KIT Karlsruhe Institute of Technology

IAM Institut für Angewandte Materialien

FUSION
KIT - EURATOM
ASSOCIATION

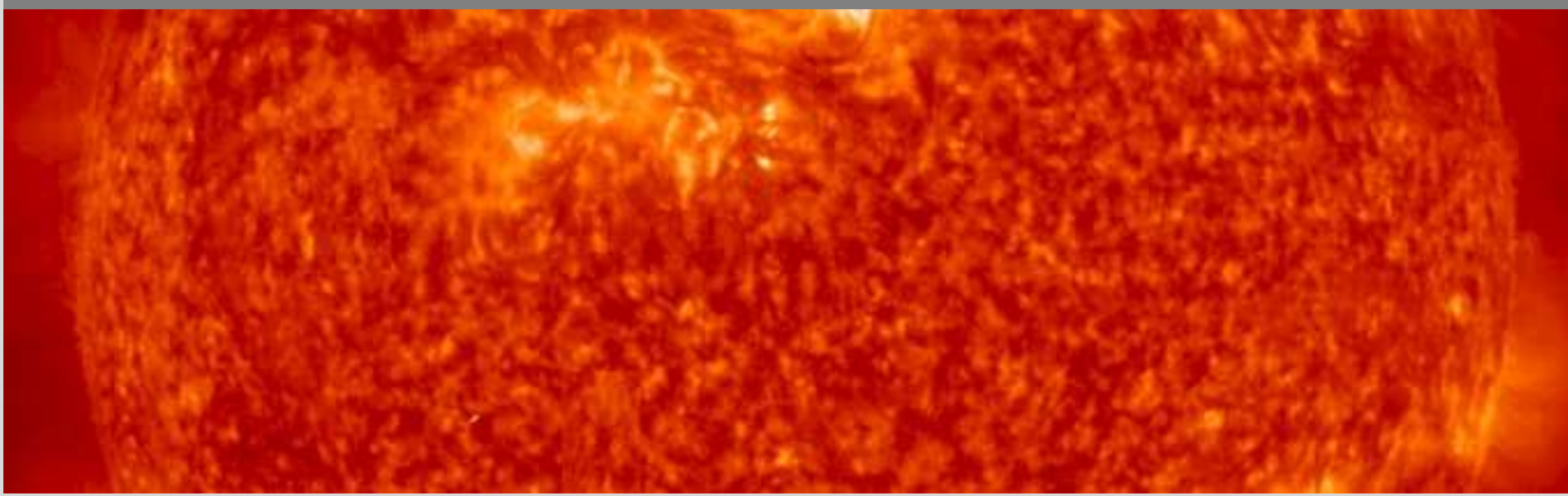
EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

Power Plant Divertor

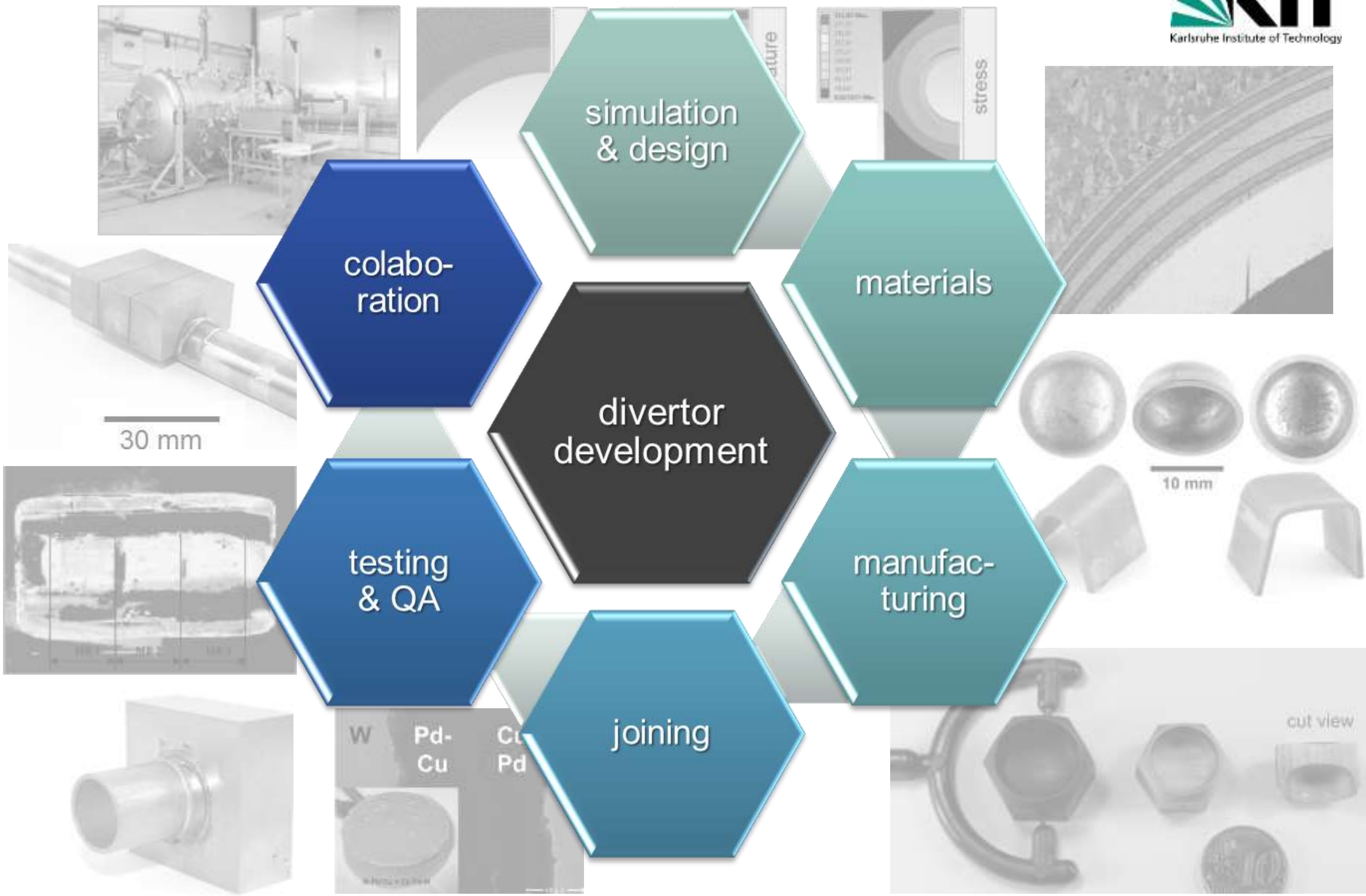
Design Options & Materials

Michael Rieth

KARLSRUHE INSTITUTE OF TECHNOLOGY, INSTITUTE FOR APPLIED MATERIALS, APPLIED MATERIALS PHYSICS DEPARTMENT



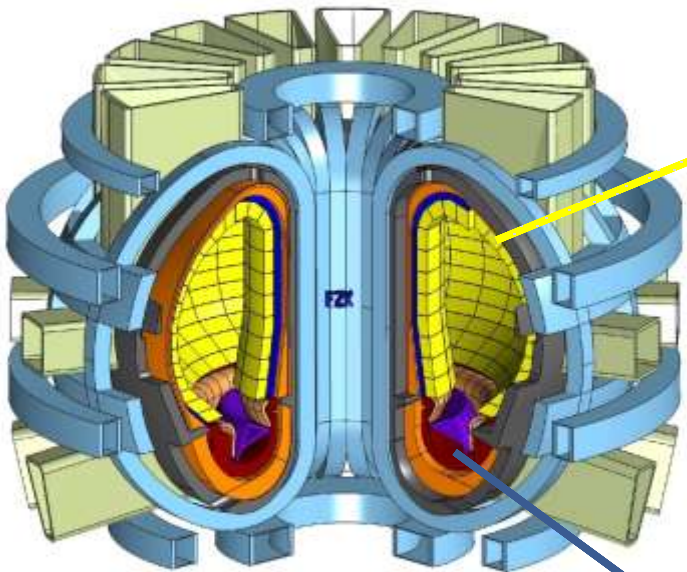
Overview



simulation & design
colabo-ration
materials
divertor development
testing & QA
manufac-turing
joining
30 mm
10 mm
stress
W
Pd-Cu
Pd
cut view

DEMO – THE STEP IN BETWEEN

Karlsruhe Institute of Technology



DEMO
2011

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

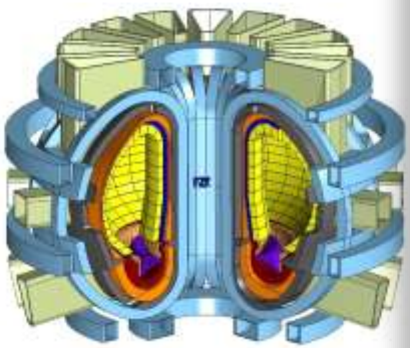
Materials unknown
Operating temperature 350-1300 °C ?

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

DEMO "LIGHT" – A FASTER APPROACH

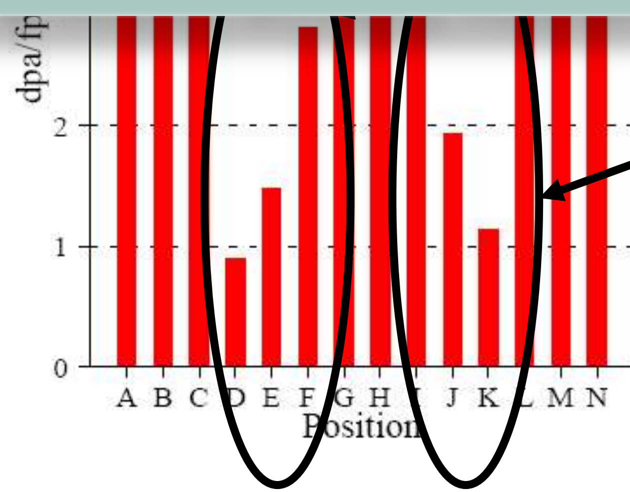
New boundary/operating conditions

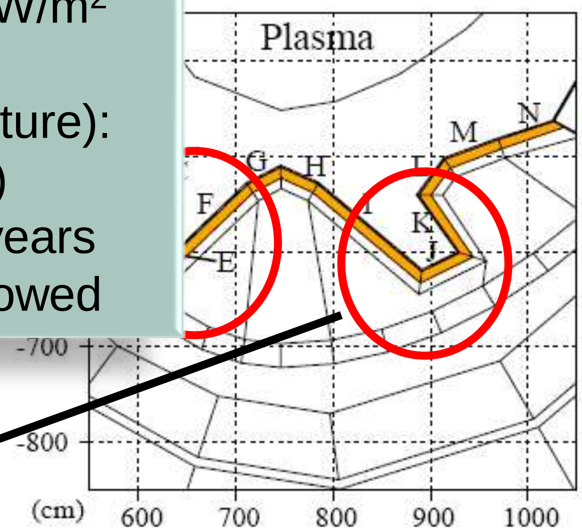
- Thermal power ~2 GW_{th}
- Size: R~9 m, a~2.25 m
- Divertor (unshielded) power loading peak ~13 MW/m^2
  → conservative estimate 20 MW/m^2
- Pulse length ~2.5 hours
- Neutron dose (strike zone structure): <3 dpa/fpy (Cu), <1 dpa/fpy (W)
- Divertor life time ~2 full power years
- Medium activating materials allowed



DEMO 2012

Early DEMO, DEMO-1, etc.





- dpa/fpy ranges from 0.9 to 5.9 dpa/fpy

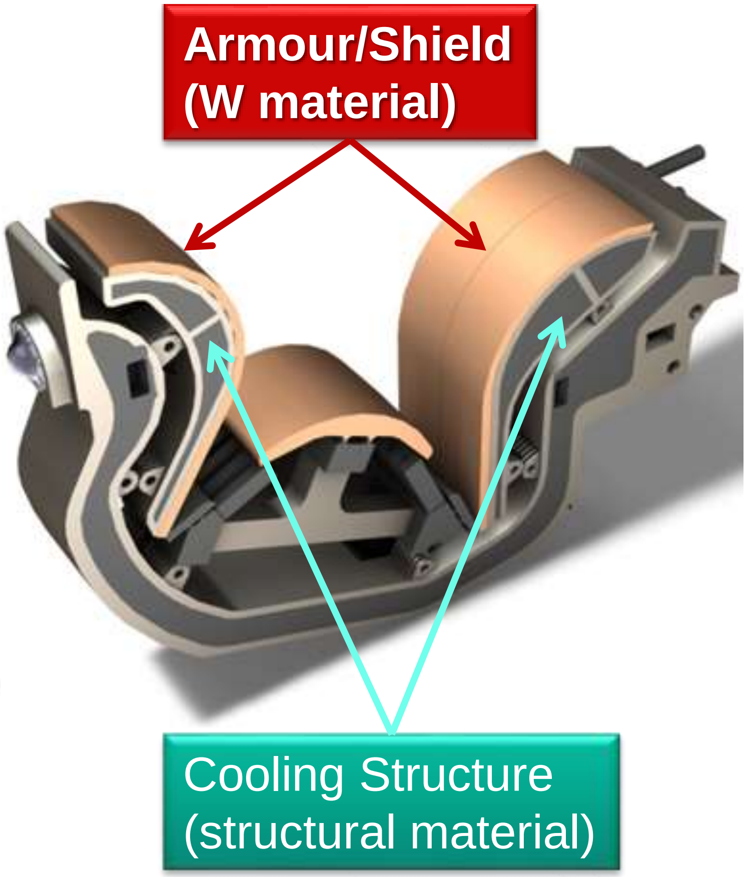
M. Gilbert, CCFE, 2012

DESIGNS

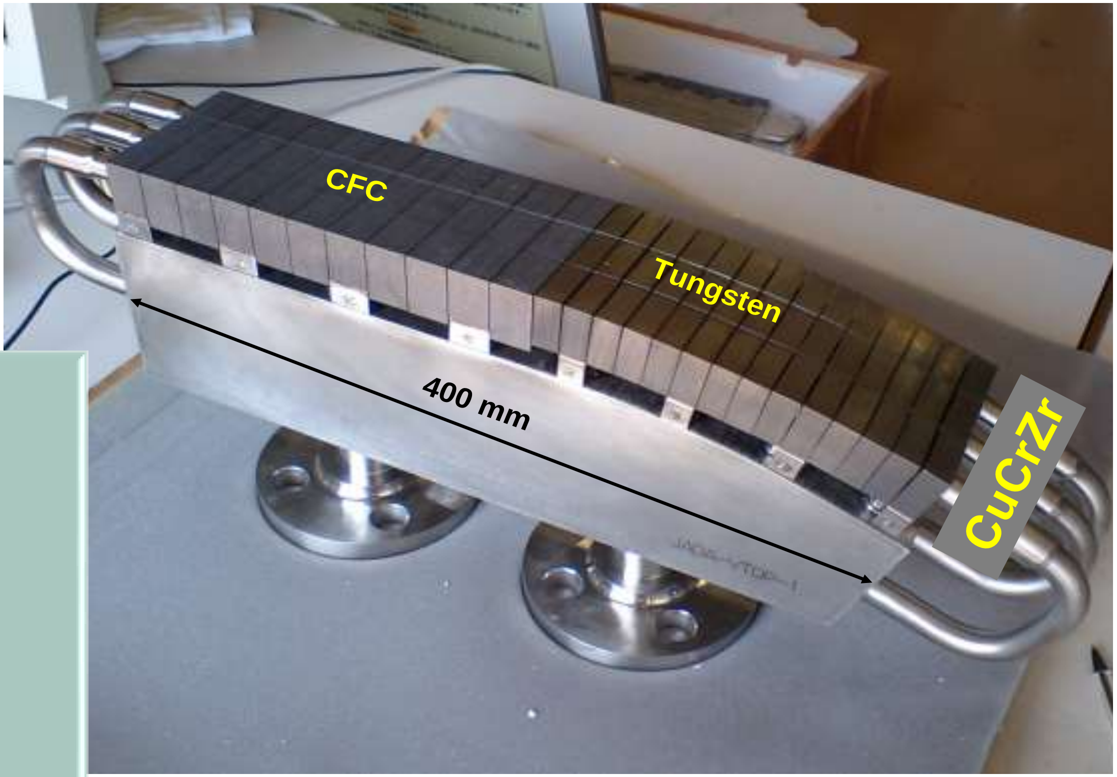
Conventional	Alternative
Gas cooled (He)	Liquid surface
Water cooled	Moving targets (solid, pebbles, etc.)
Liquid metal cooled	

