





Tungsten as a structural material for nuclear fusion reactors

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Contents



- Introduction to Nuclear Fusion
- High Heat Flux Components
- **Divertor Designs**
- Criteria for Structural Material Selection
- Overview of Tungsten Materials
- **Basic Properties of Tungsten Materials**
- **Fracture Behavior of Tungsten Materials**
- Conclusions

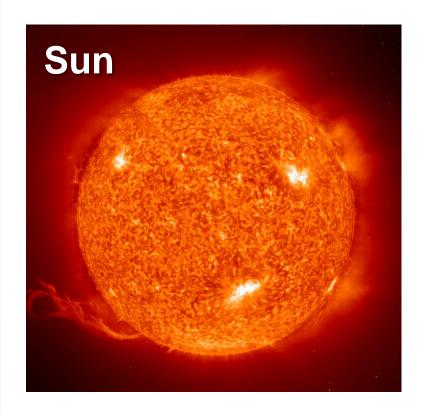


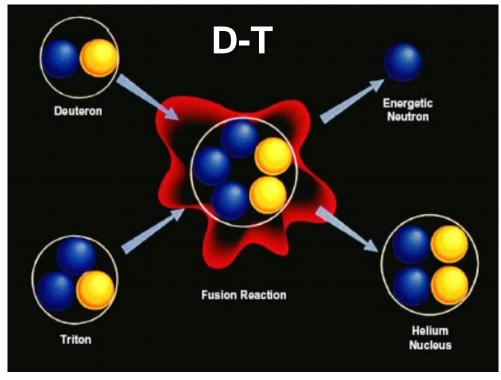
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Nuclear Fusion







T = 15 Mio. °C

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

 $\Rightarrow \rho_E = 30 \text{ W} / \text{m}^3$

 $E_t \sim 3.5 \text{ GW}$ $\rho_E \sim 4 \text{ MW / m}^3$ $\rightarrow T = 150 \text{ Mio. } ^{\circ}\text{C}$



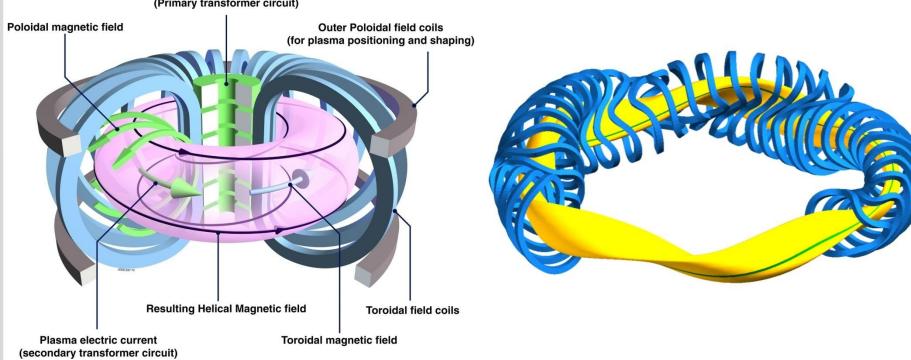
Magnetic Confinement



Tokamak

Stellarator

Inner Poloidal field coils (Primary transformer circuit)



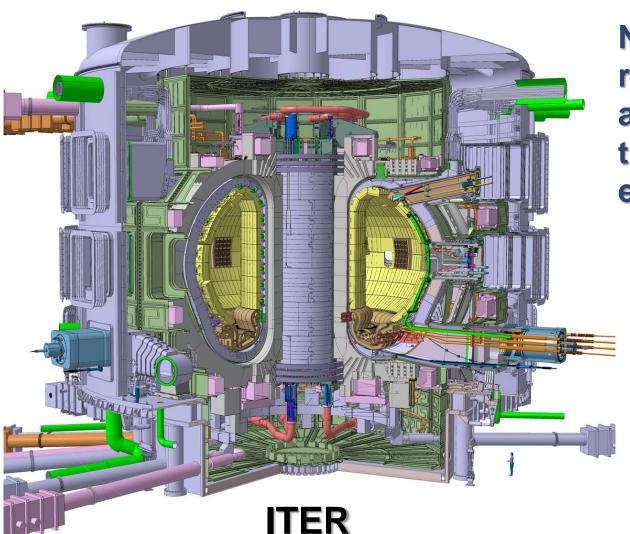
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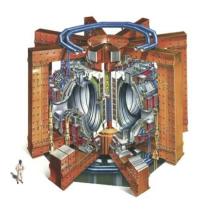
Research TOKAMAKs





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

JET

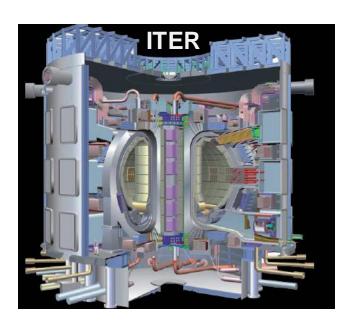


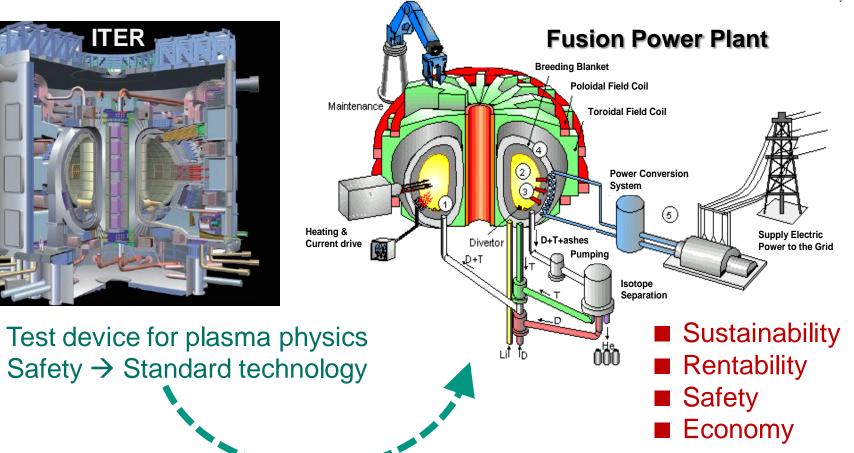




Where is the challenge?







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



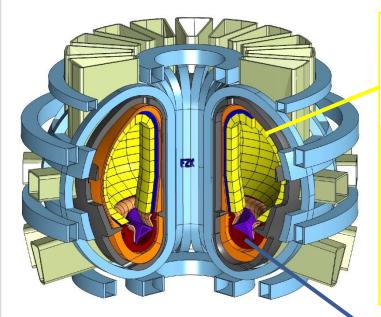
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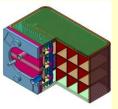
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High Heat Flux Components







Blanket: ≤150 dpa/5 years, 2.5 MW/m²

Reduced activation ferriticmartensitic steels

EUROFER (9Cr-WVTa) 350-550 °C

EUROFER-ODS 350-650 °C

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

DEMO



Divertor: ~30 dpa/2 years, ≥10 MW/m²

Materials unknown Operating temperature 350-1300 °C?

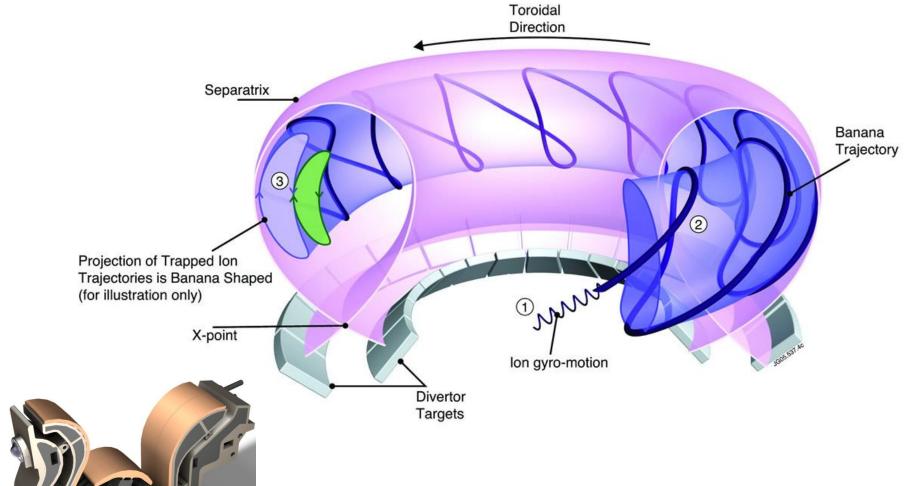
Cooled tungsten shield to remove He and other particles from plasma → ~15 % power





DEMO Divertor: a demanding Component!









