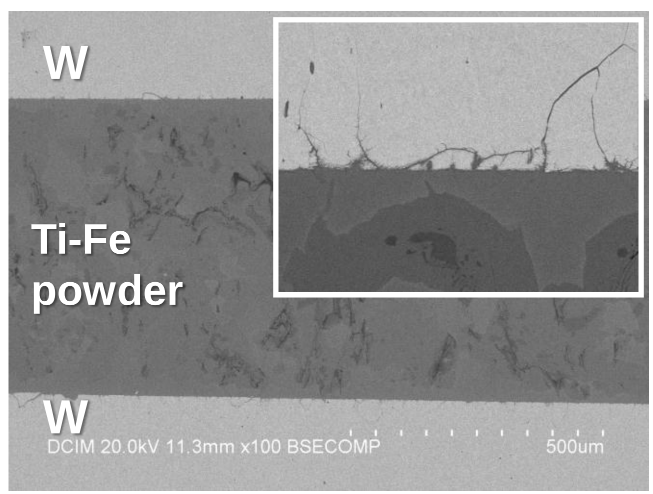




Brazing in vacuum furnace, by laser & by pulse plasma sintering



→ P. Norajitra, KIT



→ E. Fortuna, L. Ciupinski, Warsaw University

Ti-Cu green	T_{br} = 1050 ºC
Ti-Cu sinterized	T_{br} = 1050 ºC
Ti-Fe powders	T_{br} = 1250 ºC
Ni23Mn7Si5Cu	T_{br} = 1100 ºC

→ M. S. Martínez, Universidad Rey Juan Carlos, Madrid

High Performance Steels for Power Plants

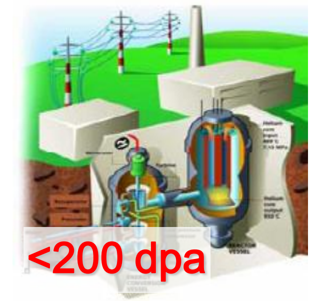
Karlsruher Institut für Technologie

First Reactors

Current Reactors

Advanced Reactors

Future Systems

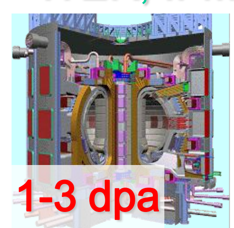


1950 | 1970 | 1990 | 2010 | 2030 | 2050

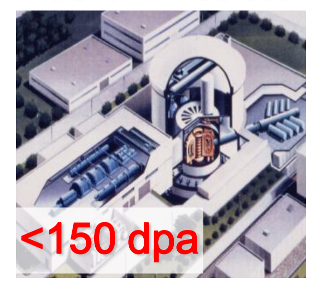
Strategic Missions:
- ✓ Electricity, Hydrogen, Heat

Technological Missions:
- ✓ Environmental compatibility
- ✓ Increased cost-effectiveness
- ✓ Better sustainability
- ✓ Improved safety

ITER, IFMIF

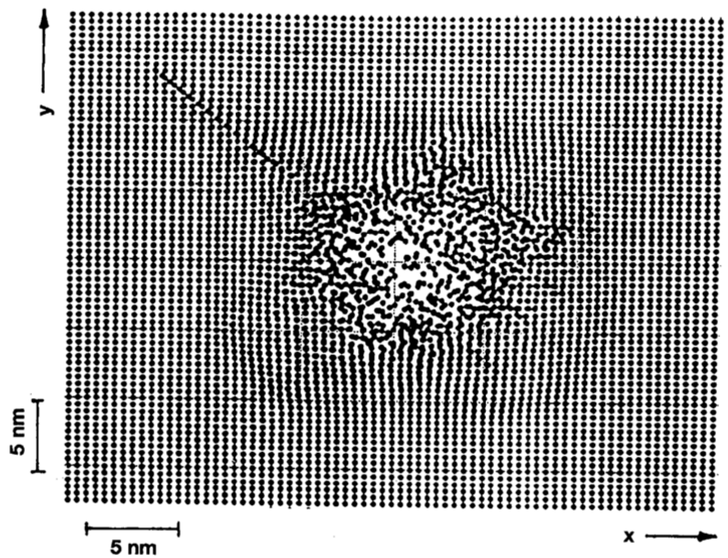


DEMO Fusion Reactor



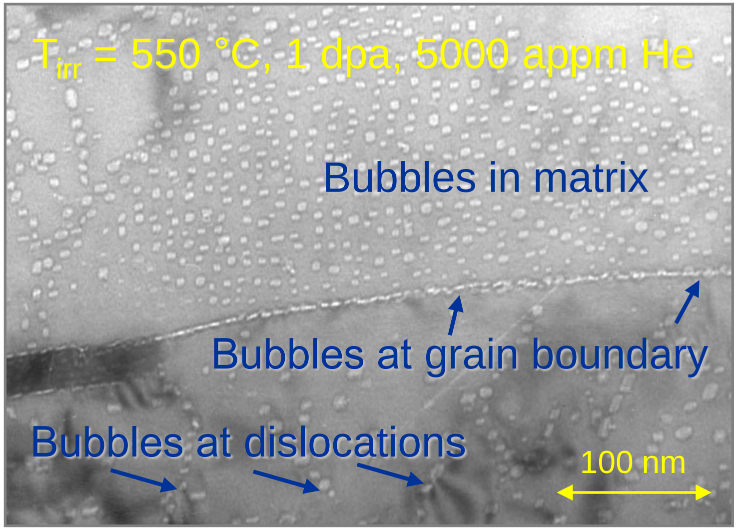
Requirements for "in vessel" fusion steels
Irradiation effects: 2 elementary reactions

Atomic displacements („dpa“)



MD simulation of a displacement cascade produced by a 10 keV primary knock-on atom in an fcc lattice (Averback et al)

Nuclear reactions (e.g. „He“)