focus of this lecture

Conventional Divertor



ITER DESIGN, WATER COOLING



Coolant

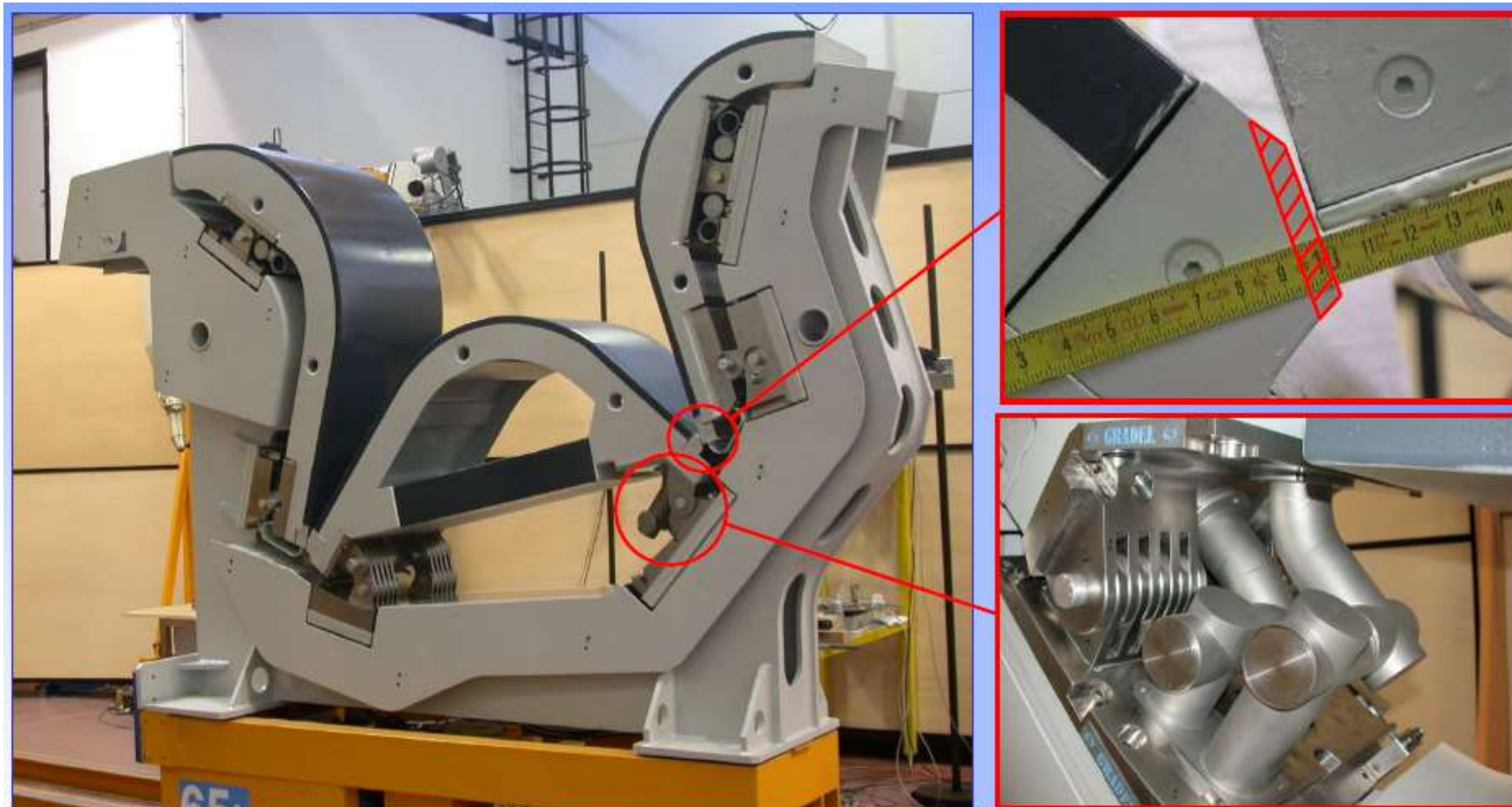
- Pressure: 4 Mpa
- Temp.: 100-150 °C
- Flow: 9-11 m/s

Performance

- Aver. heat flux: 3-5 MW/m²
- Max. heat flux: 10-20 MW/m²
- Max. heat load: 10 MJ/m²
- Lifetime: 3 years
- n-damage: **0.2 dpa**
- Full load cycles: 3000

B. Riccardi *et al.*, F4E, 2008

ITER Design, Water Cooling

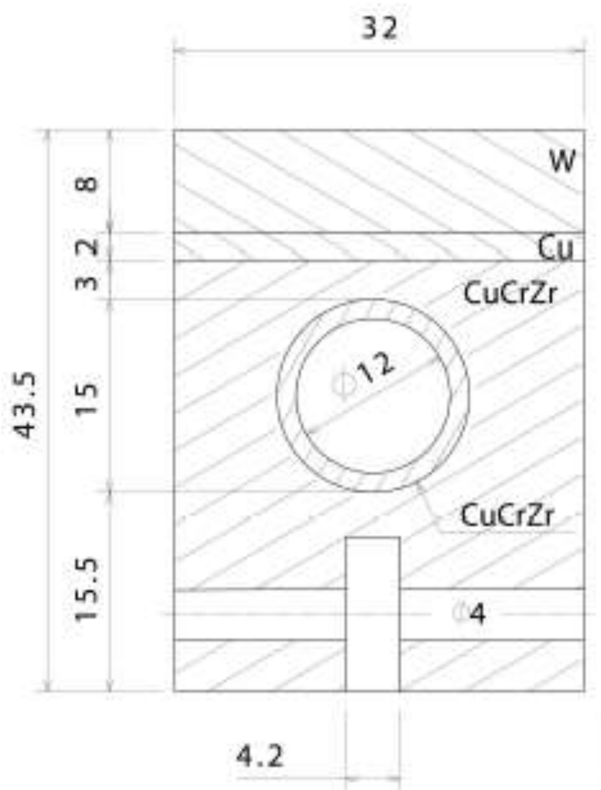


ENEA

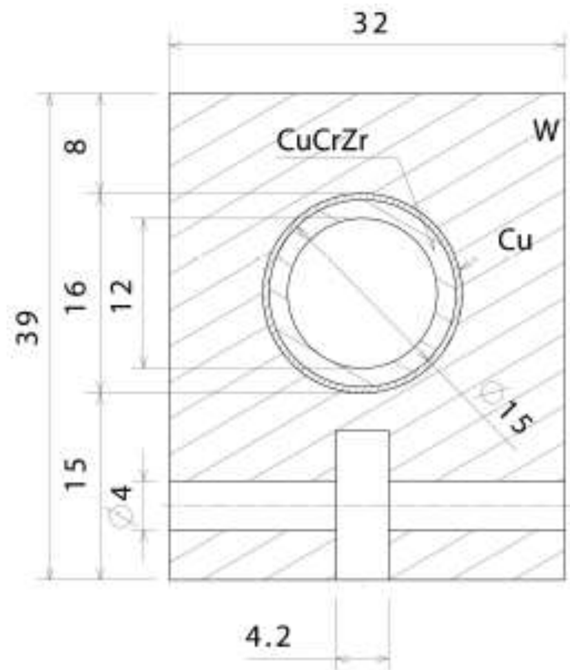
B. Riccardi *et al.*, F4E, 2008

ITER DESIGN, WATER COOLING

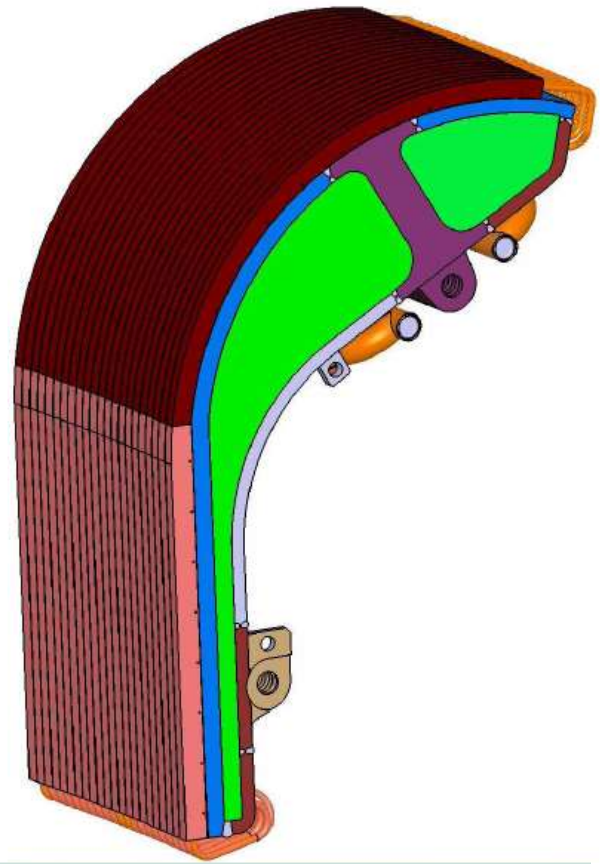
1. W Flat Tiles



2. W Monoblocks



Vertical Target

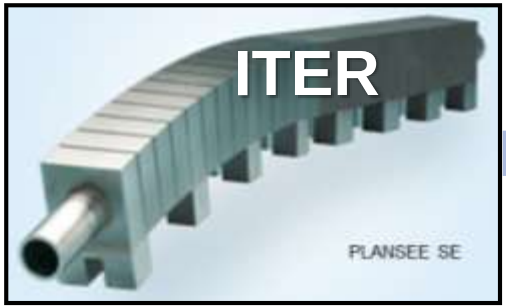


B. Riccardi *et al.*, F4E, 2008

Water cooled divertor concepts – EFDA strategy

From ITER to DEMO

- Neutron damage has to be taken into account:
  → loss of thermal conductivity
  → embrittlement
  → swelling
- Effect of n-irradiation on CuCrZr is unknown at relevant dose levels (5-10 dpa, 200-350 °C)
- Safety issues are much more important → design rules have to be more conservative



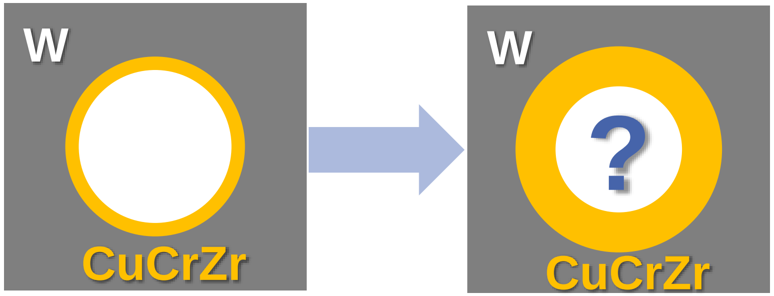
DEMO

?

	ITER	DEMO
Water:	100 °C, 4 MPa	200 °C, **>4 MPa**
	150 °C, 4 MPa	250 °C, **>4 MPa**
		300 °C, **>9 MPa**
		350 °C, **>17 MPa**
CuCrZr pipes:	<0.2 dpa/y	**5 dpa/fpy**
Max. heat:	10-20 MW/m²	10-20 MW/m²

Due to many open questions, the EFDA approach for the DEMO divertor might fail.

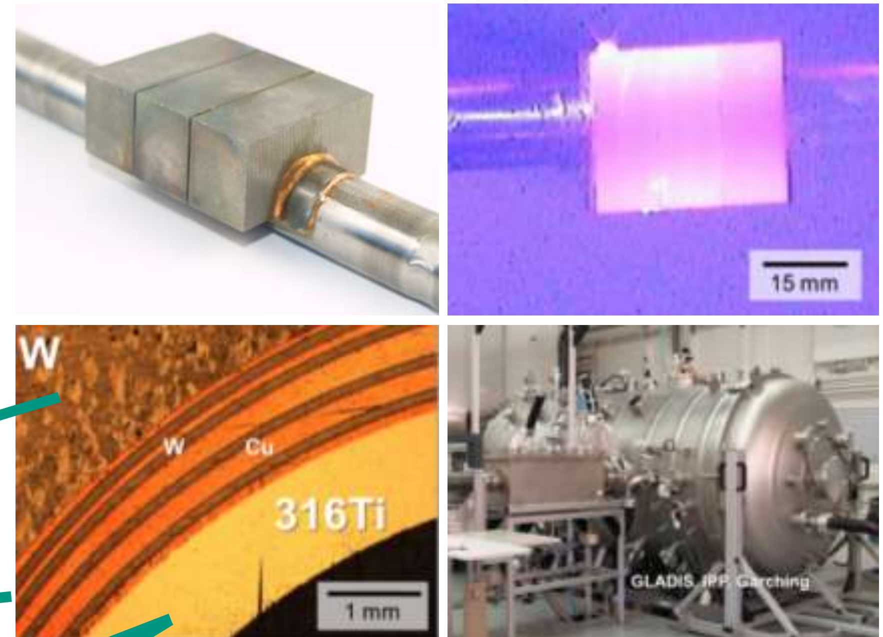
→ Backup solutions are needed !

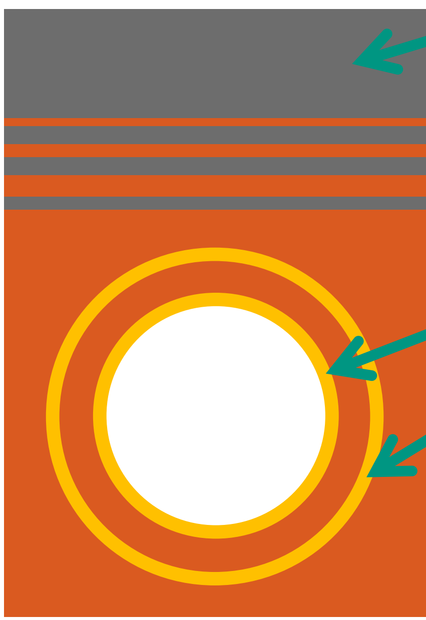


Water cooled divertor concepts – new approach

Risk mitigation strategy

- Fail-safe design (e.g. double walled structures) → **Cu-Steel composite**
- Separation of armour and structural application → **armour parts must not be loaded mechanically**

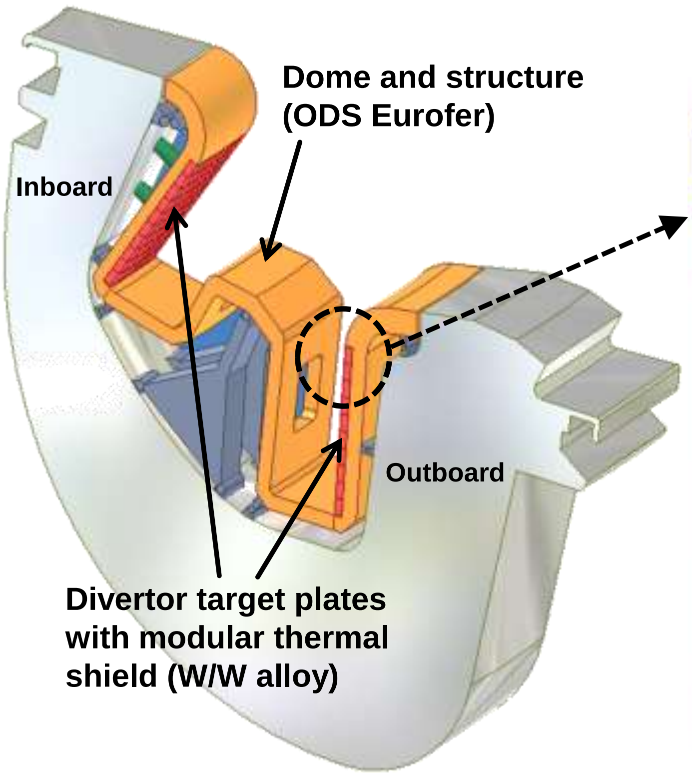




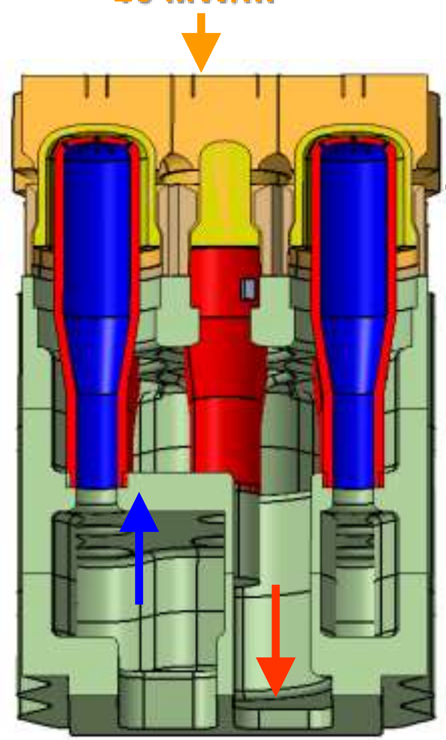
- HHF tests, GLADIS, IPP:
  - → water: RT, 10 m/s, 1.13 l/s
  - → beam: 20 s on / 40 s off
  - → heat flux: 6 MW/m²
- **result after 100 cycles: no residual damage**

Greuner (IPP), Böswirth (IPP), Reiser (KIT)

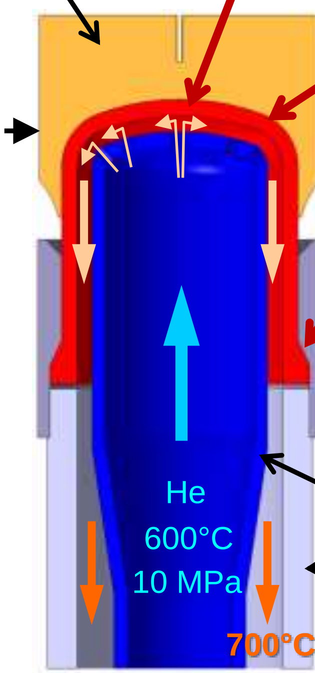
He-cooled modular divertor with jet cooling (HEMJ) – “finger concept”



Divertor cassette



9-Finger module



1-Finger module

P. Norajitra *et al.*

Manufacturing and assembly of modules

W-WL10 joint brazed with PdNi

WL10-steel joint brazed with CuPd

TIG seal welding (steel-steel joint)