Universität Karlsruhe (TH)

Research University · founded 1825

Coolants & Structural Materials



Coolants

Structural Materials

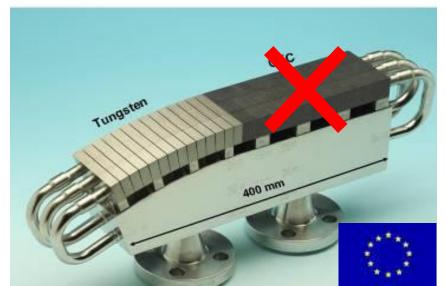
- Liquid Coolants
 - Water
 - (Lead-)Lithium
- Gas Coolant
 - Helium

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

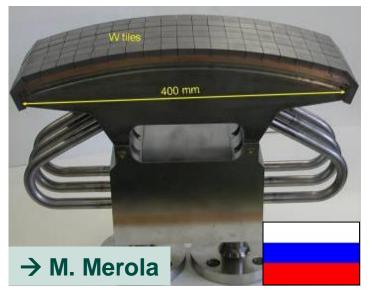


ITER Divertor Concept (Cu & H₂O)









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

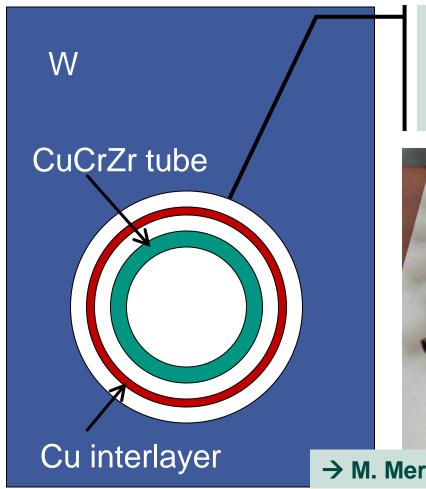




ITER Divertor Concept (Cu & H₂O)



Fabrication Technology



Hot Isostatic Pressing Brazing
Hot Radial Pressing





ITER Divertor Concept (Cu & H₂O)



Advantages

Drawbacks

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

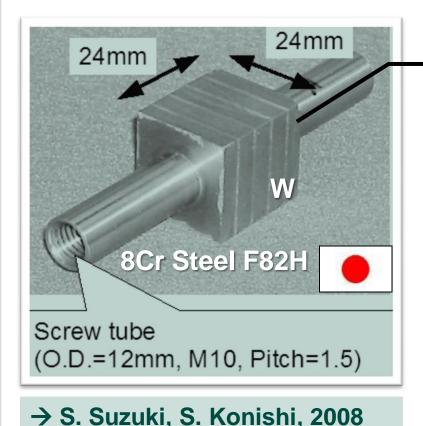
Cu is NOT applicable under DEMO conditions → T retention, embrittlement, swelling (~15 dpa/year !!!)

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"Upgrade" of ITER Concept (Steel & H₂O)





- 2 01 0020111, 01 1101110111, 200
- → B. N. Kolabasov, 2008
- → L. Giancarli et al., 2005

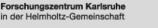


- Hot Isostatic Pressing
- 970 °C @ 150 MPa
- Tempering 750 °C, 1.5 h

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



→ B. N. Kolabasov et al., 2008



Drawbacks

- 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

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

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SiC_f/SiC & Lead-Lithium



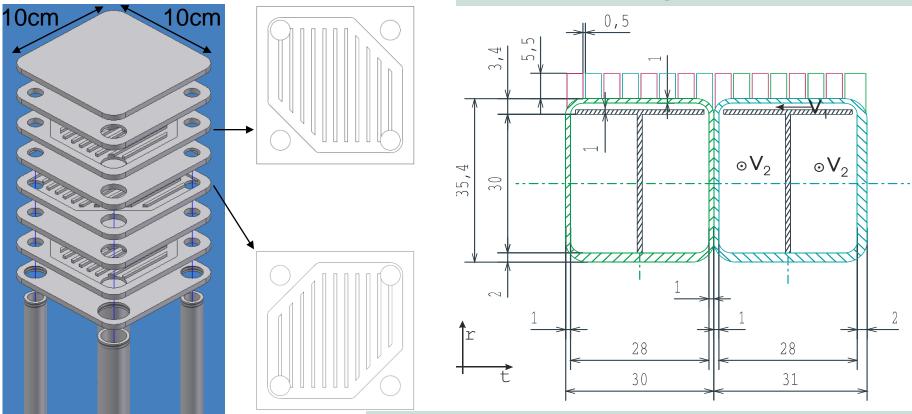
→ K. Noborio, Y. Yamamoto,

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



Theory





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

- Loss of thermal conductivity under irradiation
- **Helium production** (transmutation) 5-10 times higher than in steel

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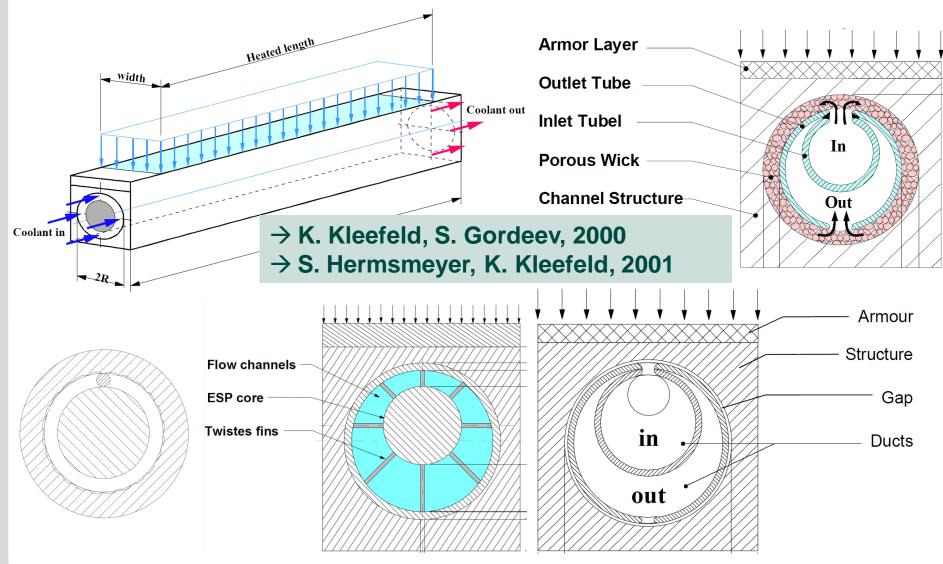
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Open fabrication/joining issues