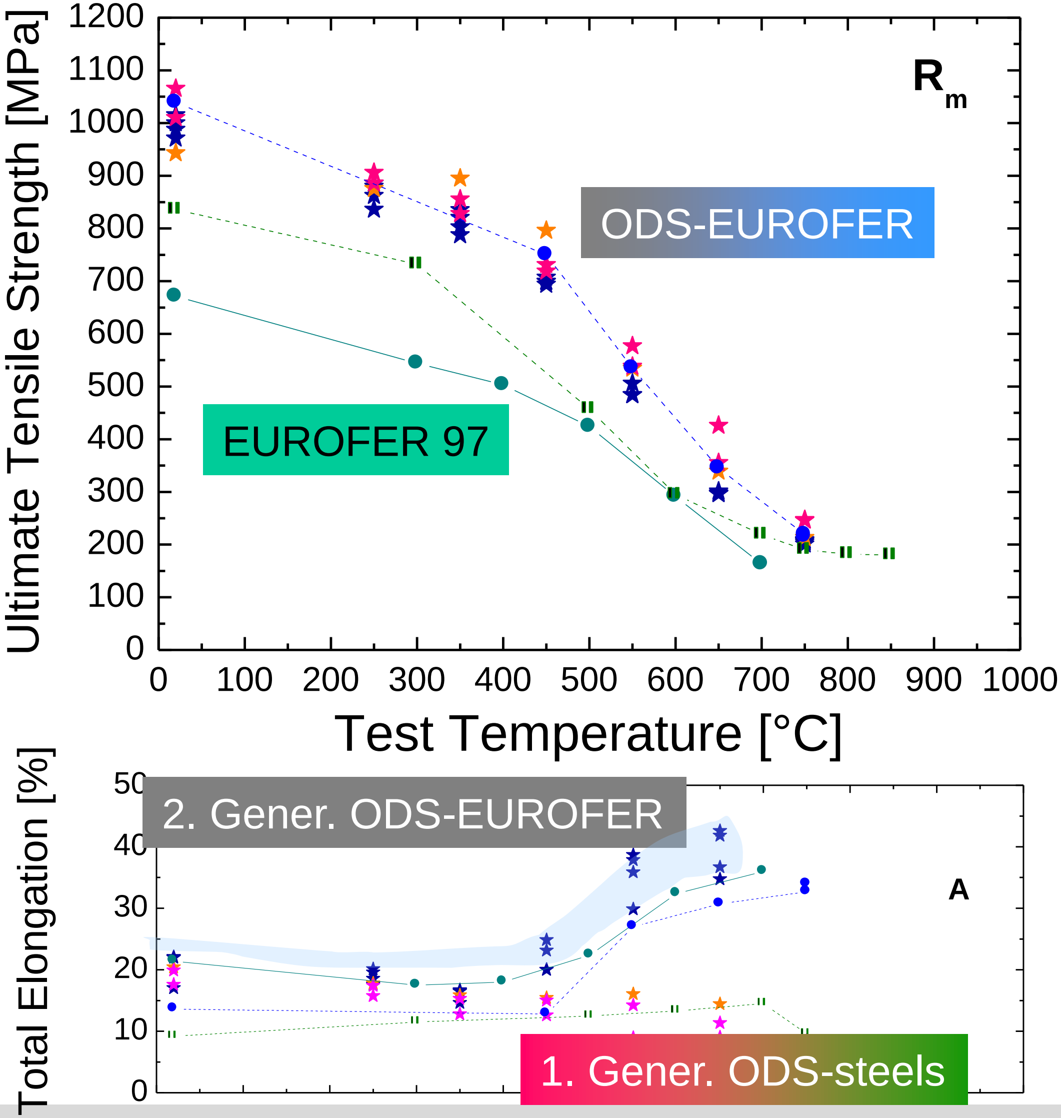


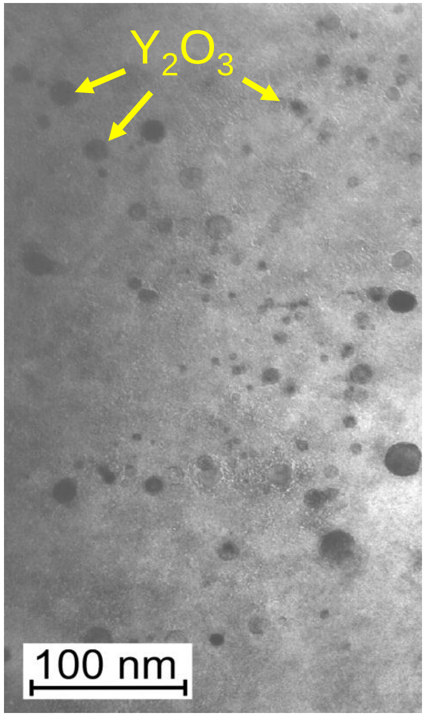
courtesy of P. Jung, FZJ

He gas bubbles:
Major reason for irradiation embrittlement

Oxide dispersion strengthened FM Steels

Tensile Strength and Ductility



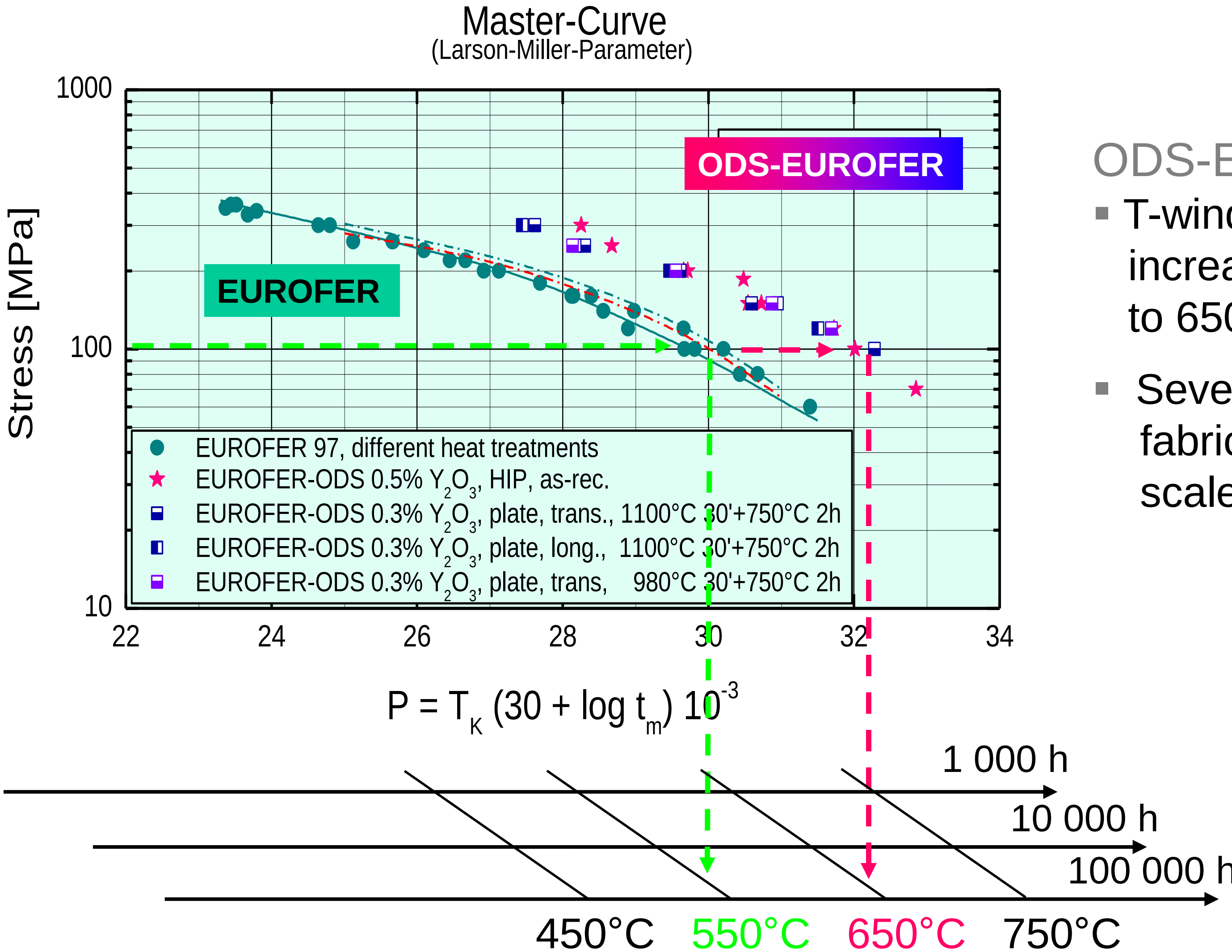


ODS EUROFER:

Superior Ductility in the entire temperature range (RT – 700 °C)

Long-term Creep Behavior: 100 MPa for 50 000 h

Karlsruher Institut für Technologie

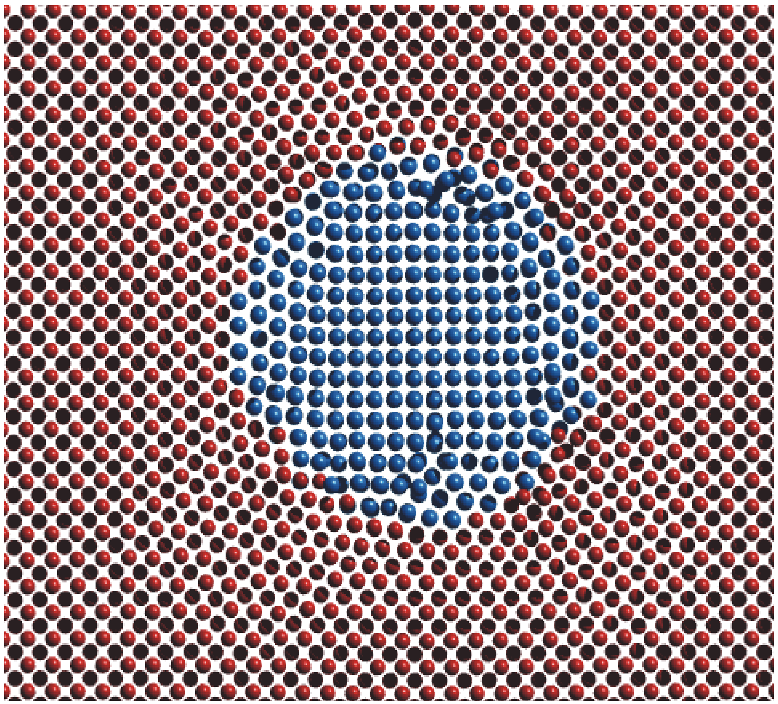


ODS-EUROFER:

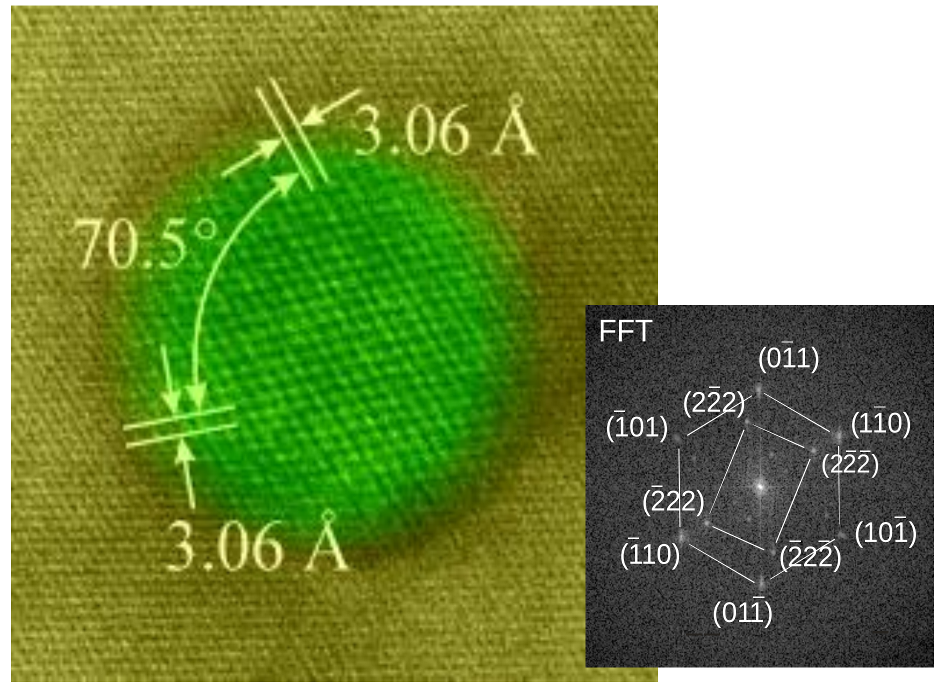
- T-window has been increased by ~100 °C to 650 °C
- Several 50 kg batches fabricated; scaleable technology