1-finger modu

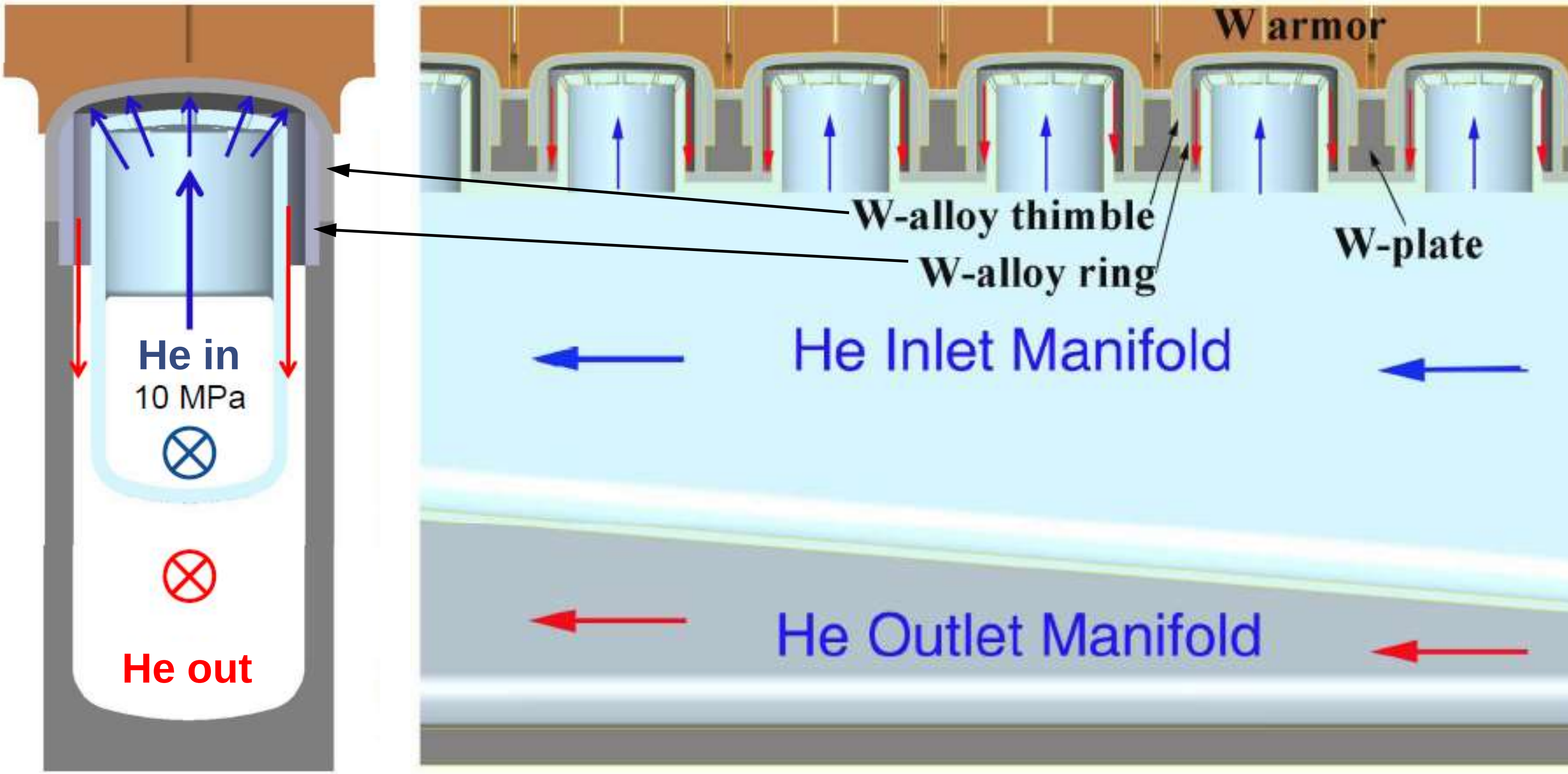
Standard fabrication and assembly routes are demonstrated.

(W) for high heat flux (HHF) tests in Efremov

9-finger module (brass) for non-destructive examination (NDE) with SATIR at CEA

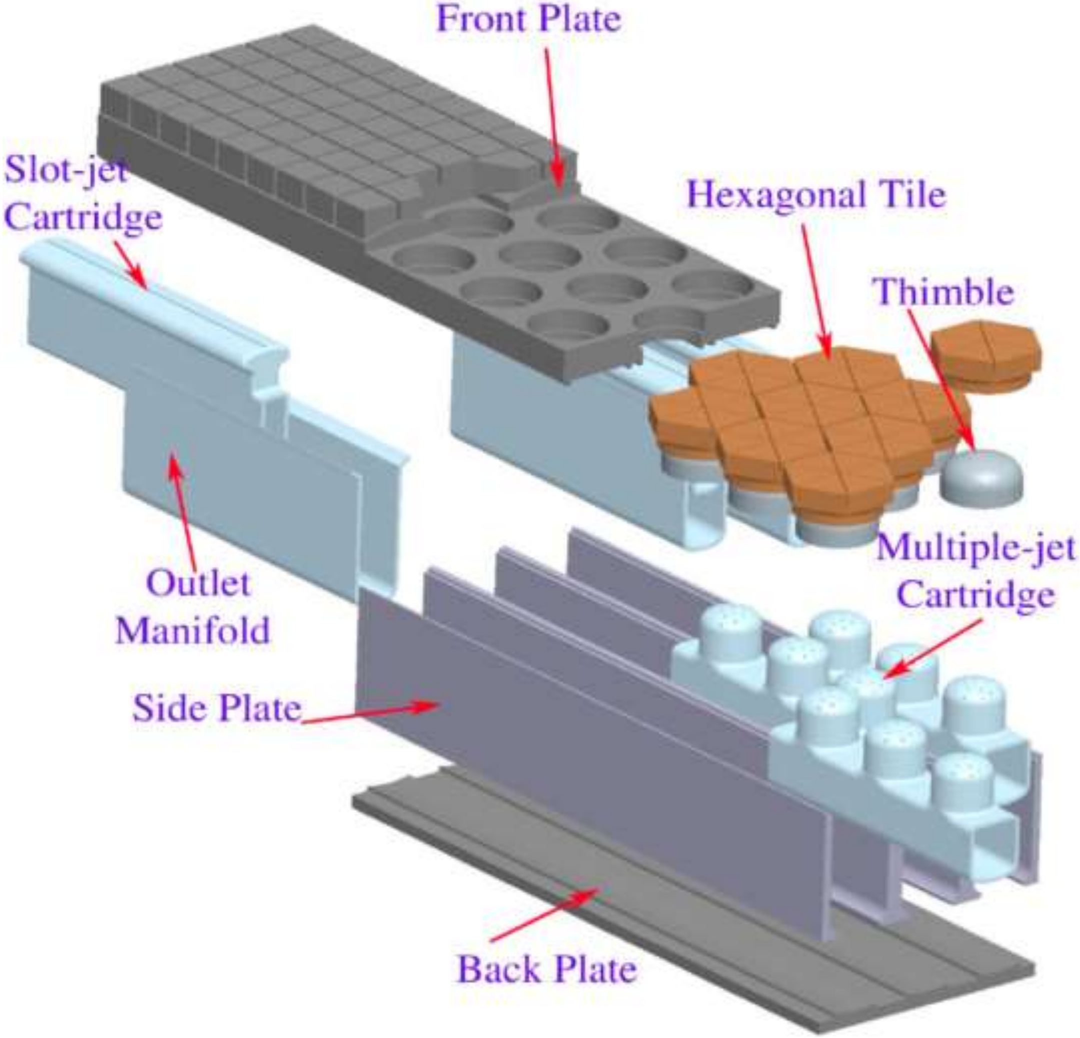
P. Norajitra *et al.*

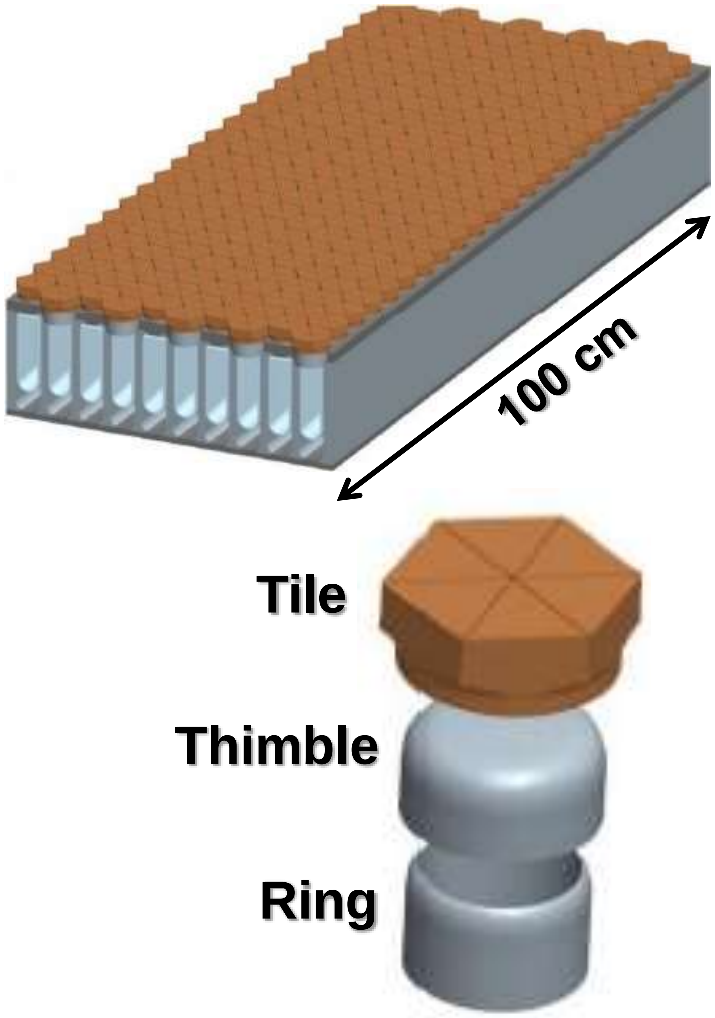
Plate Design (ARIES), Jet Cooling



X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

PLATE DESIGN (ARIES), JET COOLING





X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

PLATE DESIGN, FOAM PROMOTER

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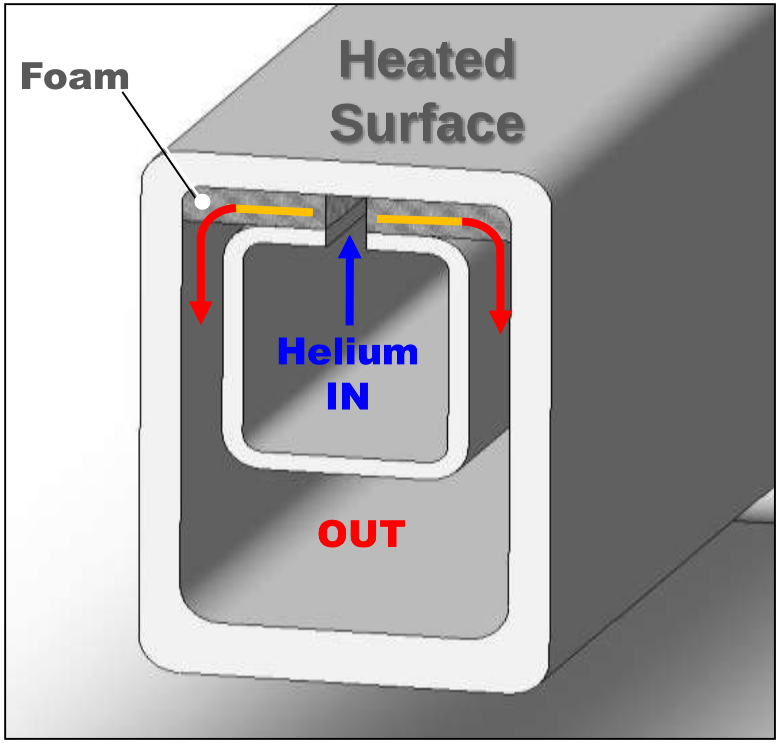
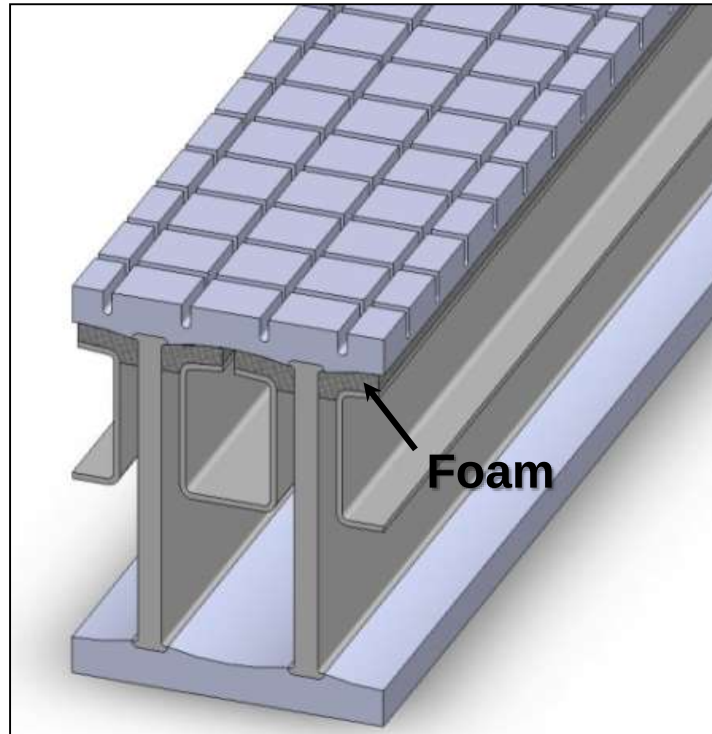
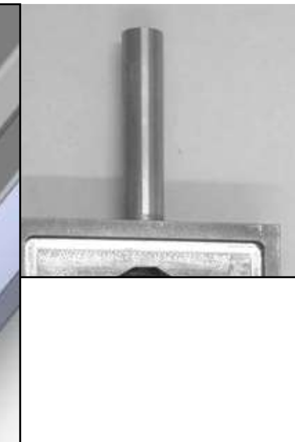
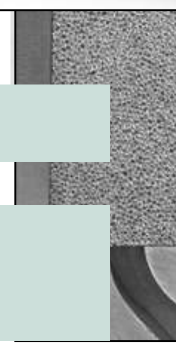
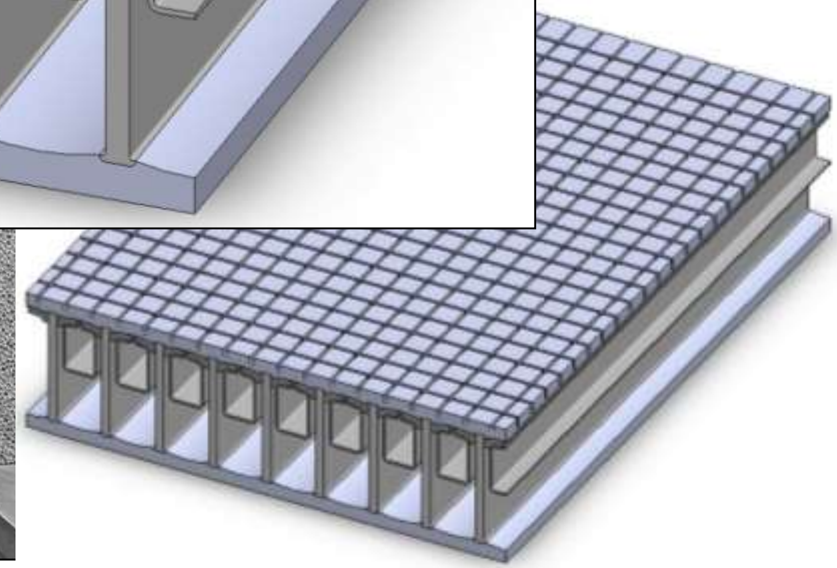










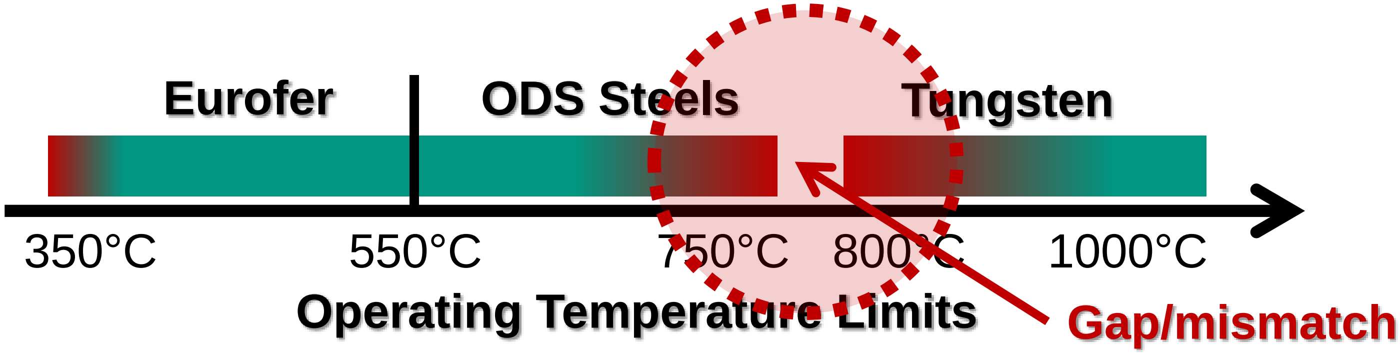
S. Sharafat *et al.*, UCLA, 2005-2009

Mo, Nb, SiC Foam:
D. Youchison *et al.*, SNL,2011

Lessons learned

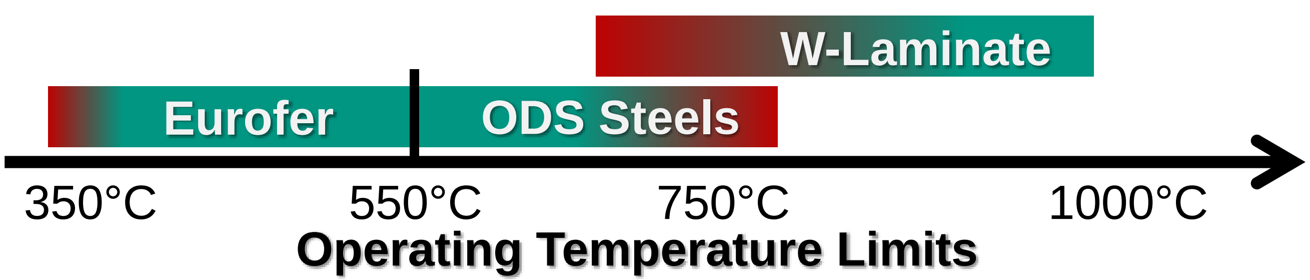
- Efficient He cooling operation **requires W as a structural material** to allow for sufficiently high operating temperatures.
- A **small-size multi-component approach** is needed to reach acceptable low thermal stress levels.
- Mastering heat fluxes in the order of **10 MW/m²** for extended periods is only possible by **jet impingement cooling**.
- Tungsten based materials will suffer from **additional embrittlement under neutron irradiation**. To what extend and under which conditions (irradiation temperature, dose, neutron spectrum) is **not exactly known** yet.
- There is (still) **no structural W alloy available** which meets all design requirements.
  → Thin tungsten sheets seem to be the best choice so far
  → Tungsten composite materials might be the key for alternative designs?