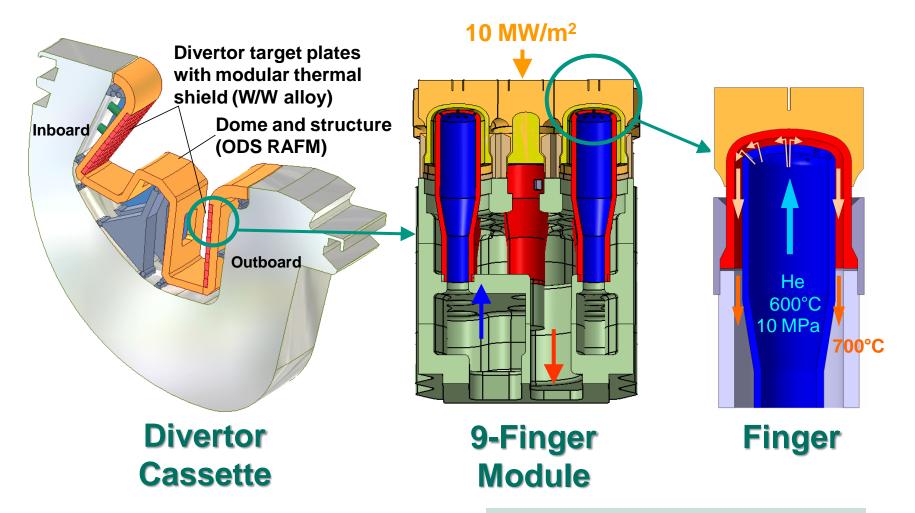
Tungsten & Helium, 5 MW/m² Concepts





Tungsten & Helium, 10 MW/m² Concepts





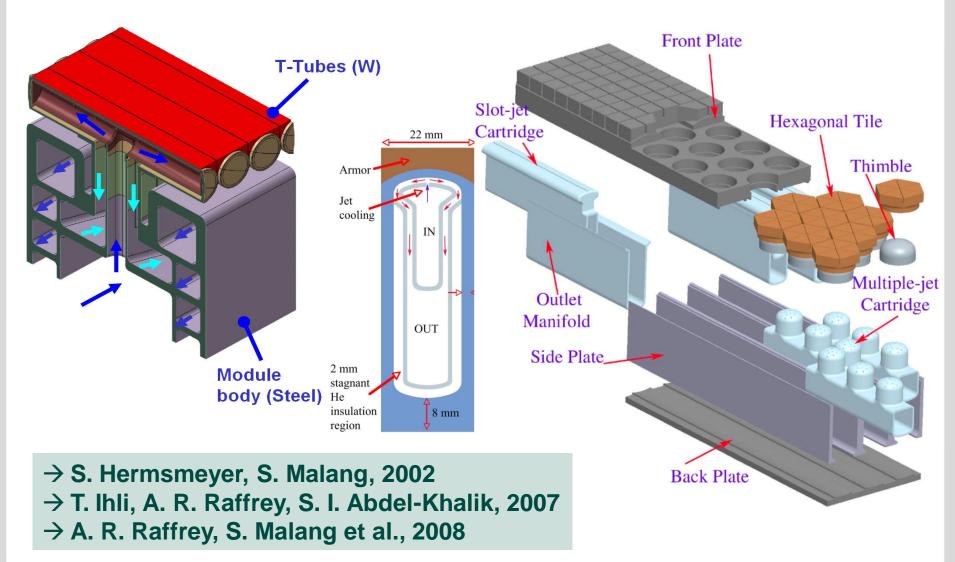
→ P. Norajitra et al., 2003-2009





Tungsten & Helium, 5-10 MW/m² Concepts

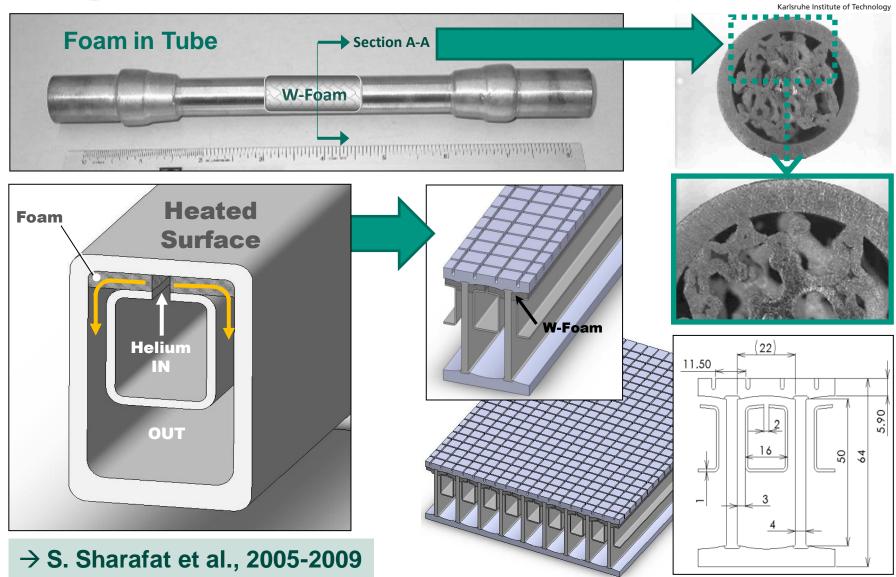






Tungsten & Helium, 10 MW/m² Concepts









Tungsten & Helium



Facts

Drawbacks

- Heat flux 5-10 MW/m²
- **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)

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Ranking of Divertor Concepts



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

- Low Activation Steel (Eurofer) not likely!? → coolant? concept? ...
- SiC₄/\$i no go!? → long-term option, R&D needed
- Tungsten (W, WL10, ...) Not yet! But ...
 - → solution for ductility problem needed!

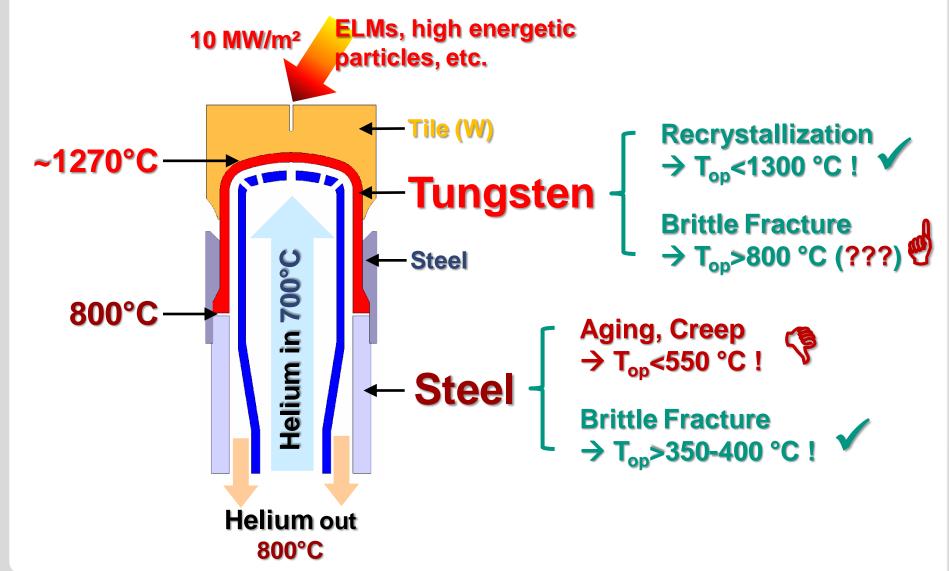


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He Cooled Divertor Dilemma





M. Rieth: Tungsten as a structural material

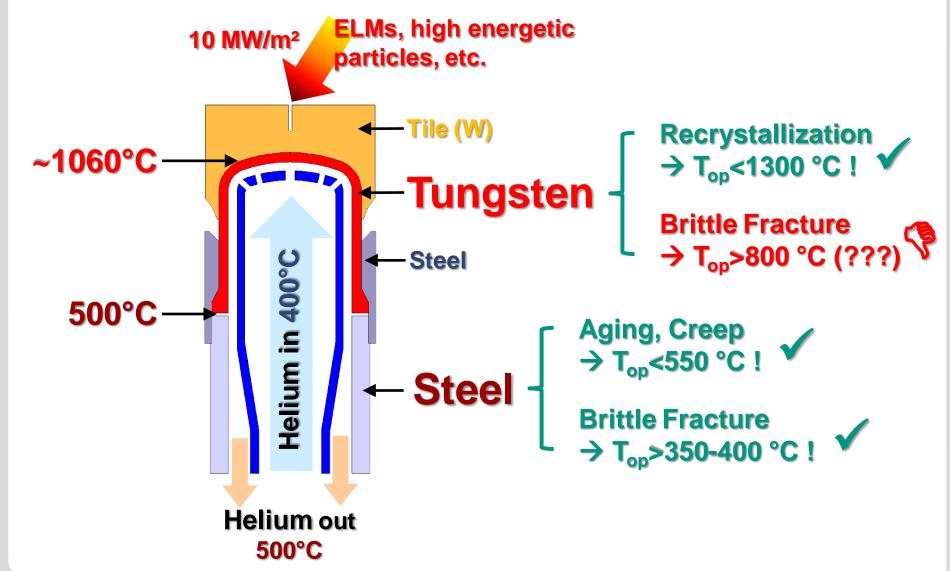
for fusion reactors





He Cooled Divertor Dilemma









Main Criteria for Structure Divertor Material



Heat Flux (10 MW/m²)