Coherency properties of nano-dispersoides in steel matrix

Molecular Dynamics Simulation



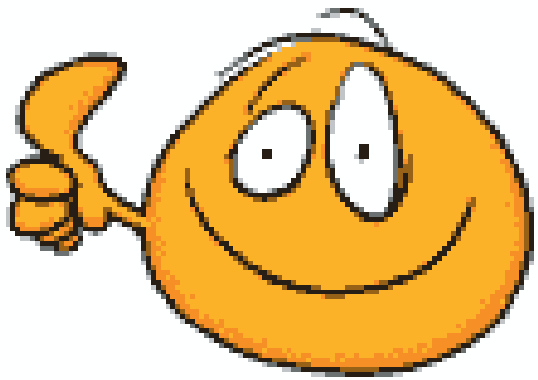
Experimental validation via HRTEM



- $(111)Y_2O_3$ || $(110)FeCr$ - orientation of atomic planes, misfit only 0.5 %
- Coherence despite of the high melting temperature (~2500 °C) of Y_2O_3

Karlsruher Institut für Technologie

… and that are just a few reasons why fusion is so challenging!

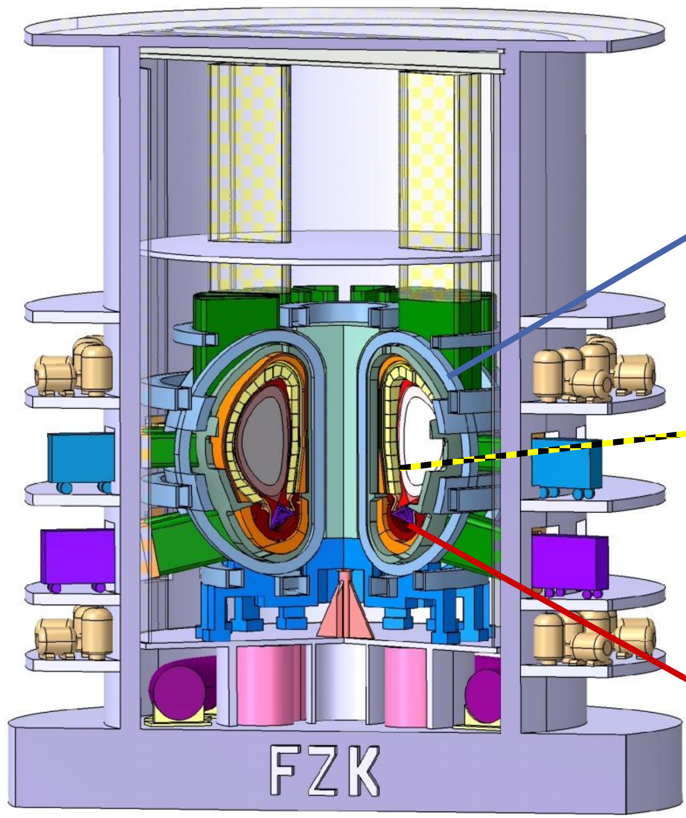


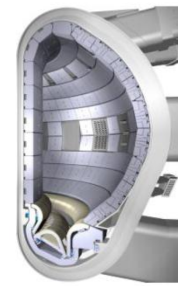
THANKS

for your interest

Additional Slides

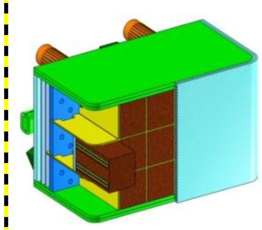
Fusion Power Plant:
Estimation of high purity steel demand





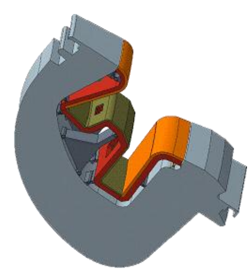
Vacuum vessel:

Austenitic steel:
~12 000 tons



Blanket:

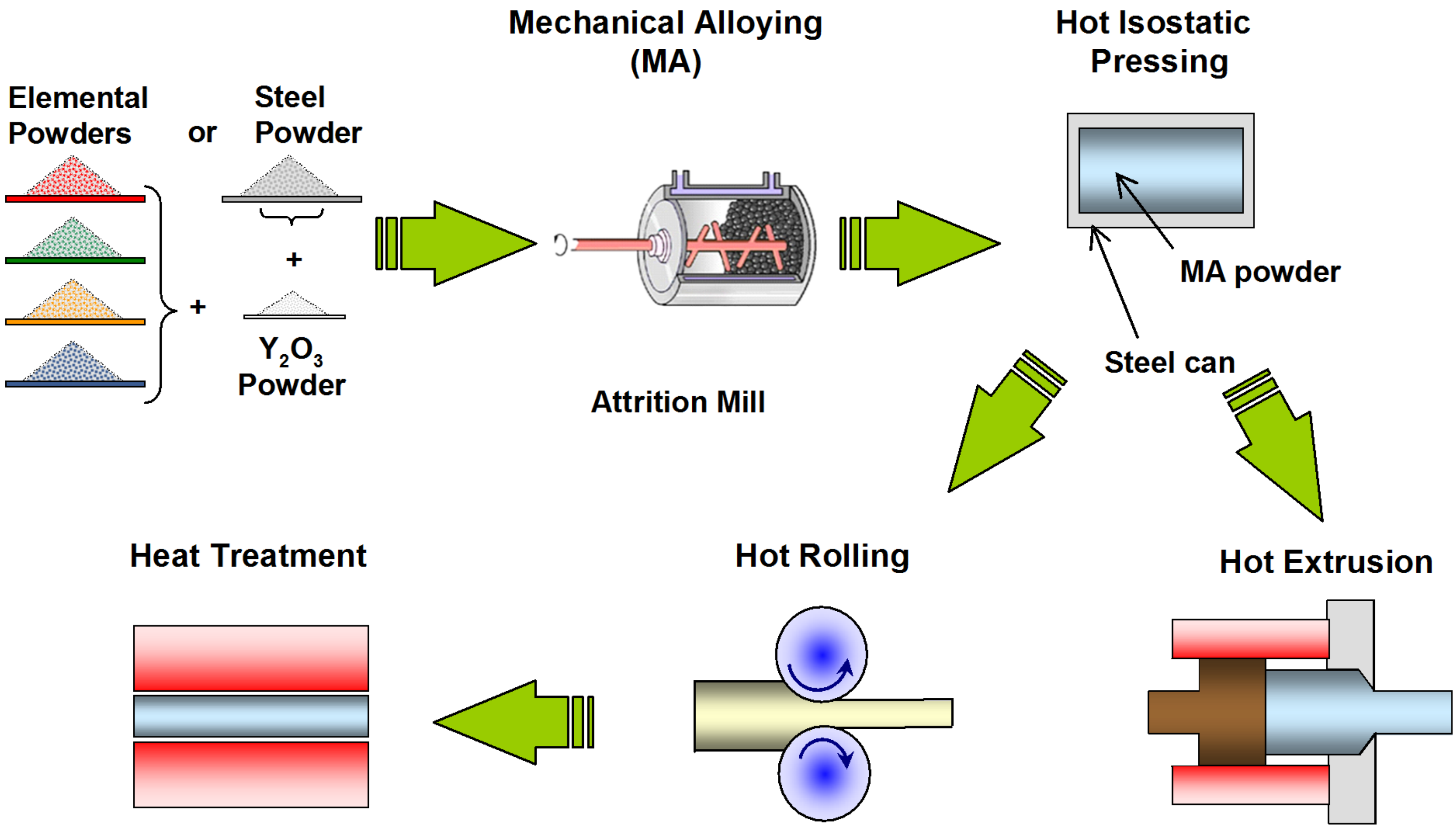
9CrWTa steel:
~800 tons / 5 yrs
~8000 tons/lifetime



Divertor:

RAF-ODS steel:
~300 tons / 5 yrs
~3000 tons/lifetime

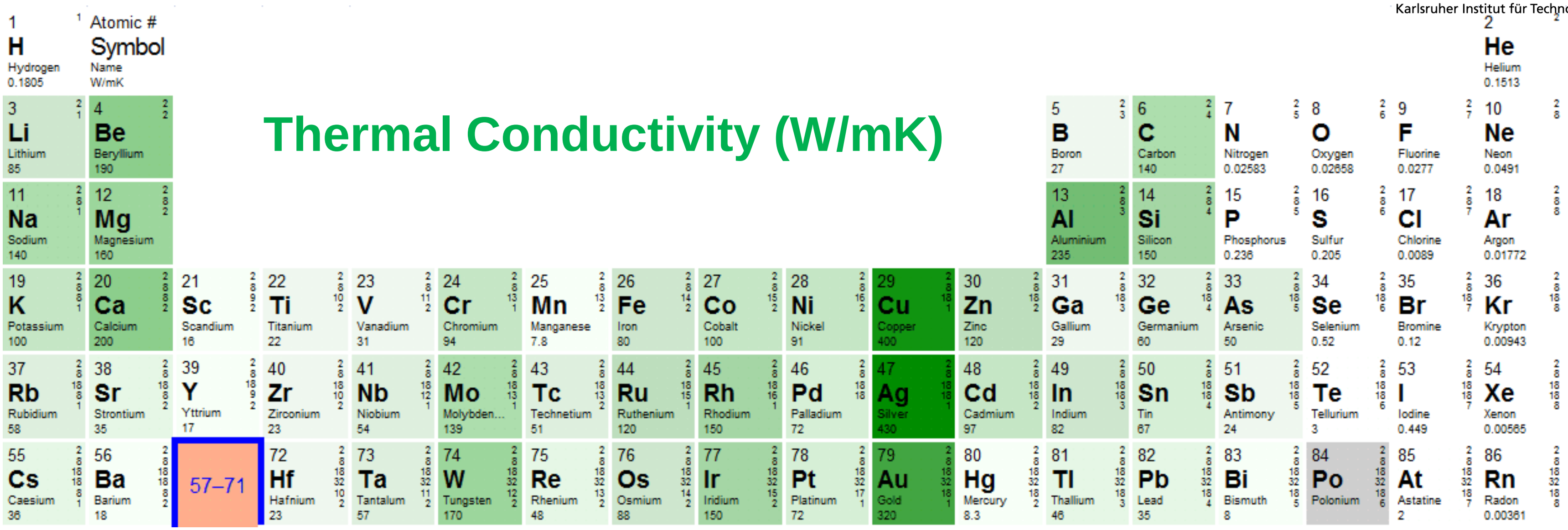
ODS Steel Production Route



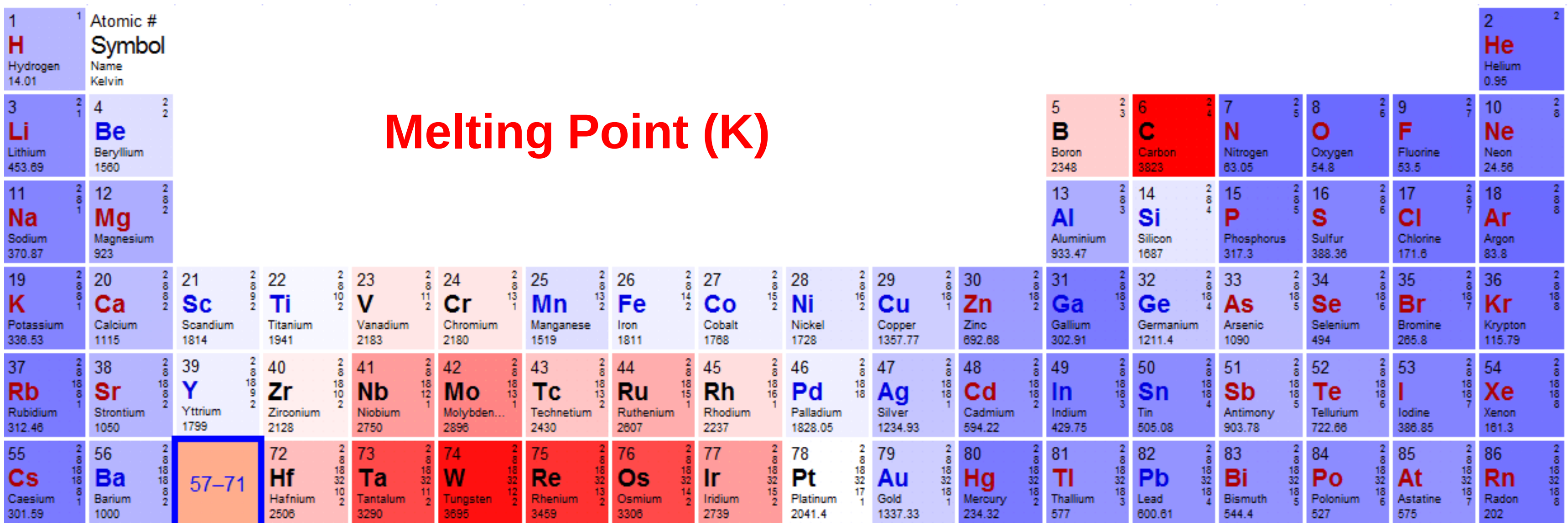
Why Tungsten? → Element Selection

Karlsruher Institut für Technologie

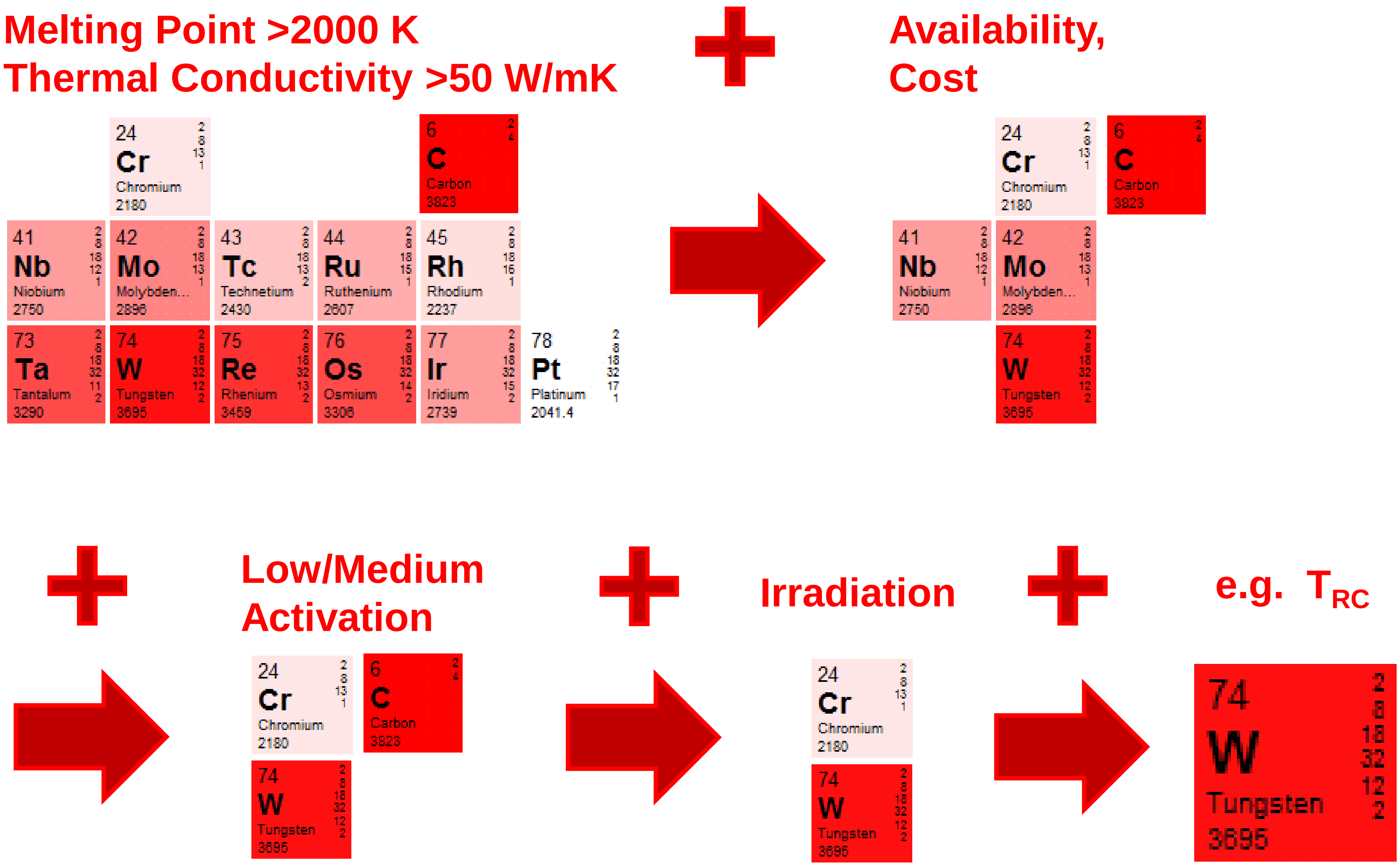
Thermal Conductivity (W/mK)



Melting Point (K)