Conclusions



For T < 750 °C partial embrittlement has to be tolerated in tungsten materials !

- Development of design rules for brittle materials
- Risk/failure assessment of the multi-component design
- Design studies to reduce risk of leaks and their consequences (e.g. possible use of double walled parts)



He-cooled concepts – based on pipes

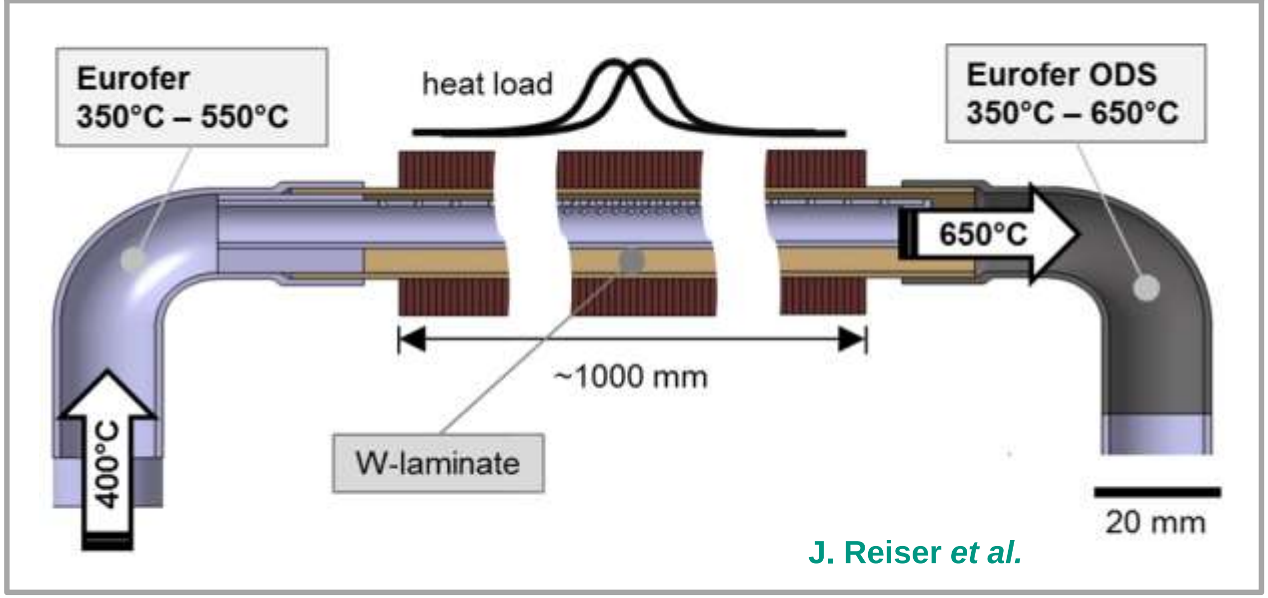
Boundary conditions

- Available materials
- Joining technology
- Mockup performance
- Known operating limits (T, p, dpa, …)
- Cost efficiency

Future issues

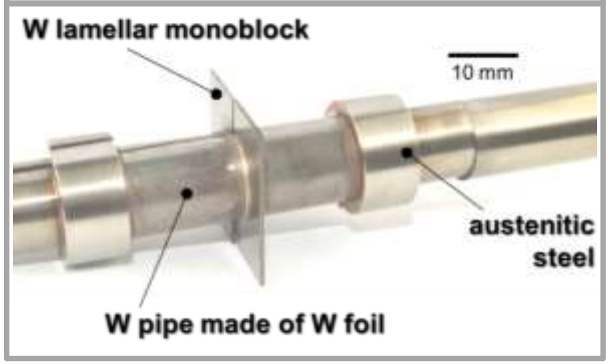
- Thermo-hydraulic calculations
- Unknown material limits (fatigue, dpa)
- HHF testing

Preliminary design study



J. Reiser *et al.*

Fabrication studies



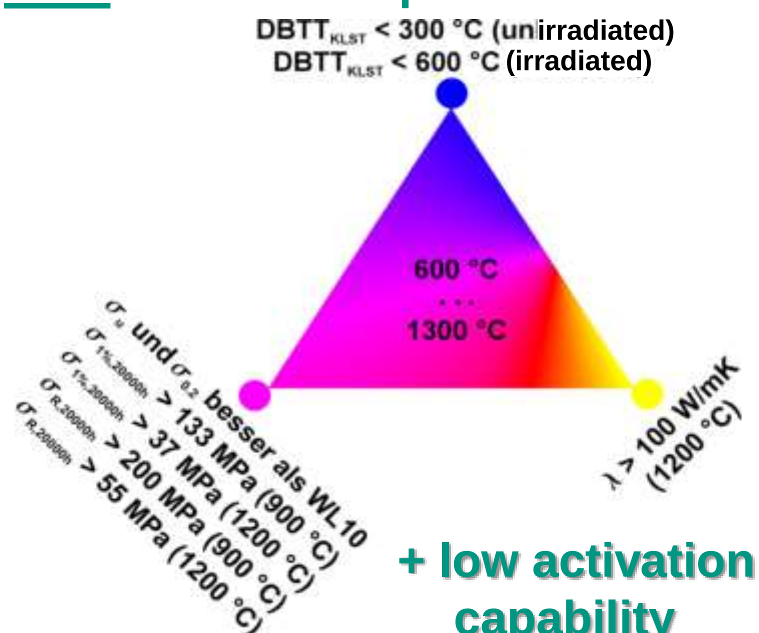
Pressurized pipe tests

Huber, Zabernig (PLANSEE SE)

Design Criteria for Structural Materials

- During the last decade far too many and mutually exclusive design criteria have led to the following situation:
  - NONE of the divertor studies/candidates/concepts would be feasible
  - Even worse: there is NO hope for a DEMO divertor at all
  - Examples for He cooling:

2006: material requirements



+ low activation capability

2009

- q = 10-15 MW/m²
- N = 15 dpa/fpy
- K_{Ic} > 30 MPa $m^{1/2}$
- Low activation filler braze materials
- …

Why Tungsten? → Element Selection

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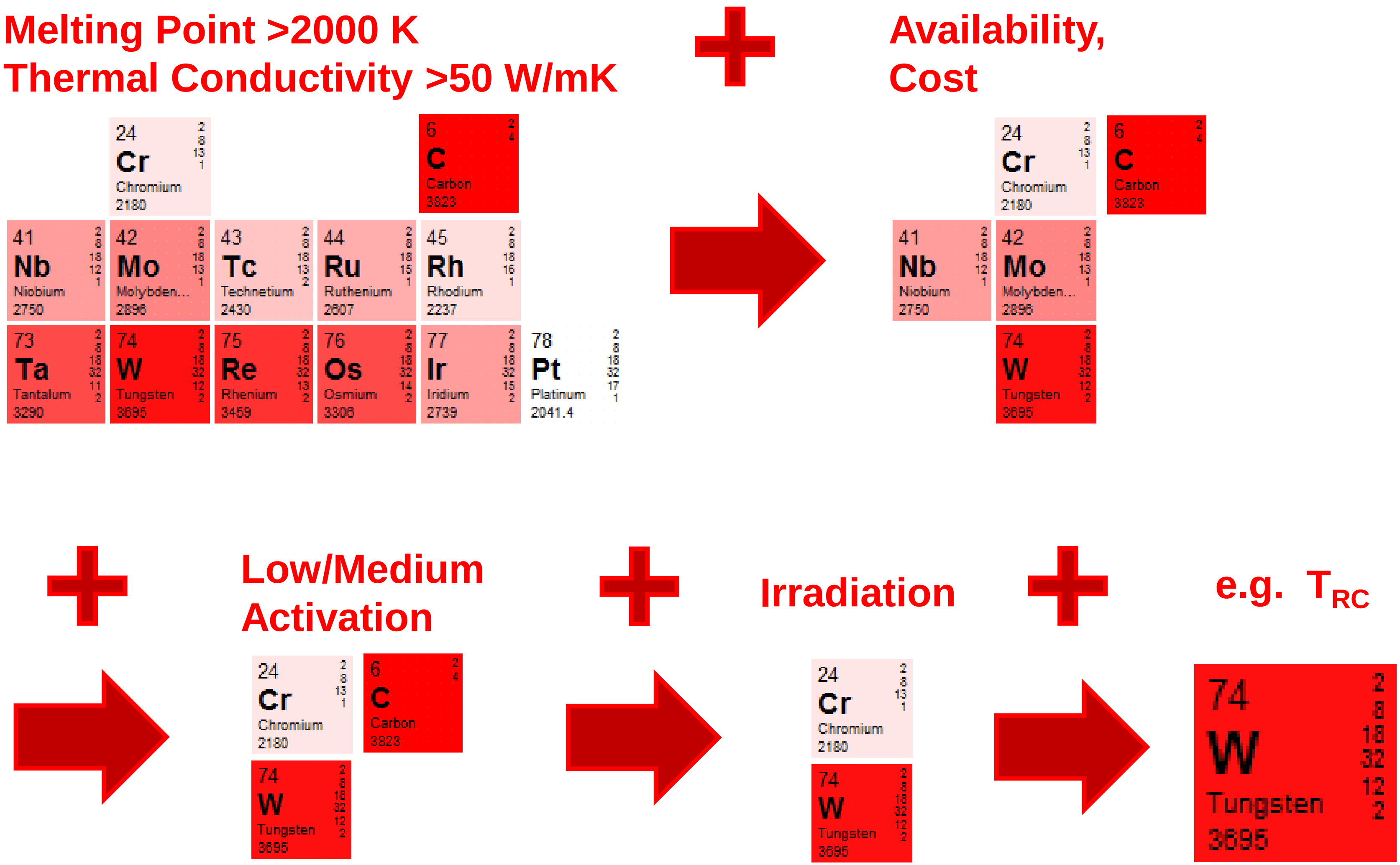
Thermal Conductivity (W/mK)

1 H Hydrogen 0.1805	Atomic # Symbol Name W/mK																2 He Helium 0.1513
3 Li Lithium 85	4 Be Beryllium 190											5 B Boron 27	6 C Carbon 140	7 N Nitrogen 0.02583	8 O Oxygen 0.02658	9 F Fluorine 0.0277	10 Ne Neon 0.0491
11 Na Sodium 140	12 Mg Magnesium 160											13 Al Aluminium 235	14 Si Silicon 150	15 P Phosphorus 0.236	16 S Sulfur 0.205	17 Cl Chlorine 0.0089	18 Ar Argon 0.01772
19 K Potassium 100	20 Ca Calcium 200	21 Sc Scandium 16	22 Ti Titanium 22	23 V Vanadium 31	24 Cr Chromium 94	25 Mn Manganese 7.8	26 Fe Iron 80	27 Co Cobalt 100	28 Ni Nickel 91	29 Cu Copper 400	30 Zn Zinc 120	31 Ga Gallium 29	32 Ge Germanium 60	33 As Arsenic 50	34 Se Selenium 0.52	35 Br Bromine 0.12	36 Kr Krypton 0.00943
37 Rb Rubidium 58	38 Sr Strontium 35	39 Y Yttrium 17	40 Zr Zirconium 23	41 Nb Niobium 54	42 Mo Molybden... 139	43 Tc Technetium 51	44 Ru Ruthenium 120	45 Rh Rhodium 150	46 Pd Palladium 72	47 Ag Silver 430	48 Cd Cadmium 97	49 In Indium 82	50 Sn Tin 67	51 Sb Antimony 24	52 Te Tellurium 3	53 I Iodine 0.449	54 Xe Xenon 0.00565
55 Cs Caesium 36	56 Ba Barium 18	57–71	72 Hf Hafnium 23	73 Ta Tantalum 57	74 W Tungsten 170	75 Re Rhenium 48	76 Os Osmium 88	77 Ir Iridium 150	78 Pt Platinum 72	79 Au Gold 320	80 Hg Mercury 8.3	81 Tl Thallium 46	82 Pb Lead 35	83 Bi Bismuth 8	84 Po Polonium	85 At Astatine 2	86 Rn Radon 0.00361

Melting Point (K)

1 H Hydrogen 14.01	Atomic # Symbol Name Kelvin																2 He Helium 0.95
3 Li Lithium 453.69	4 Be Beryllium 1560											5 B Boron 2348	6 C Carbon 3823	7 N Nitrogen 63.05	8 O Oxygen 54.8	9 F Fluorine 53.5	10 Ne Neon 24.56
11 Na Sodium 370.87	12 Mg Magnesium 923											13 Al Aluminium 933.47	14 Si Silicon 1687	15 P Phosphorus 317.3	16 S Sulfur 388.36	17 Cl Chlorine 171.6	18 Ar Argon 83.8
19 K Potassium 336.53	20 Ca Calcium 1115	21 Sc Scandium 1814	22 Ti Titanium 1941	23 V Vanadium 2183	24 Cr Chromium 2180	25 Mn Manganese 1519	26 Fe Iron 1811	27 Co Cobalt 1768	28 Ni Nickel 1728	29 Cu Copper 1357.77	30 Zn Zinc 692.68	31 Ga Gallium 302.91	32 Ge Germanium 1211.4	33 As Arsenic 1090	34 Se Selenium 494	35 Br Bromine 265.8	36 Kr Krypton 115.79
37 Rb Rubidium 312.46	38 Sr Strontium 1050	39 Y Yttrium 1799	40 Zr Zirconium 2128	41 Nb Niobium 2750	42 Mo Molybden... 2896	43 Tc Technetium 2430	44 Ru Ruthenium 2607	45 Rh Rhodium 2237	46 Pd Palladium 1828.05	47 Ag Silver 1234.93	48 Cd Cadmium 594.22	49 In Indium 429.75	50 Sn Tin 505.08	51 Sb Antimony 903.78	52 Te Tellurium 722.66	53 I Iodine 386.85	54 Xe Xenon 161.3
55 Cs Caesium 301.59	56 Ba Barium 1000	57–71	72 Hf Hafnium 2506	73 Ta Tantalum 3290	74 W Tungsten 3695	75 Re Rhenium 3459	76 Os Osmium 3306	77 Ir Iridium 2739	78 Pt Platinum 2041.4	79 Au Gold 1337.33	80 Hg Mercury 234.32	81 Tl Thallium 577	82 Pb Lead 600.61	83 Bi Bismuth 544.4	84 Po Polonium 527	85 At Astatine 575	86 Rn Radon 202

HHFC Base Material



"STANDARD" STRUCTURAL MATERIALS

Water cooling: PWR conditions T=275-315 °C (at lower T ineffective energy conv.)