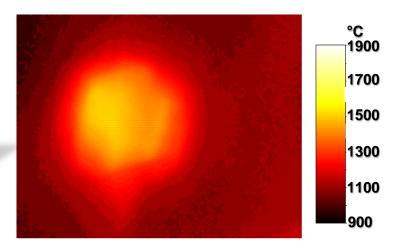
- Very Effective Cooling Strategy
- Thermal Conductivity
- High Operation Temperature

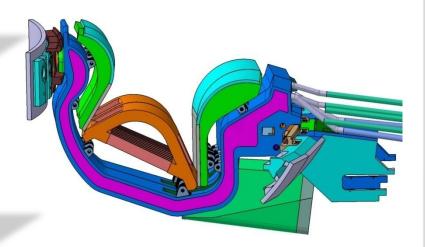
Neutron Dose (min. 30 dpa)

- Irradiation Damage
- Activation (Transmutation?)

Other Criteria

- Fabrication/Joining
- Tritium Inventory
- Availability/Cost







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Why Tungsten? → Element Selection



1 1	Atomic #																	Karlsruh	e Inst	itute of Te	echnology
Hydrogen 0.1805	Symbol Name W/mK																			He Helium 0.1513	
3 2 Li Lithium 85	4 2 Be Beryllium 190		The	rma	al Co	ndu	ıctiv	/ity	(W/	'n	ıK)			5 2 B Boron 27	6 2 C Carbon 140	7 2 5 N Nitrogen 0.02583	8 Oxygen 0.02858	2 9 F Fluorine 0.0277		10 Ne Neon 0.0491	2 K 8 L
Na Sodium	12									Al Aluminium 235	14 2 Si Silicon 150	15 2 P 5 Phosphorus 0.238	16 S Sulfur 0.205	2 8 17 6 CI Chlorine 0.0089		18 Ar Argon 0.01772	2 K 8 L 8 M				
19 K Repotassium	20 2 Ca 3 Calcium 200	21 2 SC 2 Scandium	22 8 10 2 Titanium 22	23 1 V 27 27 27 27 27 27 27 27 27 27 27 27 27	24 28 13 1 Chromium 94	25 8 Mn 13 Manganese 7.8	26	CO Cobalt 100	2 28 15 Ni Nickel 91	2 8 16 2	29 Cu Copper 400	30 Zn Zinc 120	18 2	31 2 8 18 3 Gallium 29	JZ 8	აა გ	34 Se Selenium 0.52	2 35 18 Br Bromine 0.12		Kr Krypton 0.00943	2 K 8 L 18 M 8 N
37 Rb Rubidium 58	38 2 Sr 18 Strontium 35	Y 18		Nh 1	Molybden	43 8 Tc 18 13 13 Technetium 2		45 Rh Rhodium 150	2 46 18 Pd 10 Palladium 72	2 8 18 18	47 8 Ag 18 Silver 430	48 Cd Cadmium 97	18 18 2	49 8 18 18 18 18 3 18 3		51 2 Sb 18 Antimony 24		2 53 18 18 10 lodine 0.449	18 18 7	54 Xe Xenon 0.00585	2 K 8 L 18 M 18 N 8 O
55 2 CS 18 Caesium 3	56 2 Ba 18 Barium 2 18	57–71	72 28 Hf 32 Hafnium 2 23	73 Ta 18 33 Tantalum 19	74 8 W 18 Tungsten 12 170	75 2 Re 18 Rhenium 13 48	76 28 OS 18 Osmium 2	77 Ir Iridium 150	78 18 32 15 15 Platinum 72	2 8 18 32 17 1	79 Au 3 Gold 16 320	80 Hg Mercury 8.3	18 32	81 2 8 11 18 32 Thallium 3 48	82 2 Pb 32 Lead 4 35	83 2 Bi 18 32 Bismuth 5	Polonium	2 85 18 At 32 At 18 Astatine 2	18 32	86 Rn Radon 0.00361	2 K 8 L 18 M 32 N 18 O 8 P
1 Hydrogen 14.01	Atomic # Symbol Name Kelvin																			2 He Helium 0.95	2 K
3 Li Lithium 453.69	1 4 2 Be Beryllium 1500 Melting Point (K) Melting Point (K) Service Beryllium 1500 Sagar 1500 Sag										² 6 9 Fluorine 53.5		10 Ne Neon 24.58	2 K 8 L							
11 8 Na Sodium 370.87	12 Mg Mg Magnesium 923													13 2 8 AI Aluminium 933.47	14 2 8 4 Silicon 1687	15 8 P Phosphorus 317.3	16 S Sulfur 388.36	2 6 CI Chlorine 171.8	2 8 7	18 Ar Argon 83.8	2 K 8 L 8 M
19 K Potassium 338.53	20 2 Ca 2 Calcium 1115	21 2 SC 2 Scandium 1814	22 2 8 10 2 Ti Titanium 1941	23 1 V 12 Vanadium 2183	24 28 13 13 1 Chromium 2180	25 2 Mn 13 Manganese 1519	26	27 CO Cobalt 1768	2 28 15 Ni Nickel 1728	16 2	29 8 Cu 19 Copper 1357.77	30 Zn Zinc 692.68	18	31 2 8 18 3 Gallium 302.91	32 2 8 18 4 Germanium 1211.4	33 2 8 18 18 5 Arsenic 1090	34 Se Selenium 494	2 35 18 Br Bromine 285.8	2 8 18 7	36 Kr Krypton 115.79	2 K 8 L 18 M 8 N
37 8 8 18 18 18 18 18 18 18 18 18 18 18 18	38 2 8 18 8 Strontium 1050	39 2 Y 18 9 Yttrium 2 1799	40 28 Zr 18 Zirconium 2128	41 Nb 1 Niobium 2750	23 42 8 Mo 18 Molybden	43 2 8 18 18 TC 13 2 2430	44 28 18 18 15 15 12 1607	45 Rh Rhodium 2237	2 46 18 Pd Palladium 1828.05	18 18	47 Ag Silver 1234.93	48 Cd Cadmium 594.22	18 18 2	49 8 18 18 18 18 18 429.75	Tin 505.08	51 2 Sb 18 Antimony 903.78	52 Te Tellurium 722.88	2 53 18 1 lodine 388.85	2 8 18 18 7	Xe Xenon 181.3	2 K 8 L 18 M 18 N 8 O
55 Cs 18 Caesium 301.59	56 2 Ba 18 Barium 2 1000	57–71	72 2 8 18 18 32 Hafnium 2 2 5 0 8	73 Ta 32 Tantalum 3290	74 2 8 W 18 32 Tungsten 2 3695	75 8 18 32 Rhenium 2 3459	76 8 Os 18 Osmium 14 3306	77 Ir Iridium 2739	78 18 32 15 2 Platinum 2041.4	18 32 17	79 18 29 29 29 29 29 29 29 29 29 29 29 29 29	80 Hg Mercury 234.32	18 32 18 2	81 2 8 18 32 Thallium 18 32 777	82 2 8 Pb 18 32 Lead 4 600.81	83 2 8 18 32 Bismuth 5	PO Polonium 527	85 18 32 At 18 6 Astatine 575	18 32	Rn Radon 202	2 K 8 L 18 M 32 N 18 O 8 P