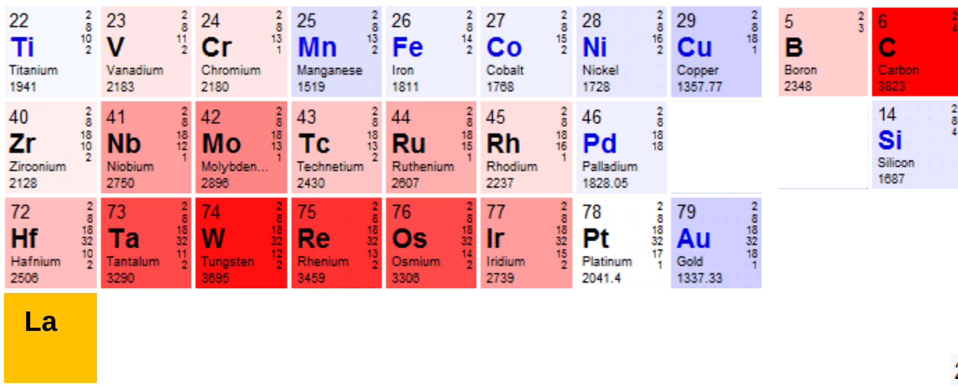
HHFC Base Material



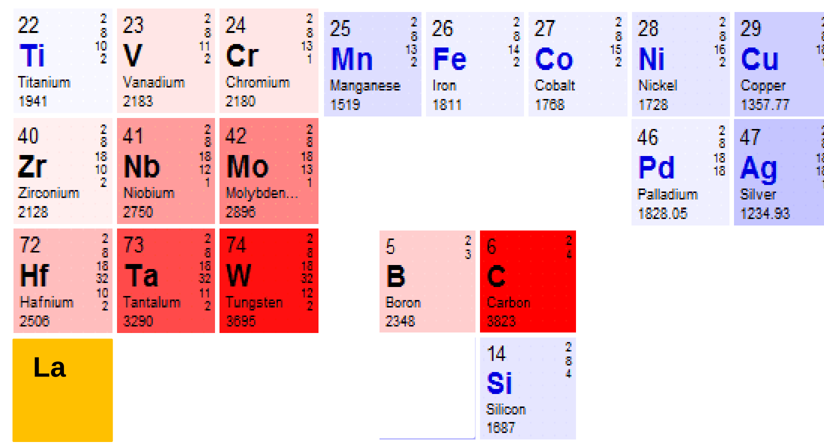
HHFC Alloying Elements (up to 1%)

Karlsruher Institut für Technologie

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

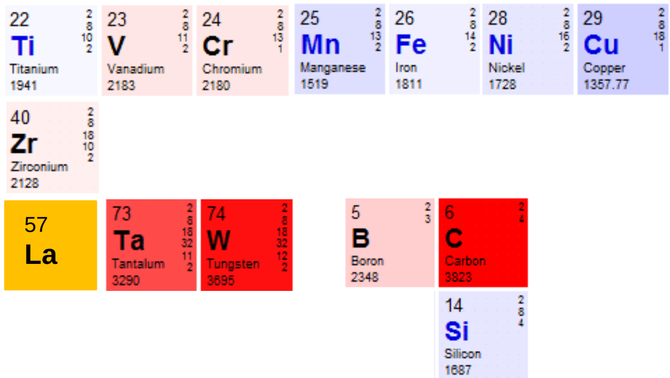


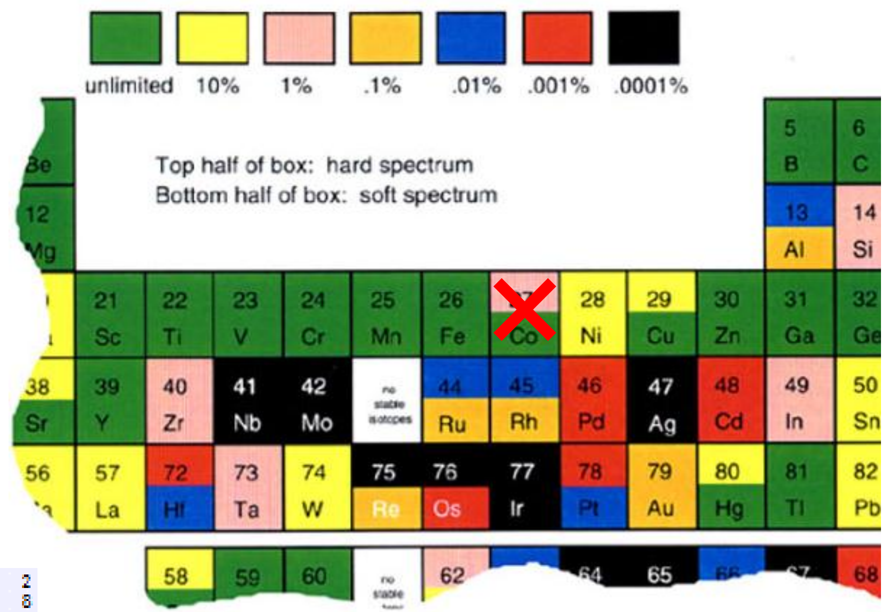
+ Availability, Cost



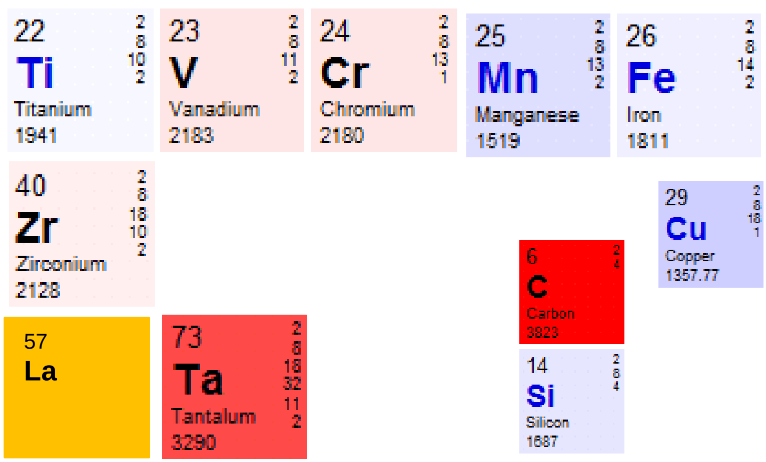
HHF Alloying Elements (up to 1%)