CuCrZr

- T<200 °C: loss of ductility, T>300-350 °C: loss of strength
- Unknown irradiation limits (for >5 dpa)
- Medium to high activation

SS

- 200°C<T<400°C: loss of ductility, T>600 °C loss of strength, etc.
- Irradiation limit: ~15 dpa
- High activation → reduced activation alloys could be developed

RAFM

- T<350°C: loss of ductility, T>550 °C loss of strength
- Conservative irradiation limit: ~20 dpa

He cooling: T adjustable (T higher than about 650 °C is a technological challenge)

W

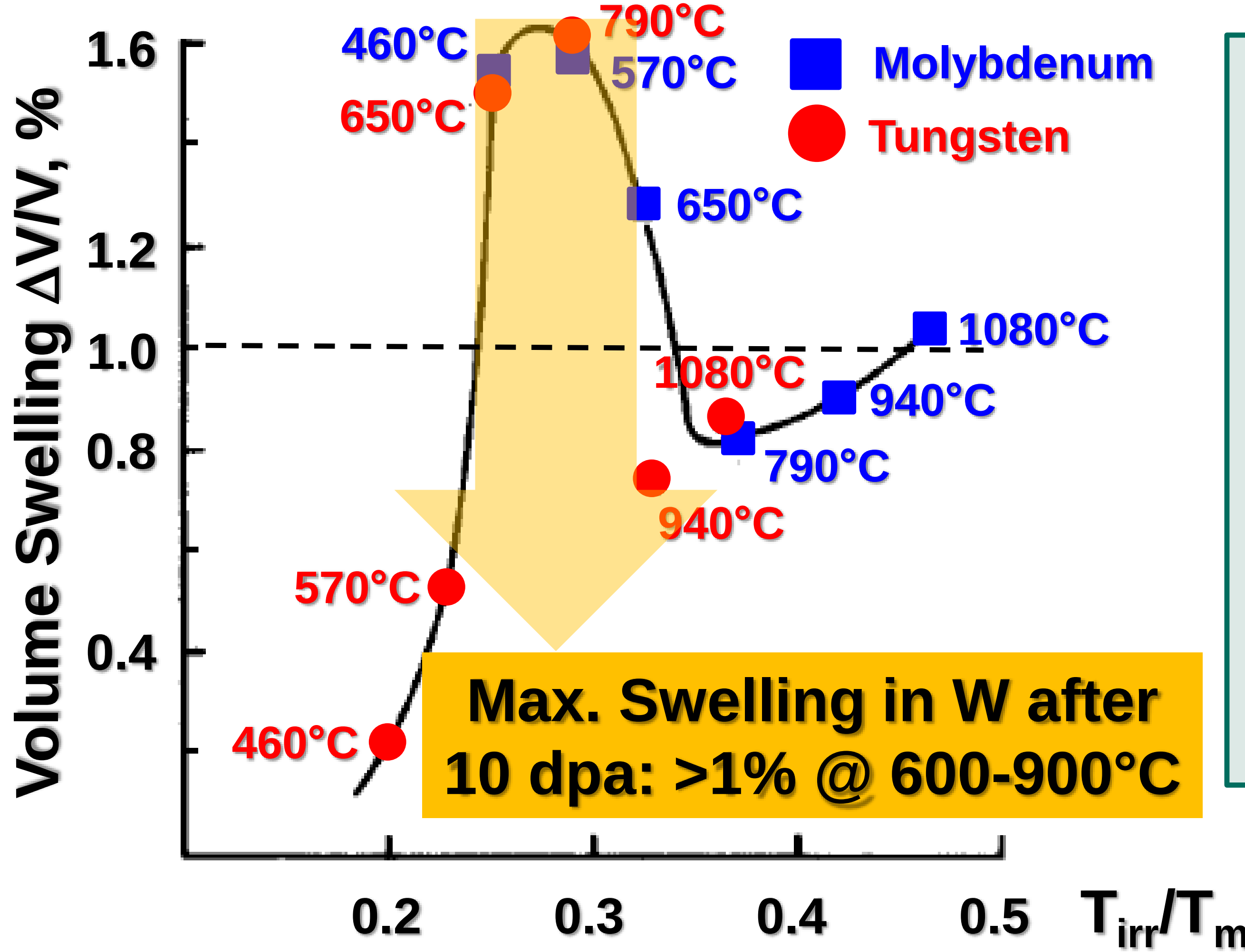
- T<800-1000°C: loss of ductility very likely
- Unknown irradiation limits

ODS Steels

- T<350°C: loss of ductility, T>650-750 °C loss of strength
- Irradiation limits: >20 dpa

TUNGSTEN (AS A STRUCTURAL MATERIAL)

IRRADIATION EFFECTS → SWELLING



Max. Swelling in W after 10 dpa: >1% @ 600-900°C

EBR-II

E_n > 1 MeV
1 x 10^{22} n/cm²

E_n > 0.1 MeV
1.6 x 10^{22} n/cm²

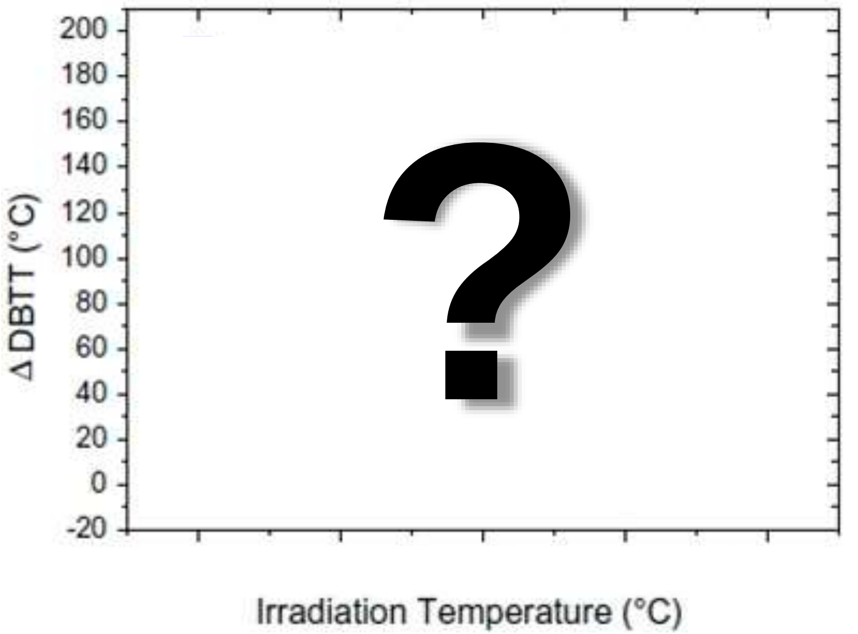
→ **29 dpa in Mo**

→ **9.6 dpa in W**

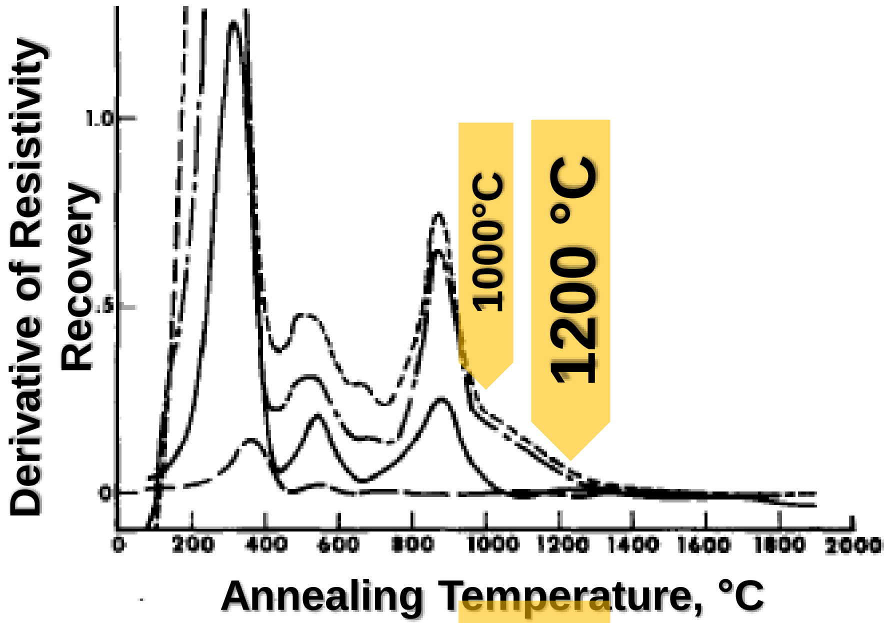
F. Lee, J. Matolich, J. Moteff, JNM 62 (1976) 115-117

IRRADIATION EFFECTS → EMBRITTLEMENT

TUNGSTEN: In-service irradiation embrittlement after 10-20 dpa



Tungsten: Recovery of ~2 dpa stage IV irradiation hardening



Possible Operating Temp.
T_{op} > 800°C … 1000°C

TUNGSTEN MATERIALS

Karlsruhe Institute of Technology

Pure Tungsten

Grain Stabilized Tungsten „ODS Tungsten“

Potassium Doping

e.g. WVM, WVMW
→ Bulb Wire

Oxides & Carbides

- La_2O_3 (e.g. WL10, WL15, WL20)
- CeO_2 (e.g. WC20)
- ThO_2 (e.g. WT20)

→ Weld Electrodes

- Y_2O_3, ZrO_2, TiC, HfC, etc.

„Heavy Metals“ (Two Phases)

- W-Ni-Fe (e.g. Densimet, Inermet)
- W-Cu

→ Functional Applications

Alloys (Solid Solution)

- W-Re (<26%)

→ only commercial alloy

- W-V
- W-Ta
- W-Mo
- W-Ti
- (W-Nb)

→ Even more brittle as pure tungsten !!!

Not suitable for structural divertor applications

Production Routes

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Powder Metallurgy

- Blending
- Pressing
- Sintering
- Hot Forming

- Blending with Bin
- Injection Moldi
- Debindering/ ng
- HIP

- Ball Milling
- Encapsulat
- HIP/Hot Formi

This is so far the only large-scale production route which could handle the <u>500 tons of W</u> needed for one divertor !

+ Mass ction
+ Ne ished cts
ogenous crostructure

Perfect for Armor

→ *S. Antusch, KIT*
→ *J. Opschoor, ECN*

+ Na cture
+ y
all Scale roduction Route

Still Under Investigation

→ *H. Kirushita, IMR*
→ *N. Baluc, PSI*
→ *A. Muñoz, CIEMAT*

Commercial Semi-Finished W Products

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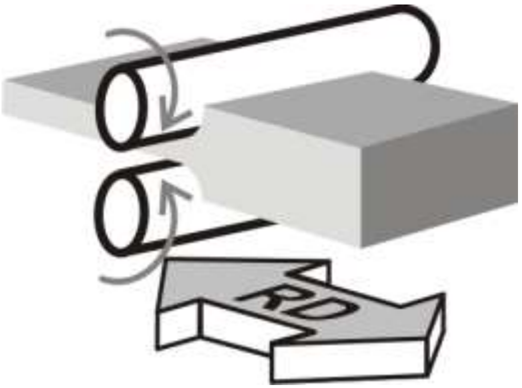
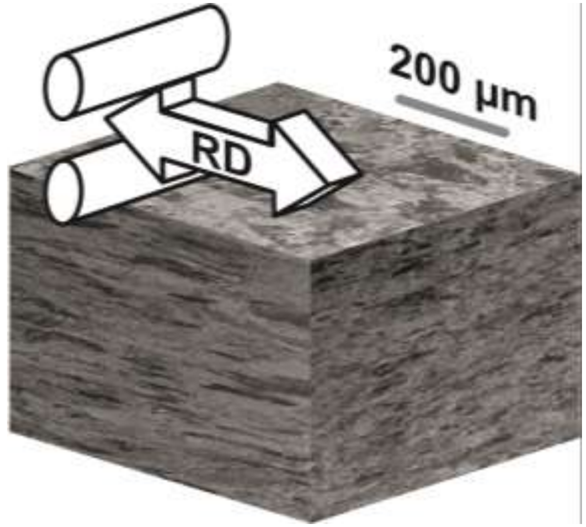
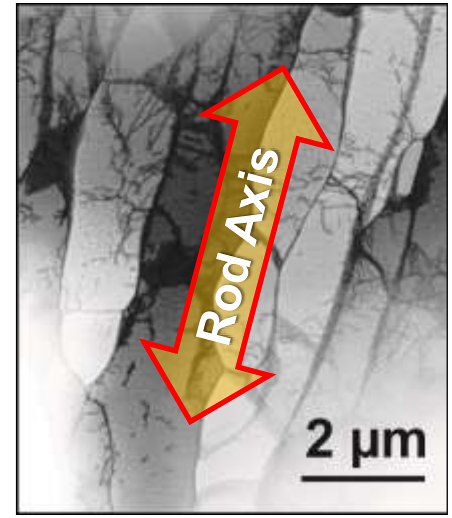
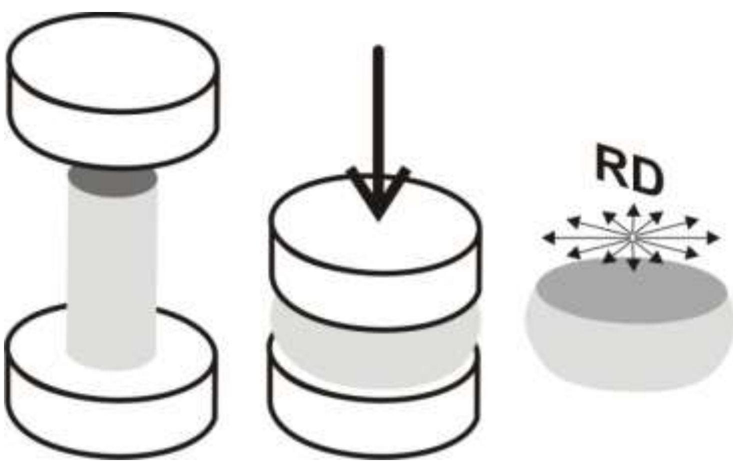
Rolling Plates