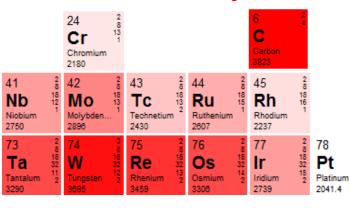
HHFC Base Material

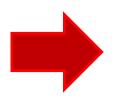


Melting Point >2000 K Thermal Conductivity >50 W/mK



Availability, Cost





	24 2 8 13 1 Chromium 2180	
41 8 Nb 18 Niobium 2750	42 8 18 18 13 Molybden 2898	
	74 2 8 18 32 Tungsten 2 3895	



Low/Medium Activation

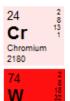






e.g. T_{RC}

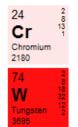




Tungsten







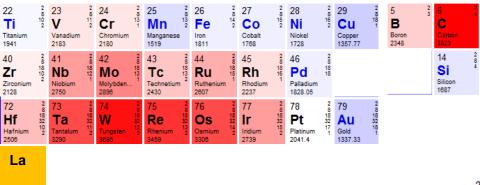




HHFC Alloying Elements (up to 1%)

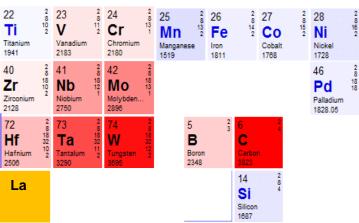


Melting Point >1300 K Thermal Conductivity >20 W/mK









Cu

47

Ag

Silver

1234.93

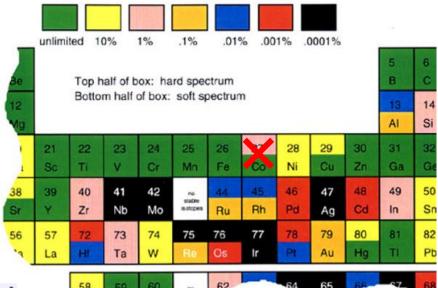
HHF Alloying Elements (up to 1%)





Activation

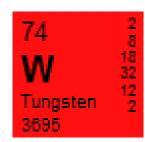




Irradiation







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What can be done with these elements? **Pure Tungsten** Grain **Tungsten Tungsten** Stabilized Compounds Alloys Tungsten W-(Ni)-Fe (Densimet) W-V W-Ta W-Cu (Elmet) (W-Ag) (W-Mo) Densimet **Potassium** Oxide **Particles** Doping La₂O₃ (e.g. WL10) e.g. WVM → Bulb Wire ZrO₂ CeO₂ (ThO₂)





Tungsten Material Production Routes



Sintering & Forming

- + Mass Production
- + Density
- -/+ Specific, anisotropic microstructure

Mechanical
Alloying &
HIP

PowderMetallurgy

Injection
Molding &
Sintering/HIP

- + Fine Particles
- + Homogenous Microstructure
- Small Quantities
- Porosity
- Brittleness?

+ Real Alloying

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

(S)Melting &

Forming

- + Mass Production
- + Nearly Finished Products
- + Homogenous Microstructure
- Porosity
- Severe Brittleness

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Where are we today?

Important Design Criteria



Thermal Conductivity 100 W/mK @ 1200 °C

Creep Strength 55 MPa, 20 kh 1200 °C

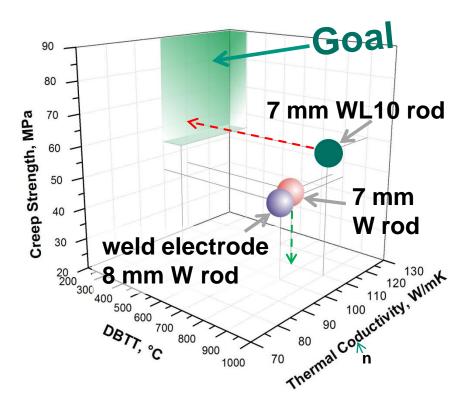
DBTT unnotched

300 °C, unirradiated

Recrystallization **Temperature**

1300 °C, for 20 kh

Present Situation



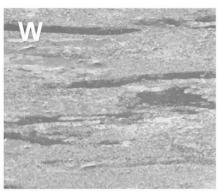


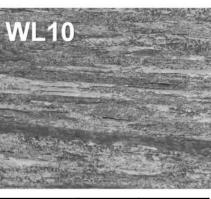


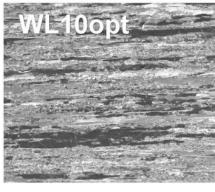
W-Materials, Rolling Texture

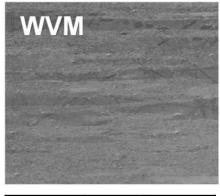
RODS









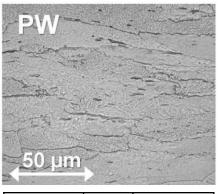


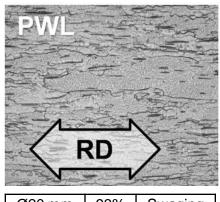
Ø6,9 mm 91% Rolling

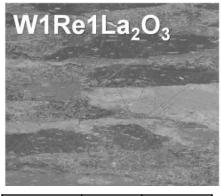
Ø6,9 mm 91% Rolling

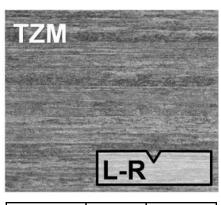
Ø6,9 mm 94% Swaging

Ø16 mm 91% Rolling









Ø20 mm 93% Swaging

Ø20 mm 93% Swaging

Ø10 mm 81% Rolling

Ø7 mm | 91% | Sw+Rol

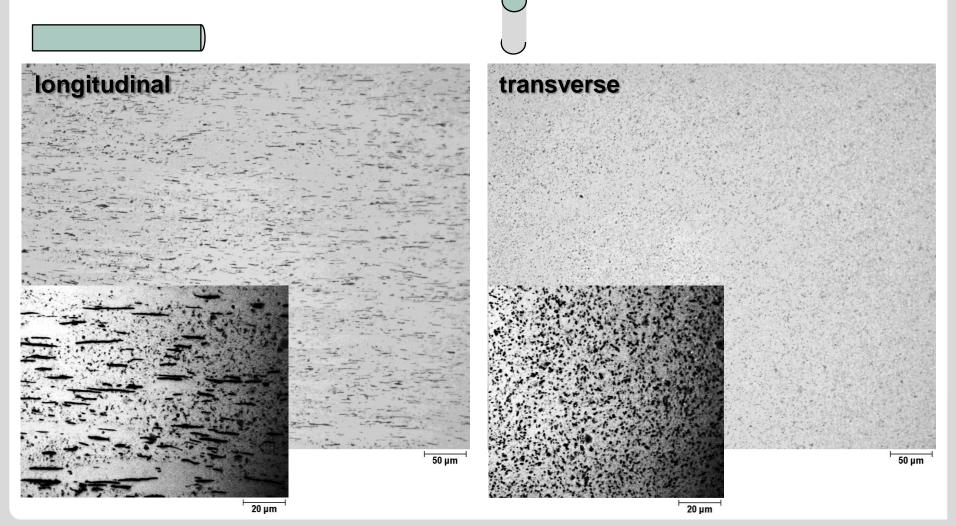
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Microstructure