Activation

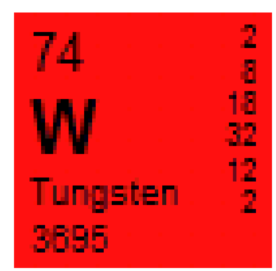




Irradiation



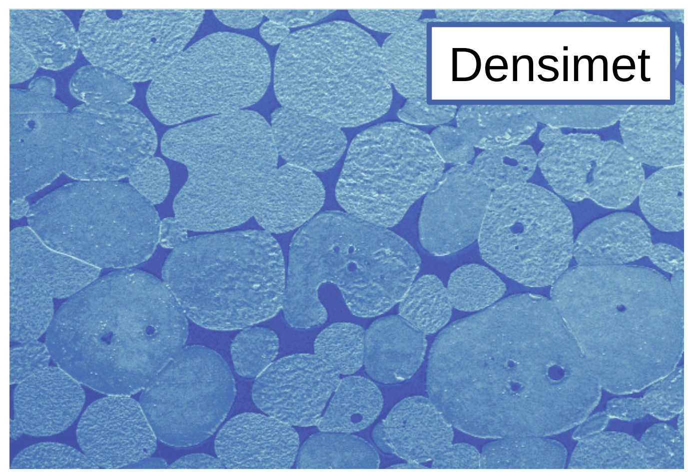
→ Class C Waste Disposal, ORNL



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

Karlsruher Institut für Technologie

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

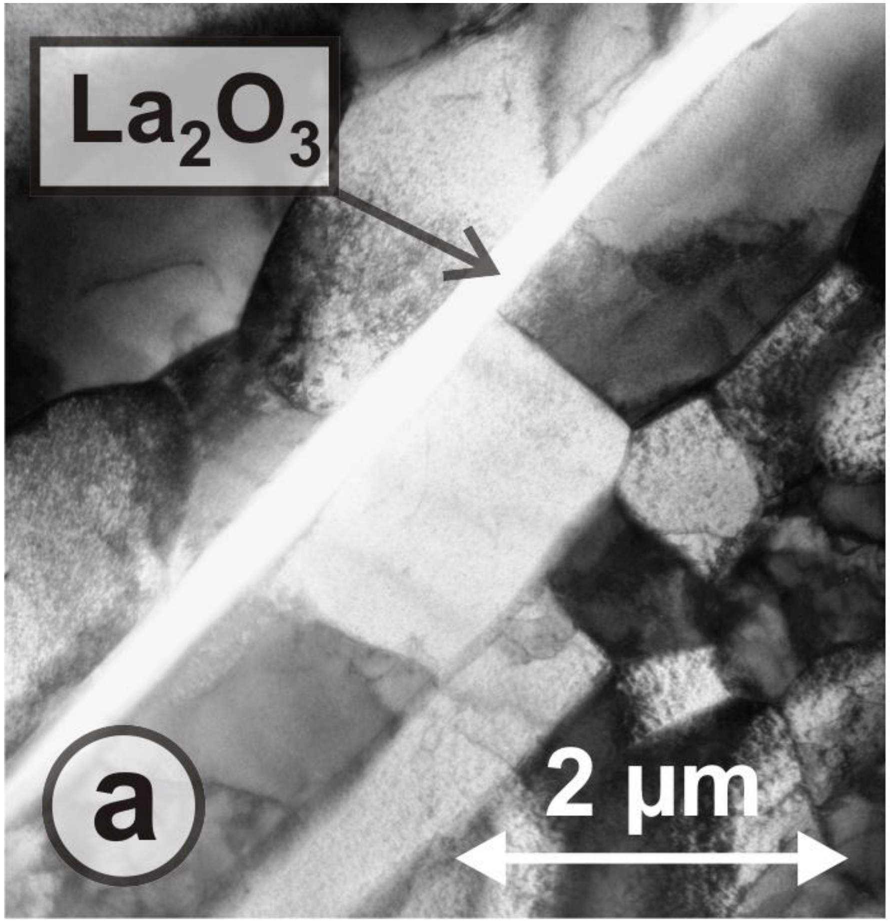
(S)Melting & Forming

+ Real Alloying

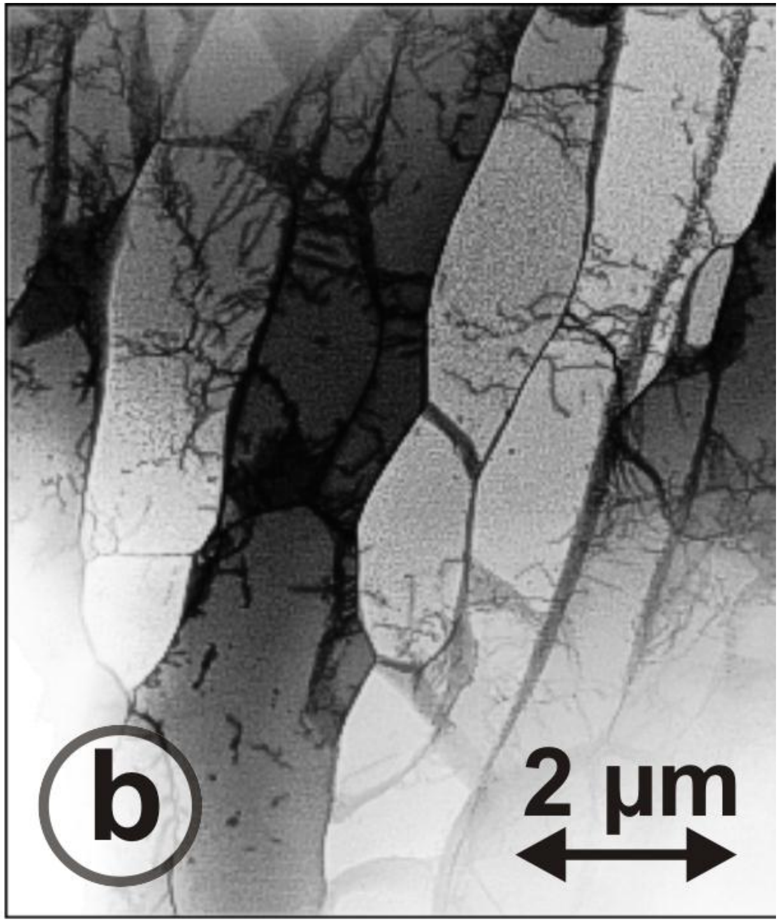
(-) sometimes expensive (→ EB, Arc, Vacuum, ...)

Microstructure
in the condition as delivered (by TEM)

WL10 Rod, Ø7 mm



W Rod, Ø7 mm



Problem of Microstructure Orientation

Pipe Impact Test