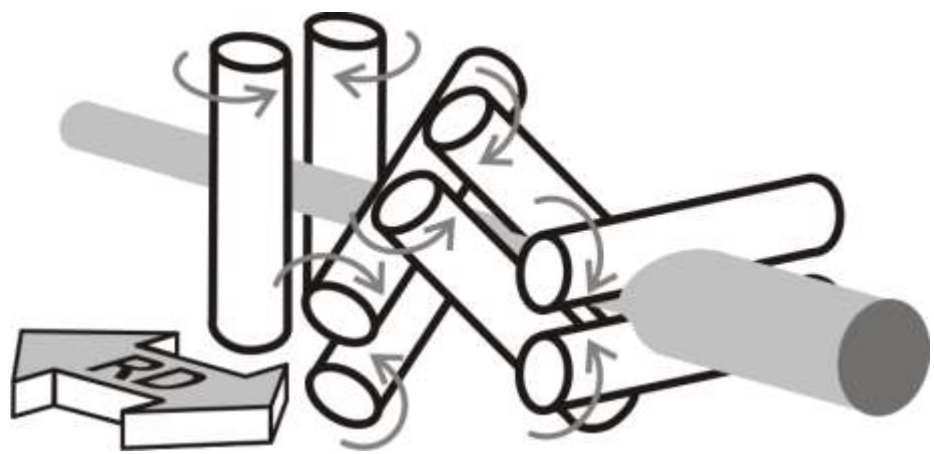




Forging Round Blanks

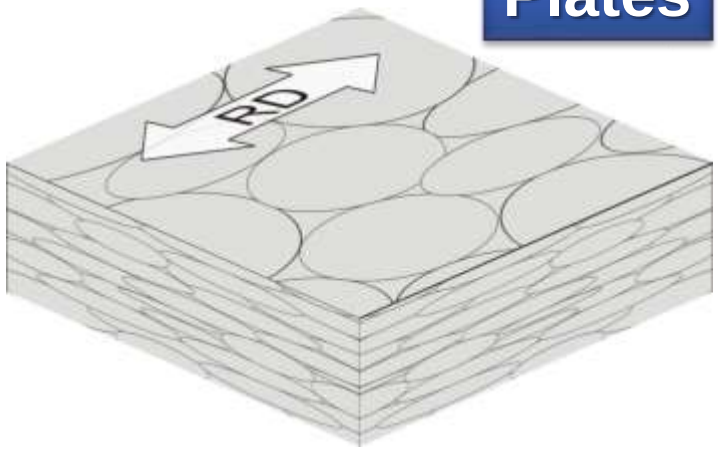


Rolling/Swaging Rods

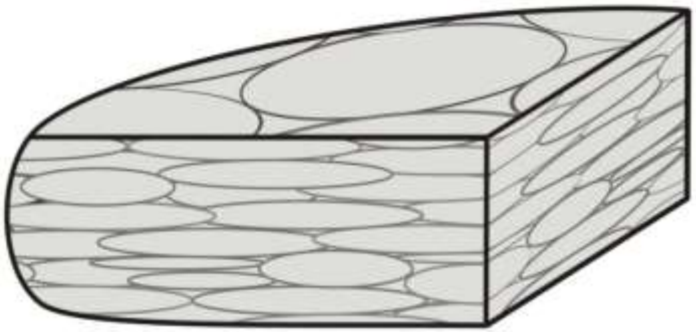


Microstructure: Simplification

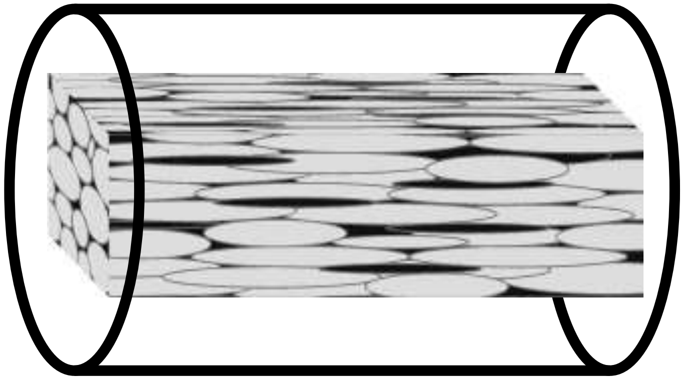
Plates



Round Blanks



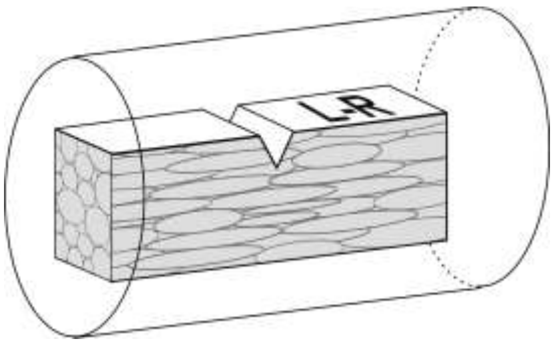
Rods

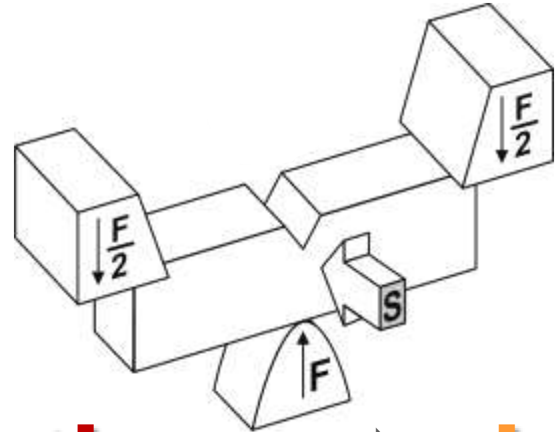


Stack of „Pancakes“

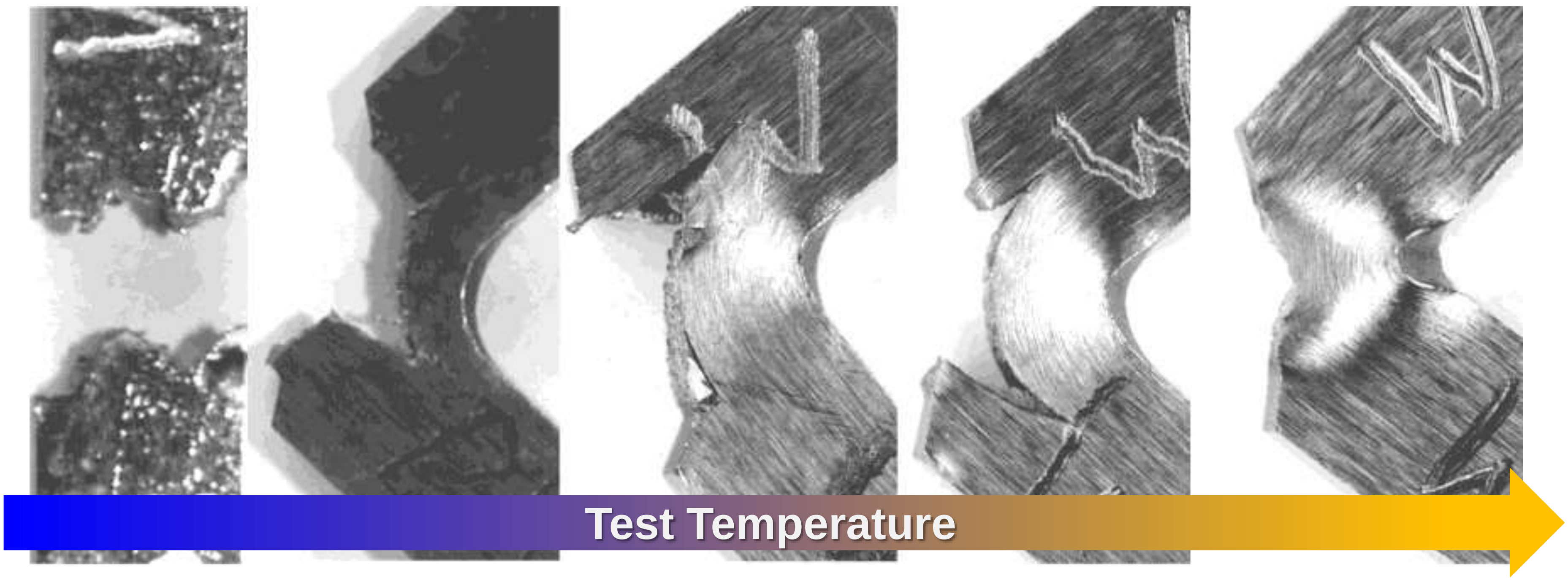
Bundle of „Fibres“

Rods: Dynamic Fracture

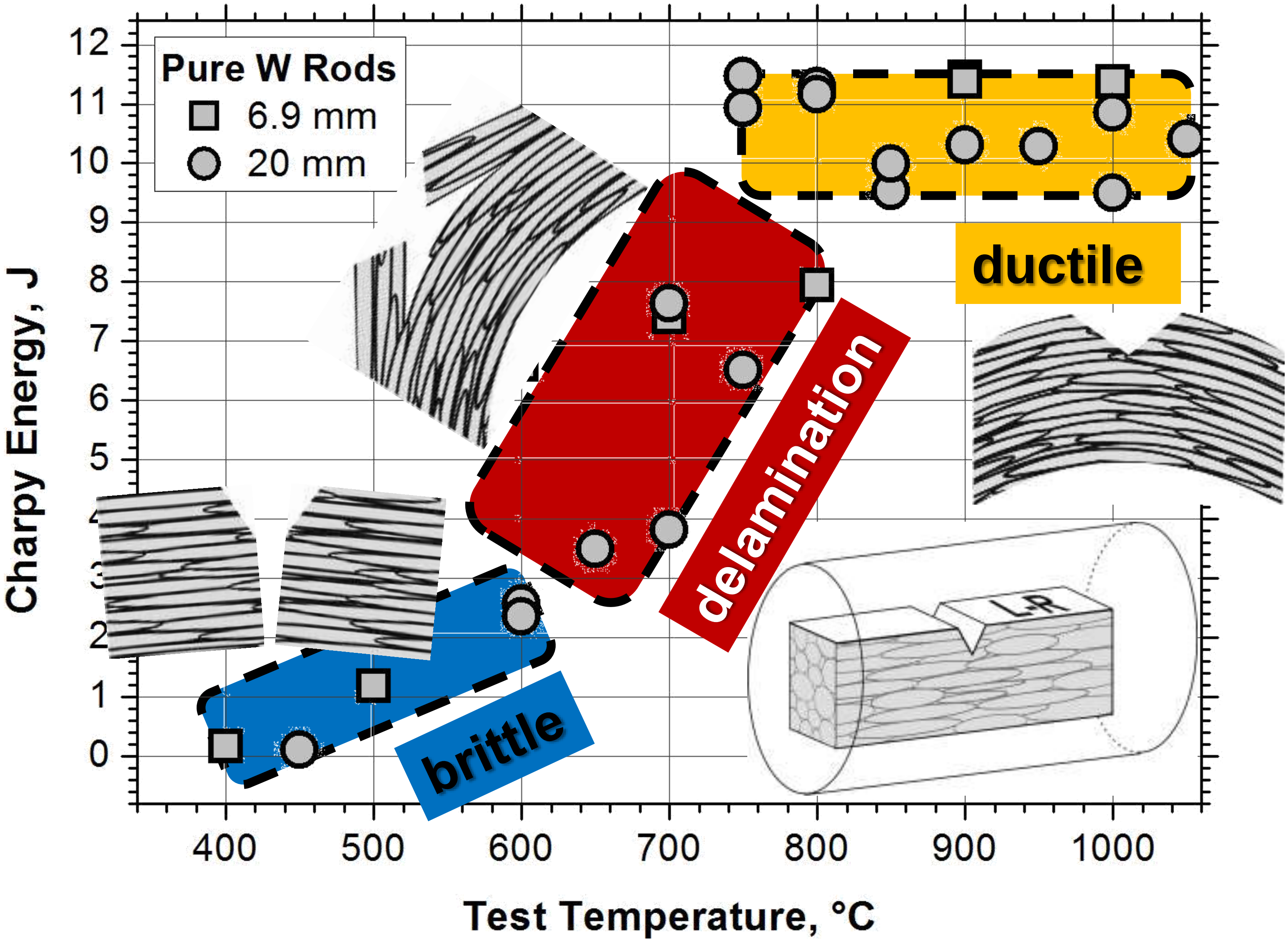




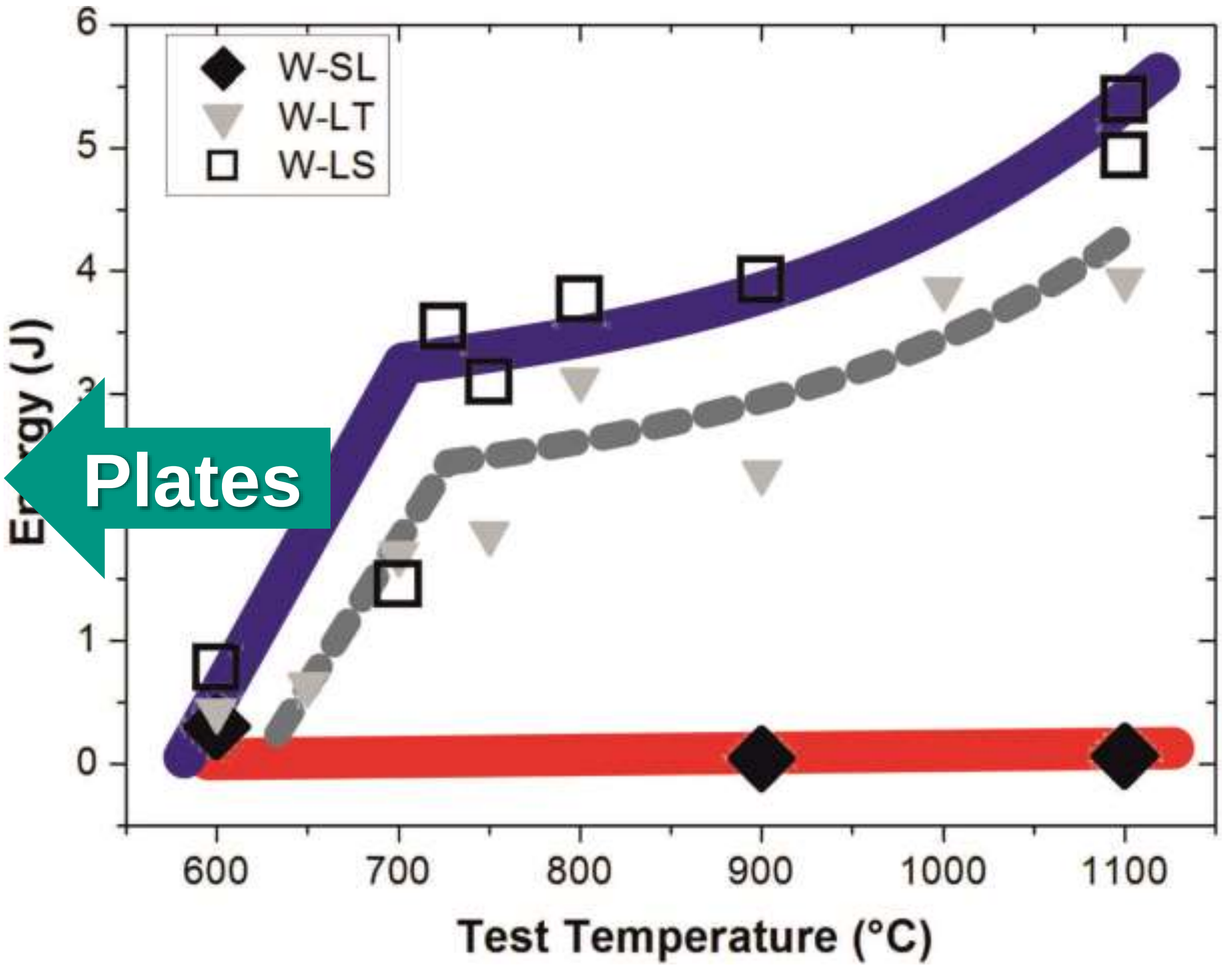
brittle → delamination → ductile

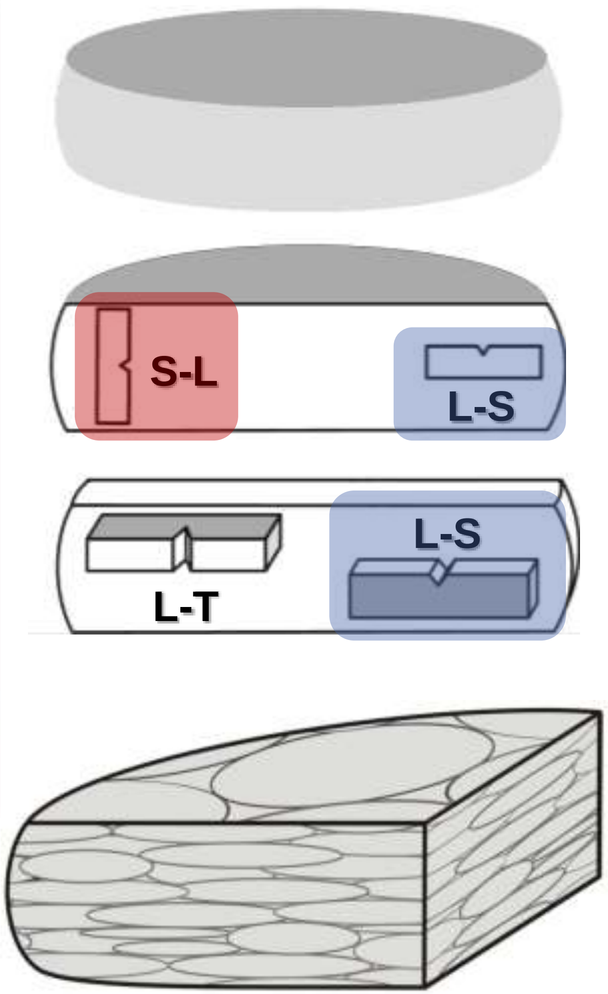


Rods: Fracture Mode Transitions

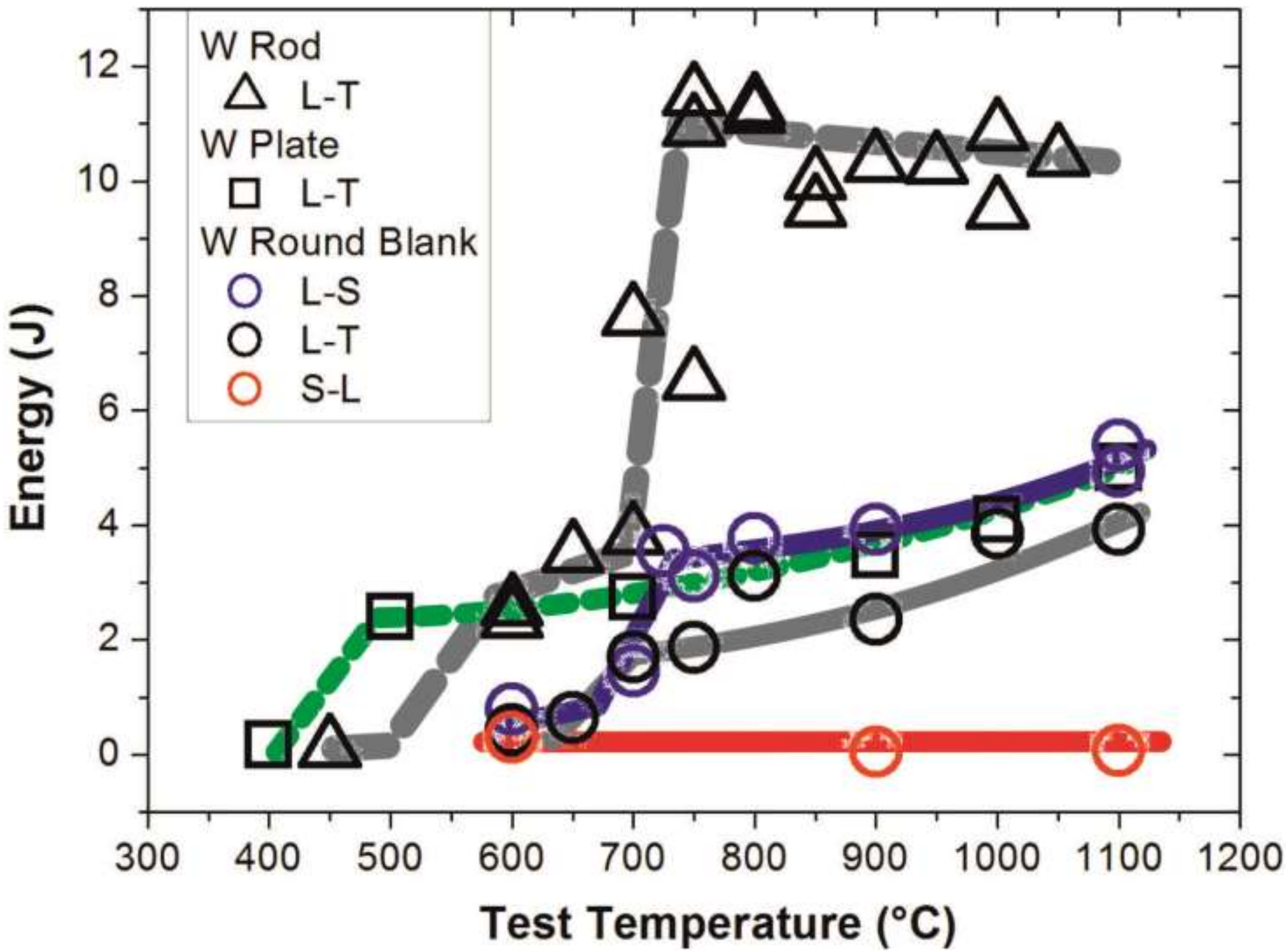


Plates/Blanks: Fracture Behavior





Pure W - Overview

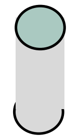


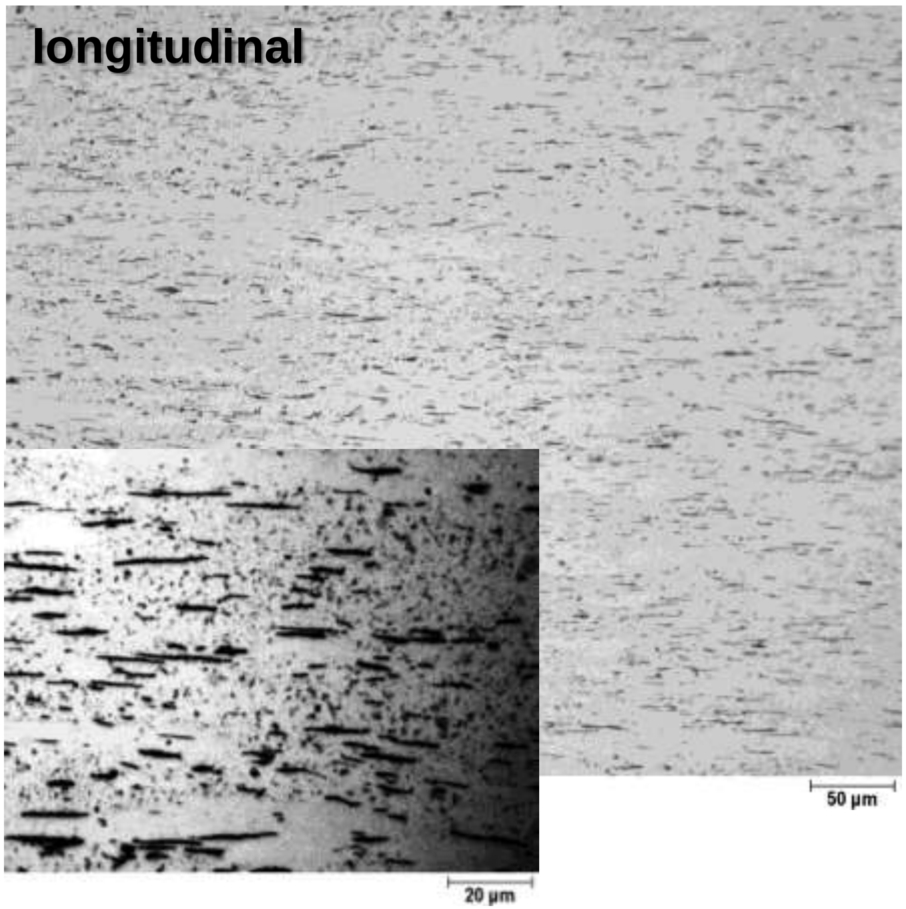
DELAMINATION DUCTILE

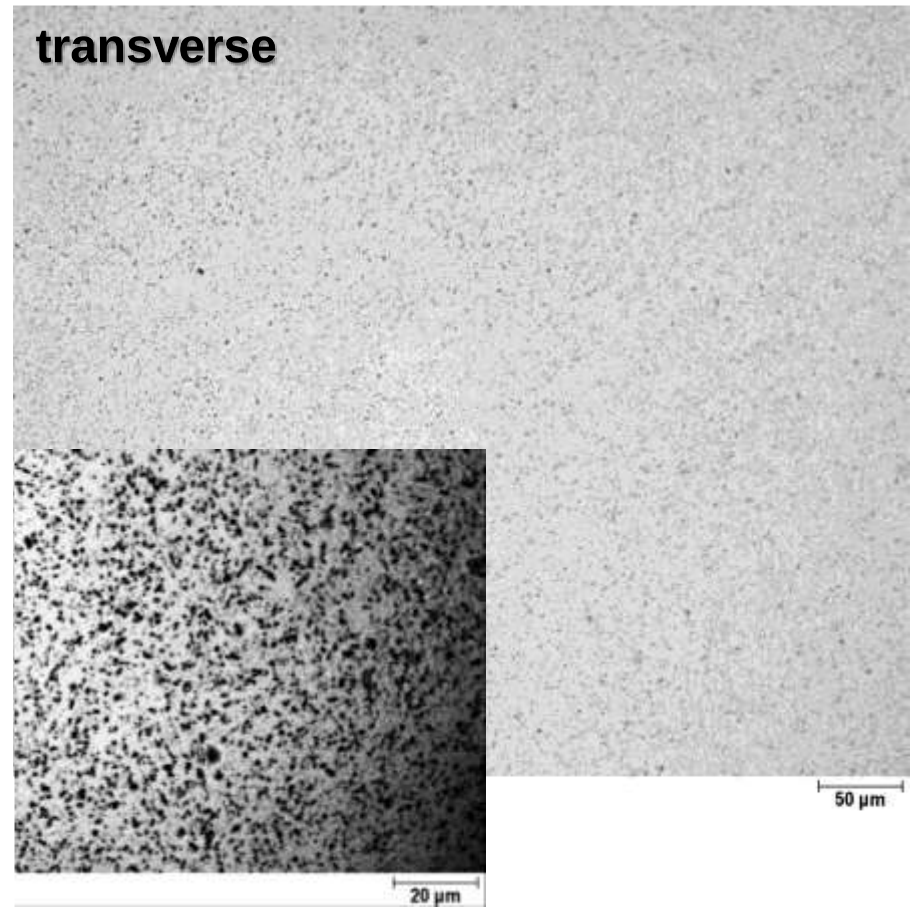
Effect of ODS particles in W

WL10 Rod, Ø7 mm

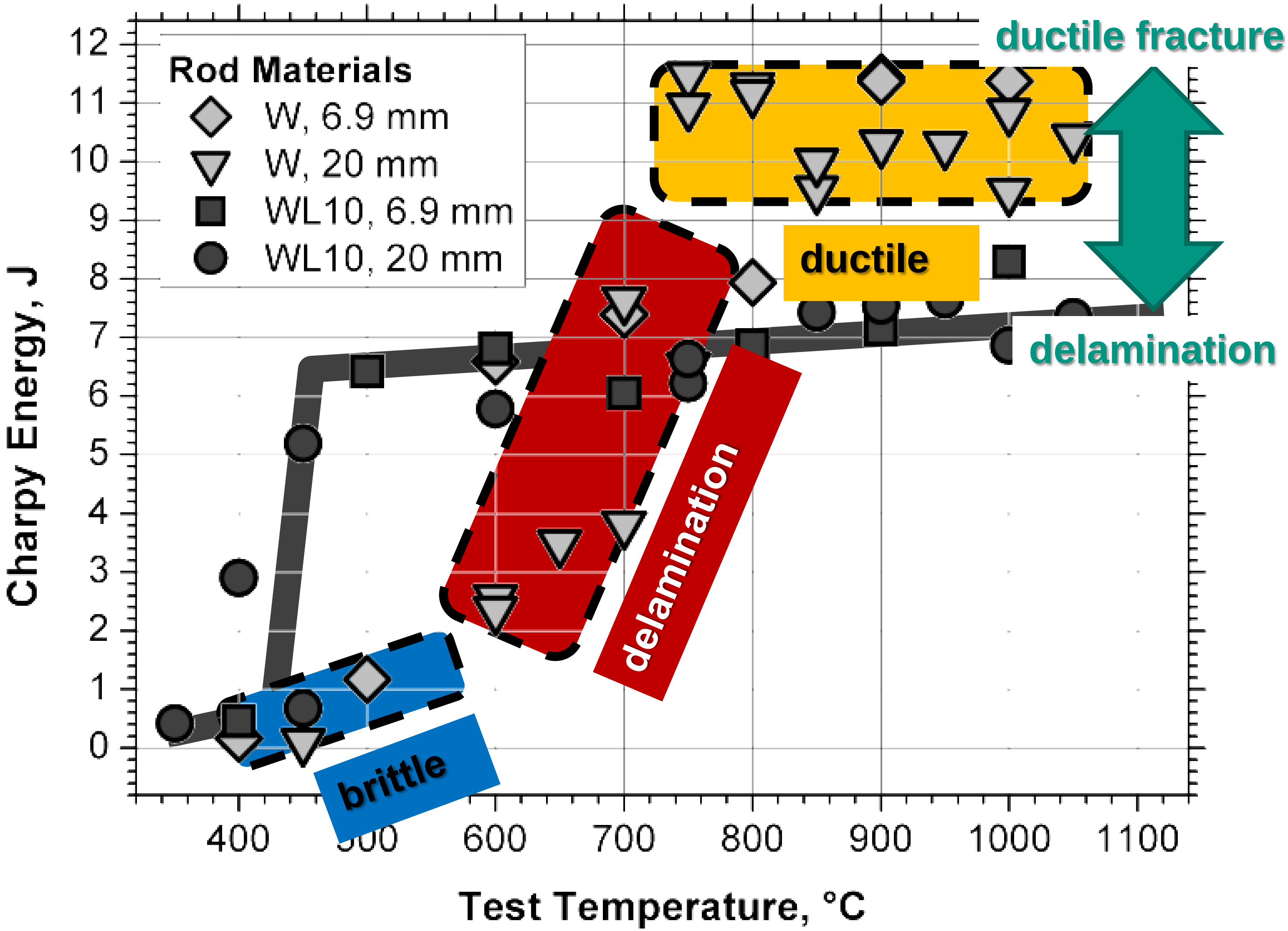
Rods: Metallography







Effect of ODS particles in W

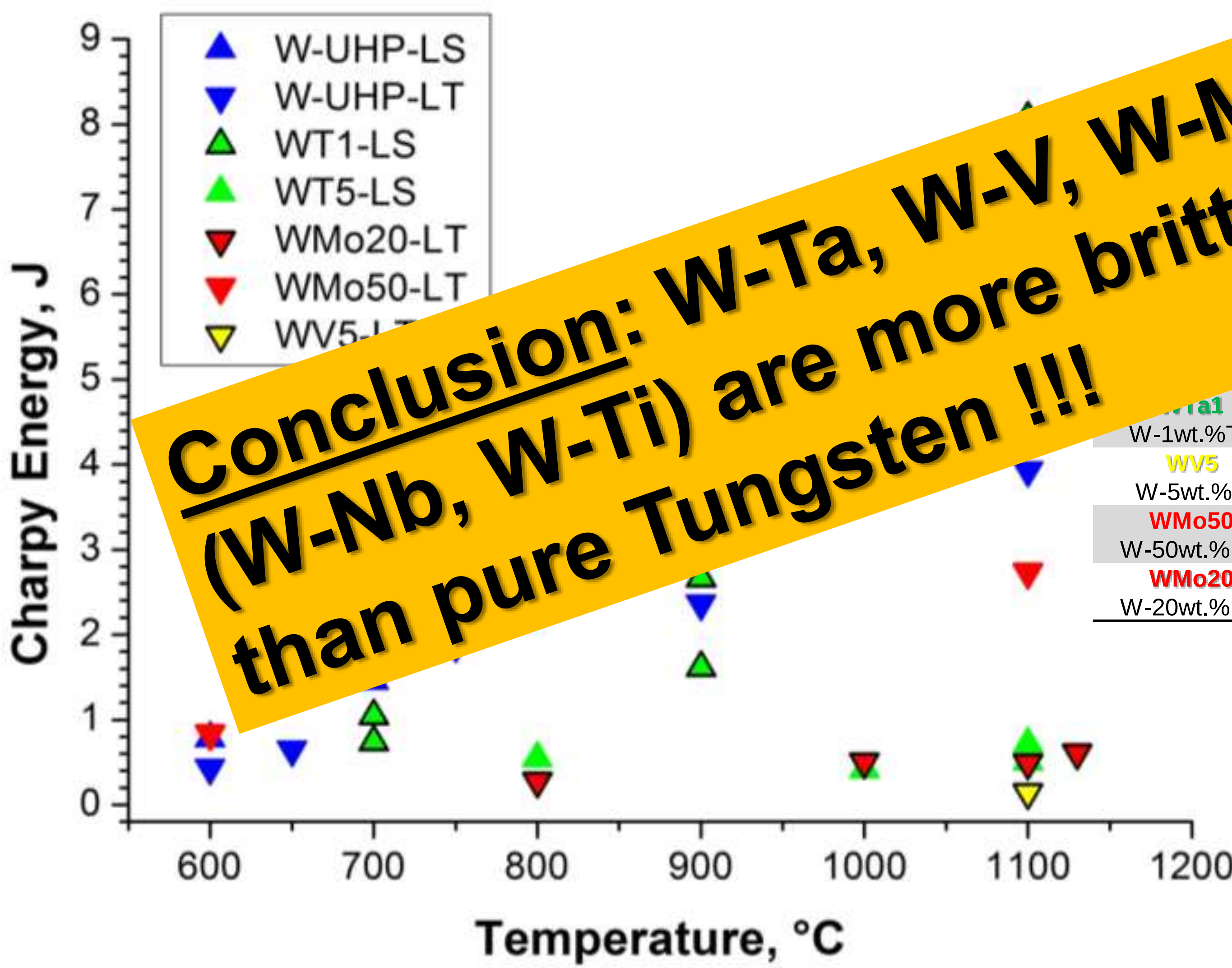


"Reasonable" Alloying Elements for W