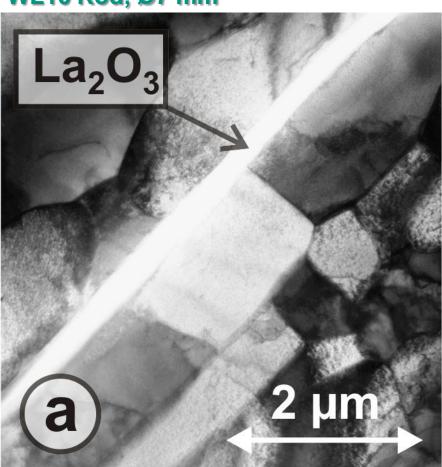
WL10 Rod, Ø7 mm



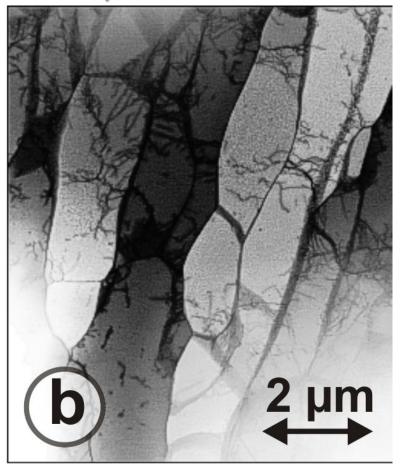
Microstructure in the condition as delivered (by TEM)



WL10 Rod, Ø7 mm



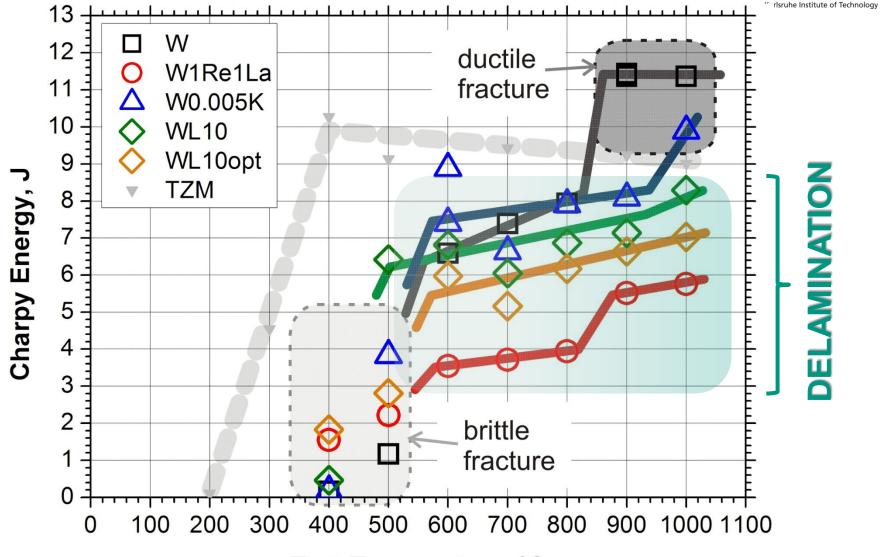
W Rod, Ø7 mm





Rods: Fracture Characteristics





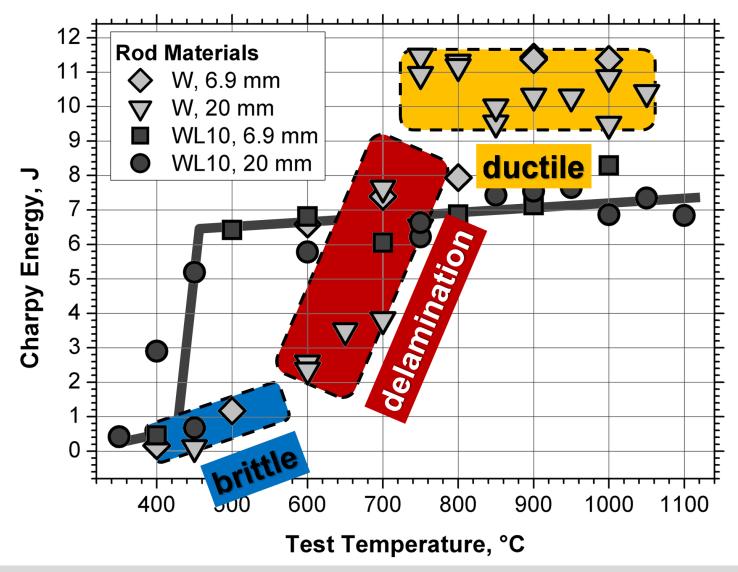
Test Temperature, °C





Rods: Fracture Characteristics

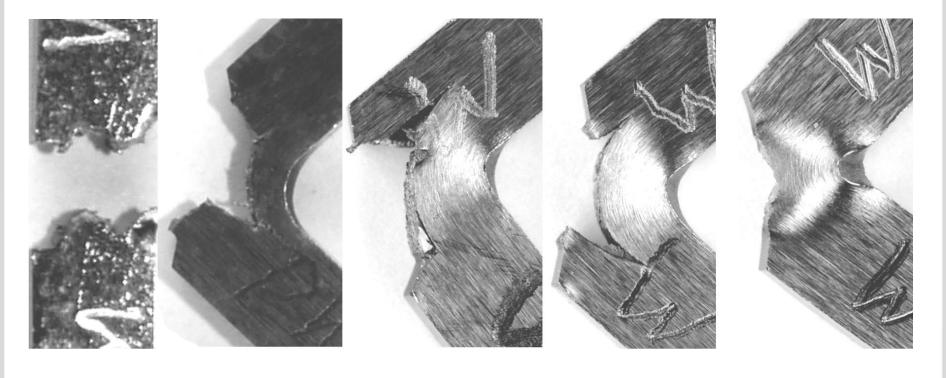




Transition of Fracture Modes



brittle -> delamination -> ductile



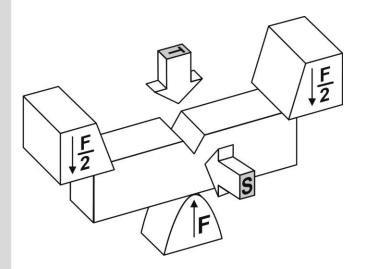
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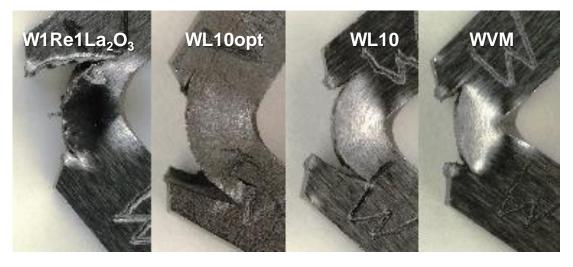
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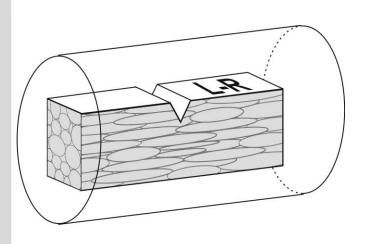


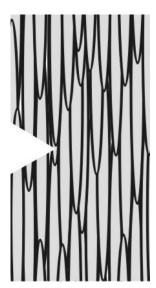
Delamination Fracture in Rods

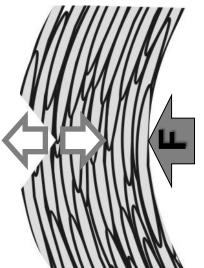


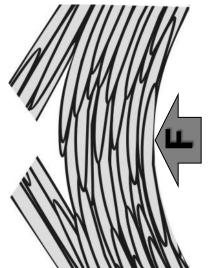








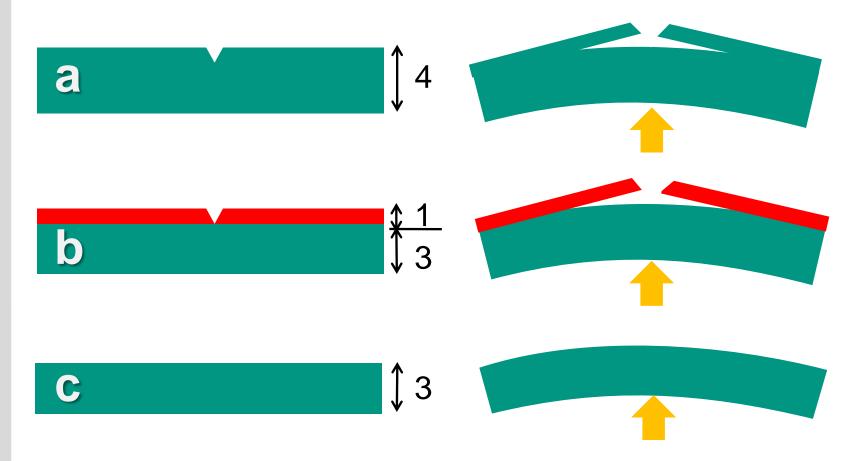






Delamination, Simple Analogy





Prediction: Delamination will disappear with flat surfaces!



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40

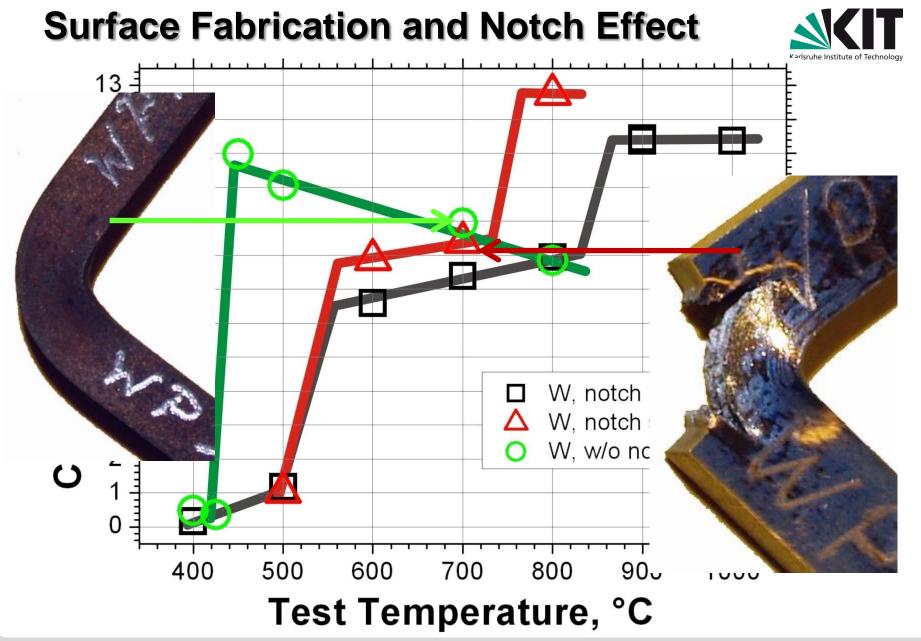


Plate Materials



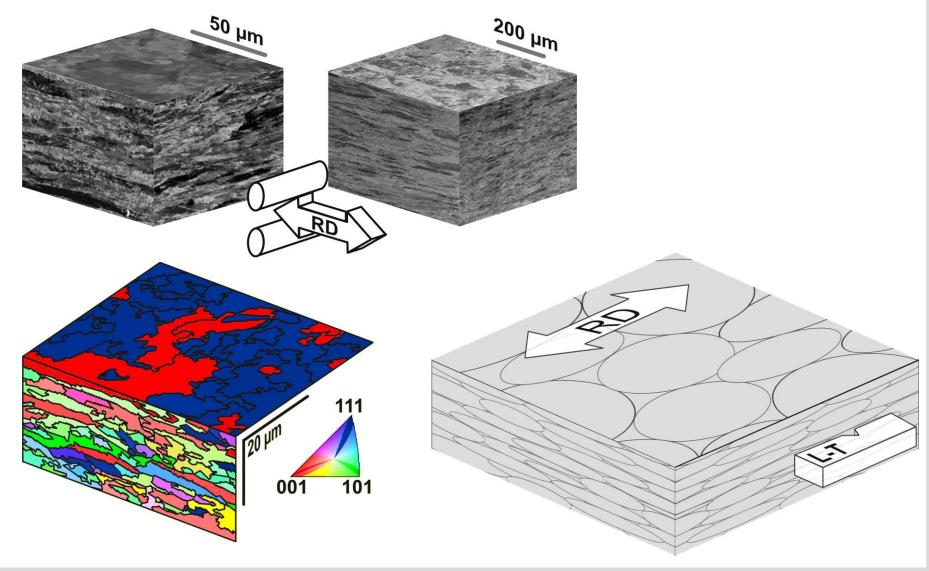
91% thickness 3.6 mm thickness 3.6 mm 91% thickness 4 mm thickness 3.6 mm 90% 91%





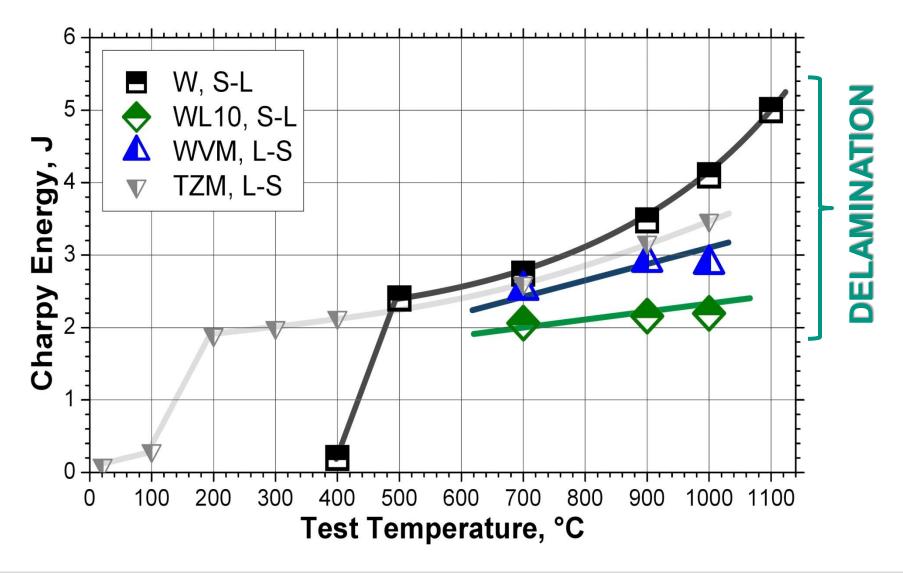
Plate Microstructure





Charpy Tests, Plate Materials





M. Rieth: Tungsten as a structural material

for fusion reactors



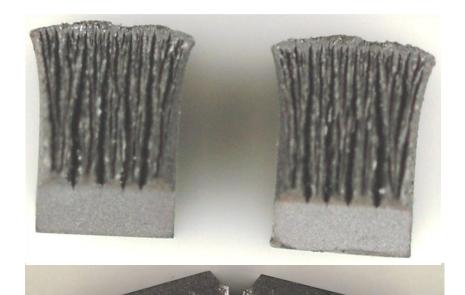


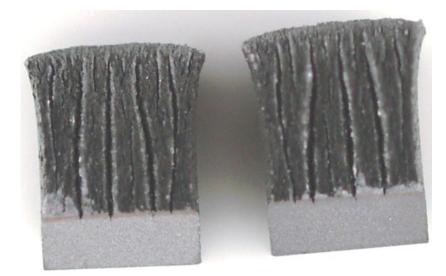
Fracture: W & WL10, plates













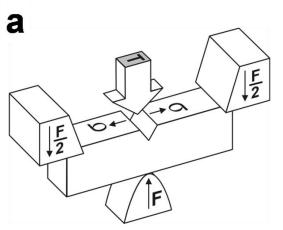
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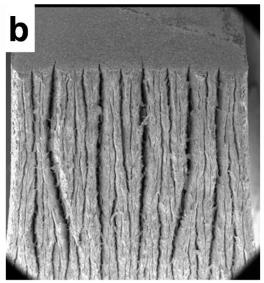
in der Helmholtz-Gemeinschaft

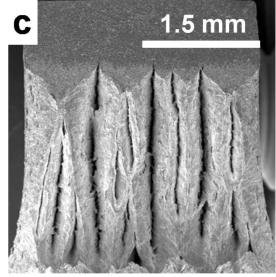
Tested at 1000 °C !!!