M_2W Be	Mg	MW B	MW_2 C $M_{1-x}W$	M_4W Al		Y	La	
Ti >3wt.% >300°C	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu	
MW_2 Zr	Nb	Mo		Ru < 3 wt. %	Rh < 2 wt. %	M_3W Pd	Ag	Cd
MW_2 Hf	Ta		MW Re < 26 %	Os < 5 %	MW Ir	MW Pt	Au	

Insoluble | Intermetallic Phases | Line Compounds | Solid Solution

Effect of Alloying Elements in W



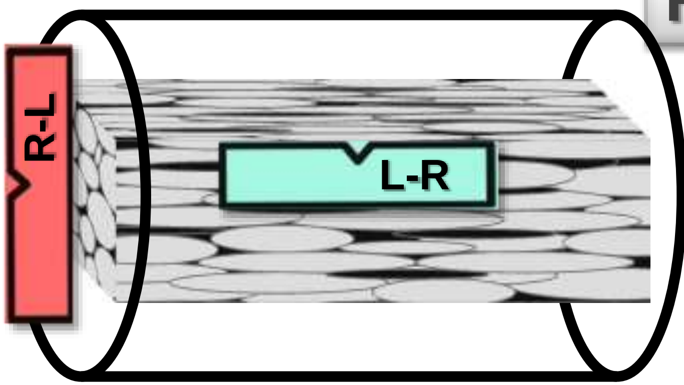
Conclusion: W-Ta, W-V, W-Mo, (W-Nb, W-Ti) are more brittle than pure Tungsten !!!

		Size
[illegible]	[illegible]	…30 mm, thickness 30 mm
[illegible]	…und blank	Ø180 mm, thickness 30 mm
…Ta1 W-1wt.%Ta	round blank	Ø180 mm, thickness 30 mm
WV5 W-5wt.%V	round blank	Ø95 mm, thickness 20 mm
WMo50 W-50wt.%Mo	round blank	Ø95 mm, thickness 20 mm
WMo20 W-20wt.%Mo	round blank	Ø95 mm, thickness 20 mm

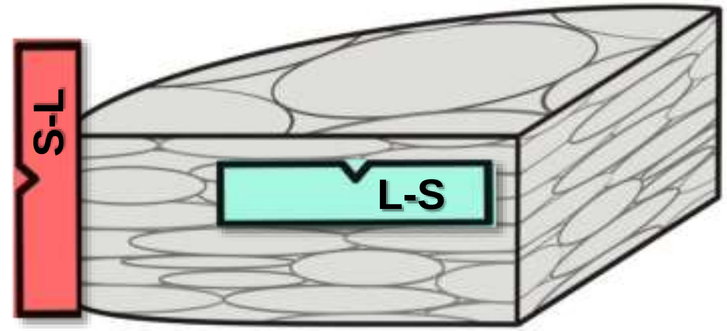
MICROSTRUCTURE AND RELATED PROPERTIES

Karlsruhe Institute of Technology

Rods

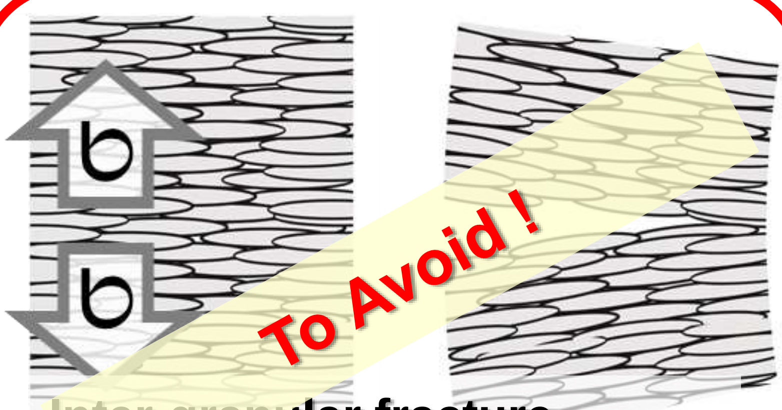


Plates **Round Blanks**



Bundle of „Fibres“

Stack of „Pancakes“



Inter-granular fracture, enhanced by oxide particles !

Partly ductile fracture, improved by deformation !