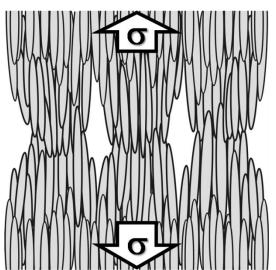
Delamination Fracture in Plates

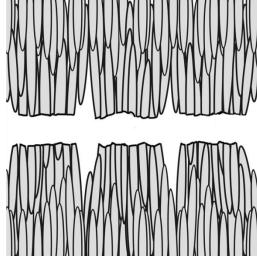


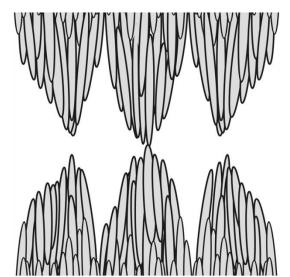














Important Conclusions for HHFCs



- 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!)

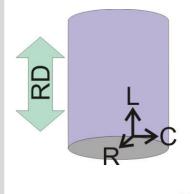


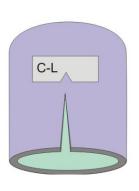
Forschungszentrum Karlsruhe

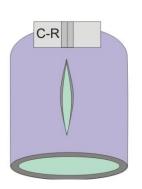


But how to fabricate divertor parts?

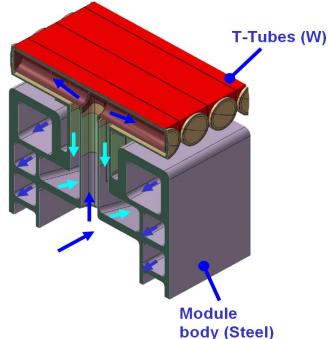


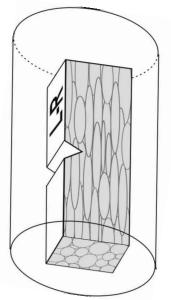






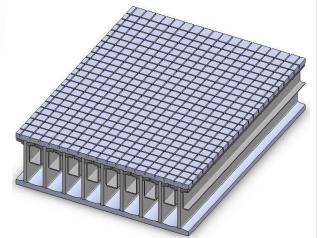








→ J. Reiser et al., FZK







Problem of Microstructure Orientation





Pipe Impact Test





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Summary



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_t/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 \rightarrow high activation!!!
- Liquid wall divertors or something completely different???



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







for your interest

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Additional Slides





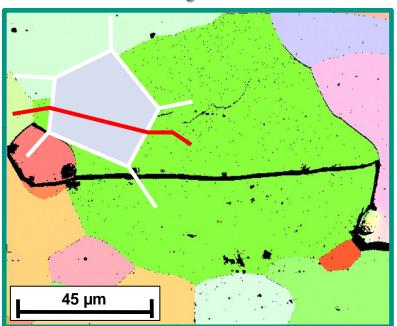
Tungsten Problematic



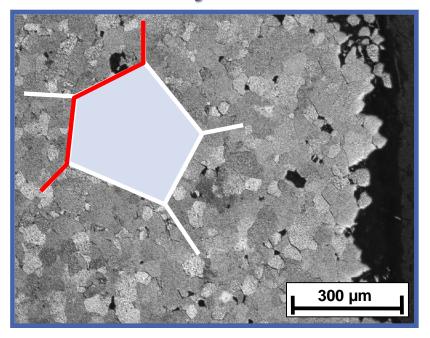
Question: Is tungsten a brittle material?

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

Trans-Crystalline



Inter-Crystalline



→ R. Pippan et al., ÖAW

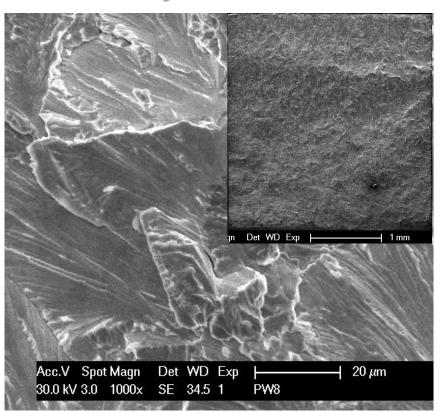




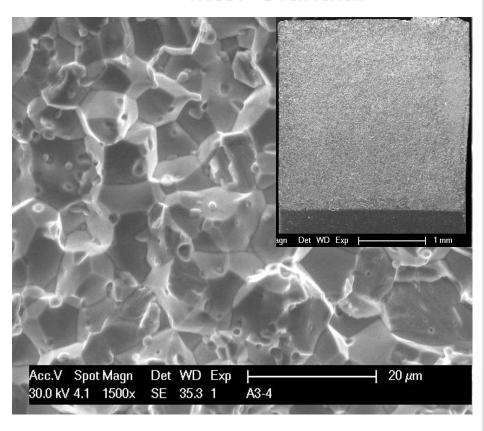
Tungsten Problematic



Trans-Crystalline



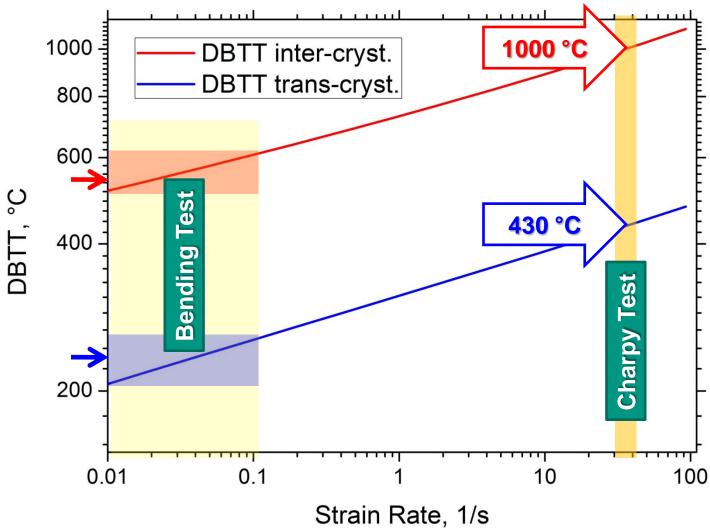
Inter-Granular





DBTT is Strain-Rate Dependent





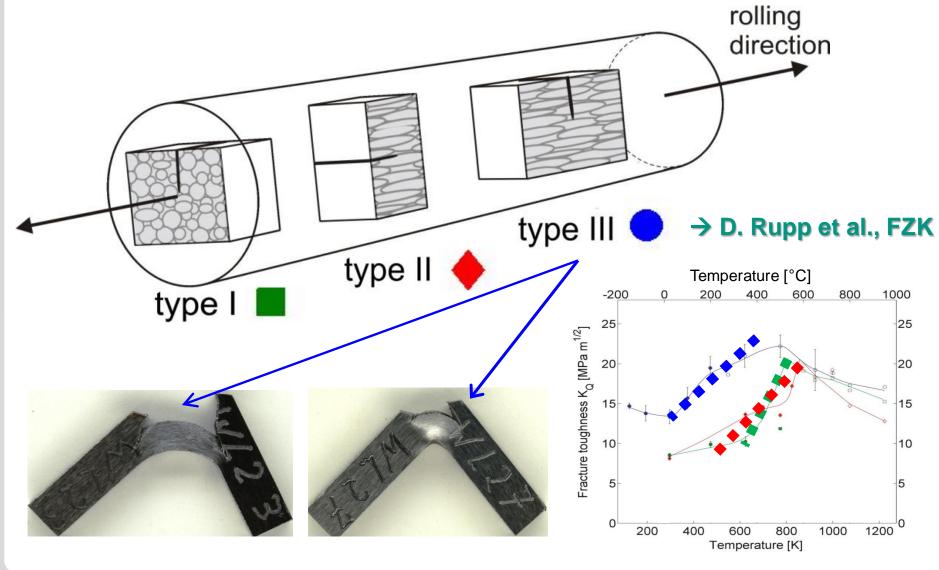
→ S. Roberts, J. Murphy, D. Armstrong, Oxford





Influence of the Grain Shape





Notches Influence Grain Boundary Fracture