Structural Tungsten Materials - Summary

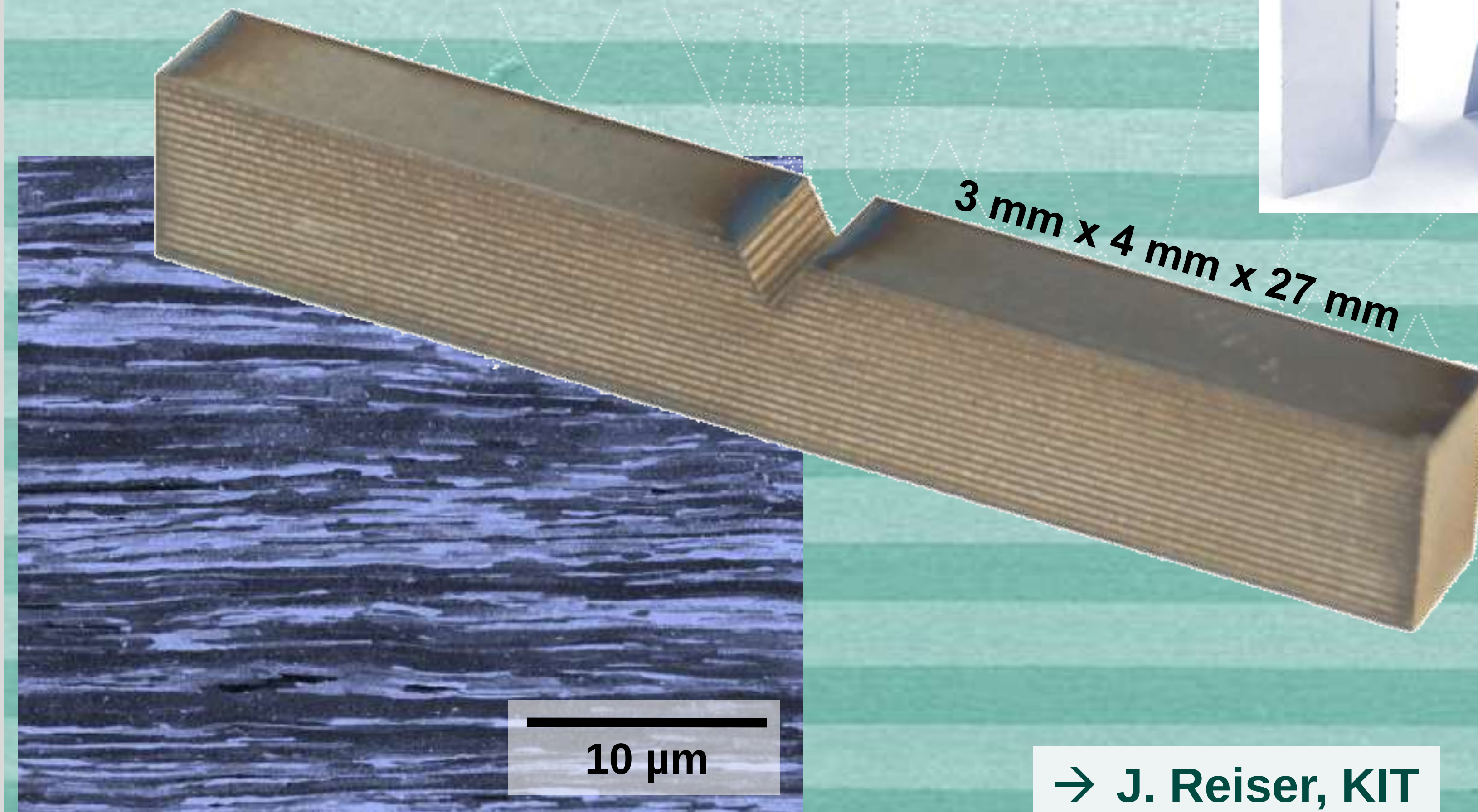
So far, the best suitable tungsten materials for structural applications (divertor or other large scale components) are

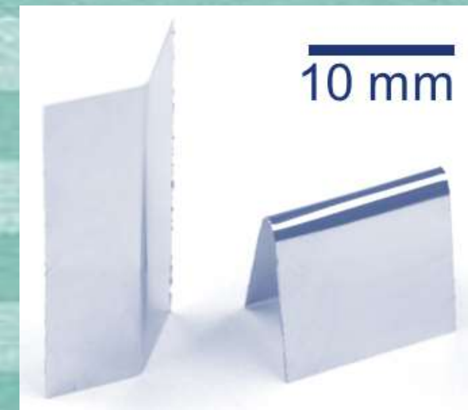
Thin Plates, Thickness < 4 mm

Produced by Sintering (Hydrogen Atmosphere) and Cross-Rolling

Pure Tungsten (maybe small amounts of grain stabilizers, like La/Y_2O_3)

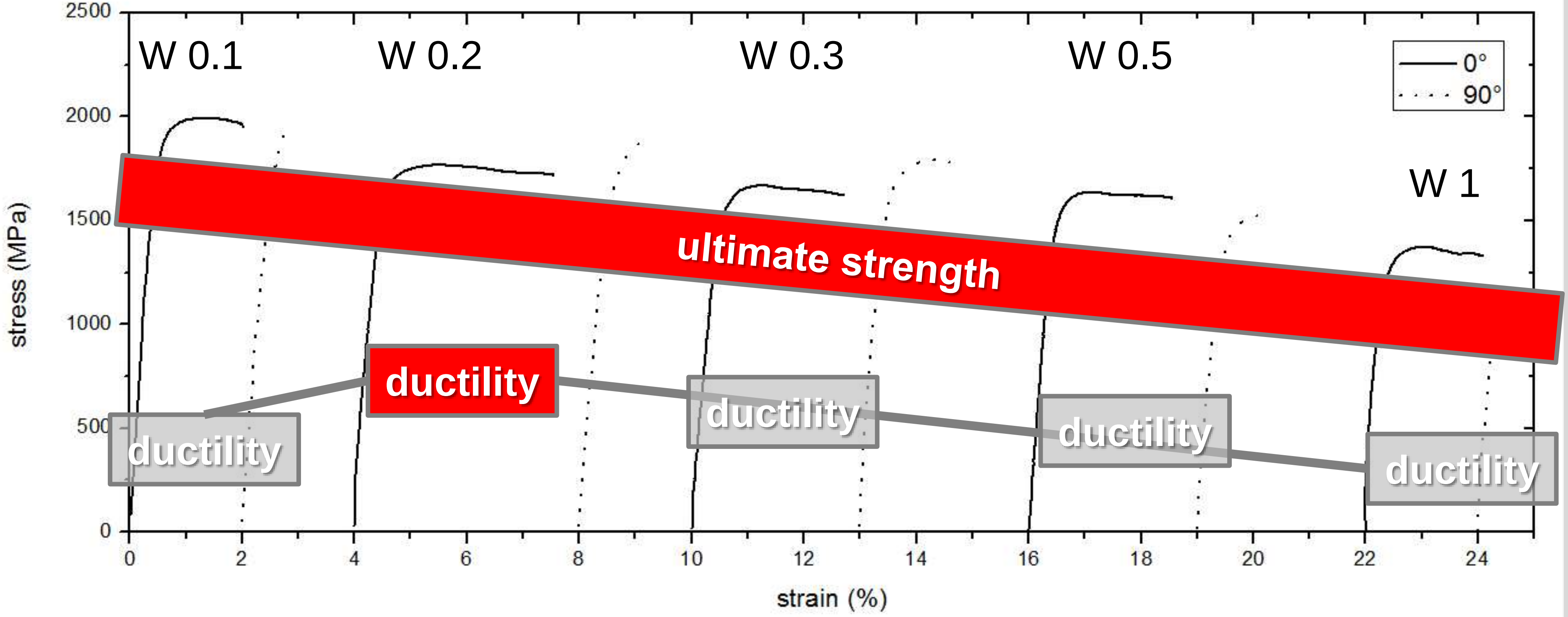
W Laminate Material





→ J. Reiser, KIT

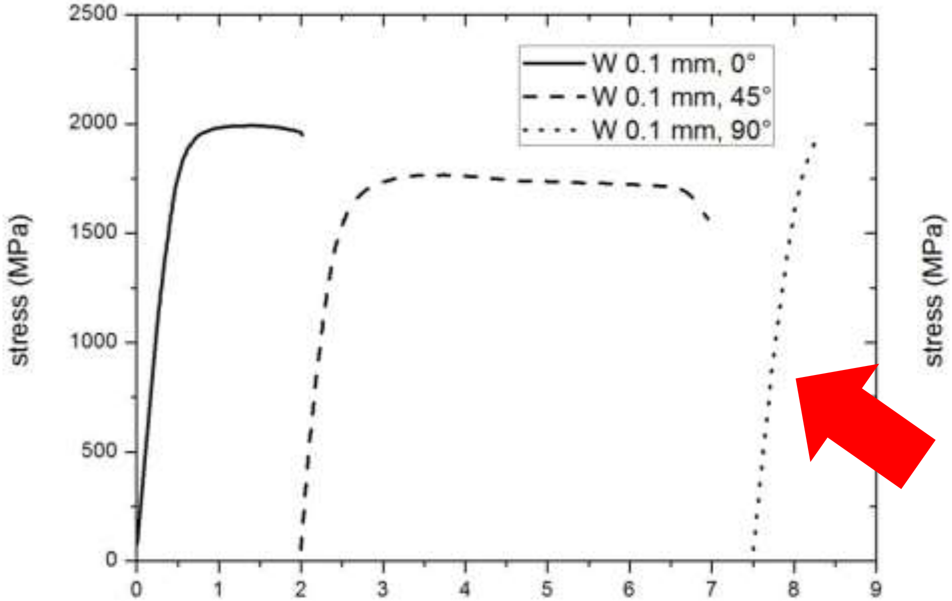
TENSILE TEST PROPERTIES: W



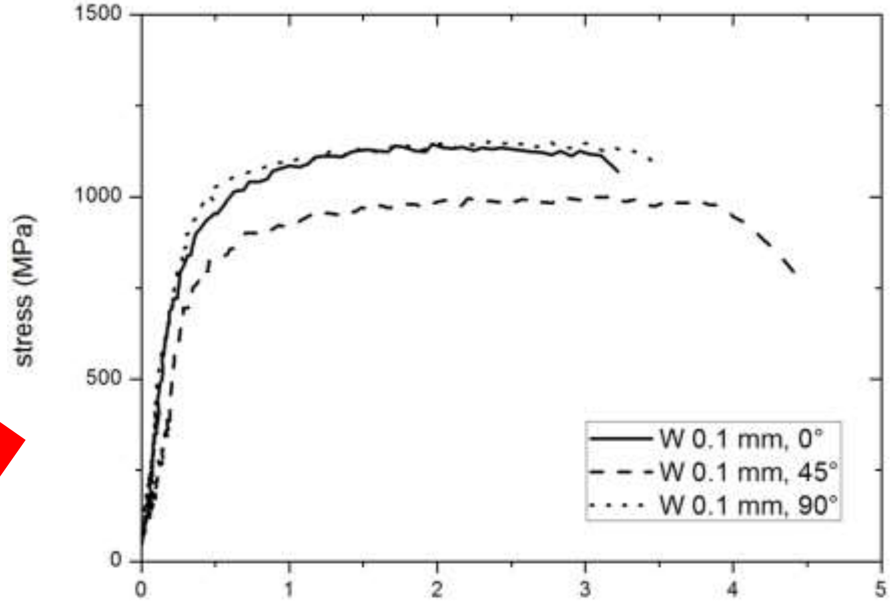
- assumption: optimum ductility at 0.2 mm thickness

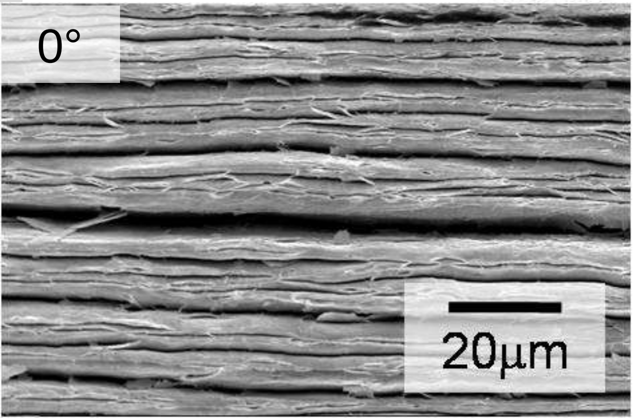
TENSILE PROPERTIES: W 0.1 MM

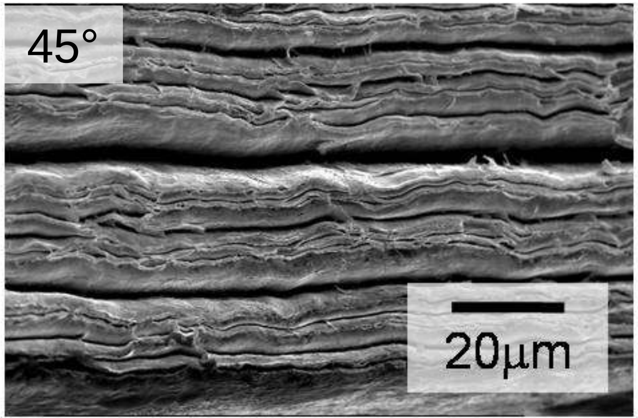
W foil, 0.1 mm, RT

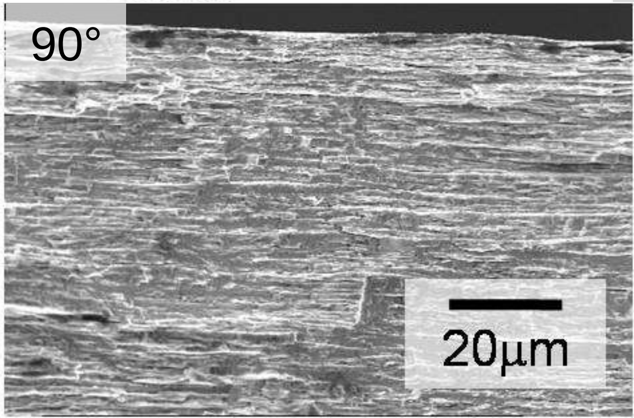


W foil, 0.1 mm, 600°C

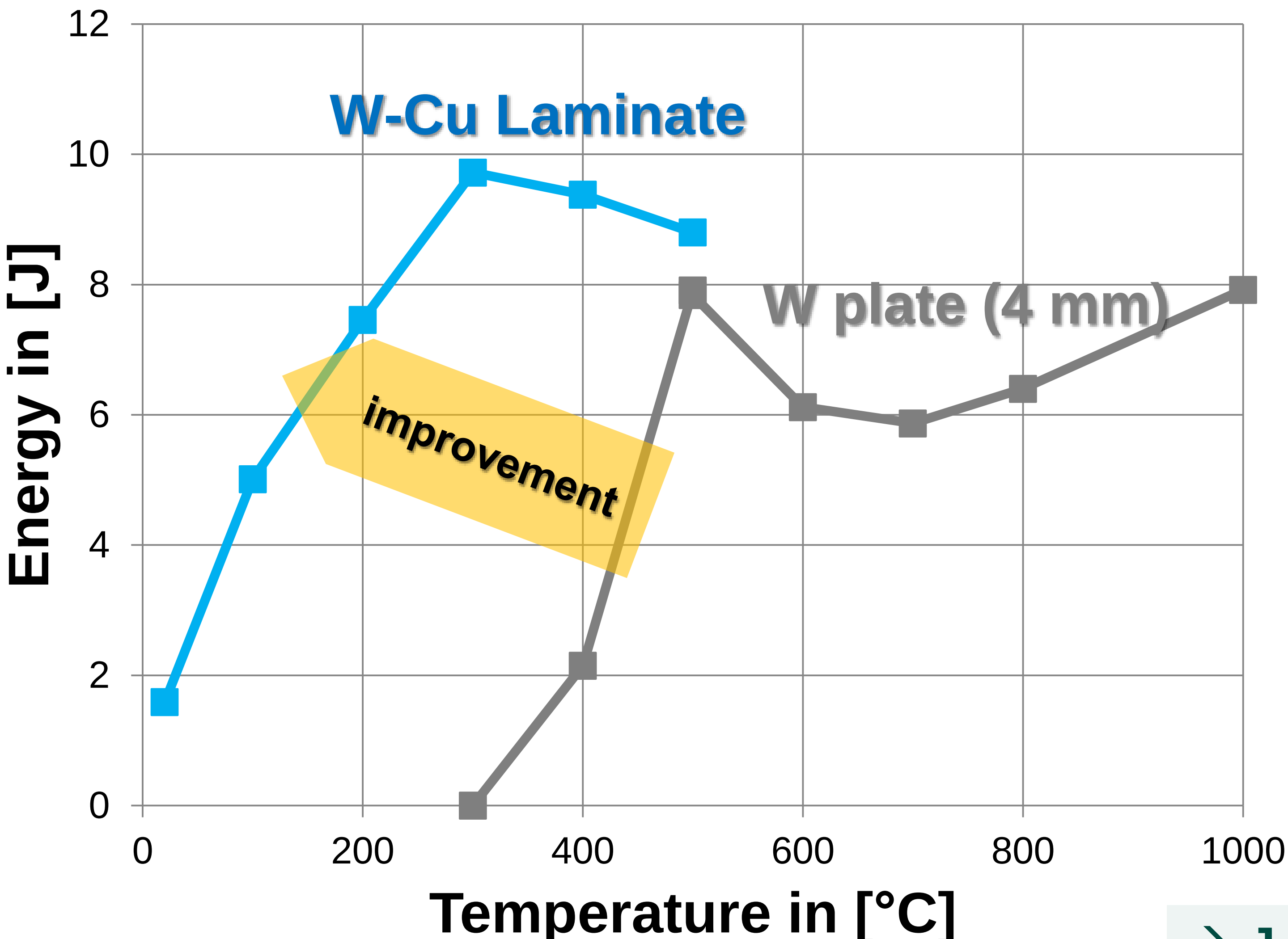








PATH FORWARD → TUNGSTEN LAMINATES



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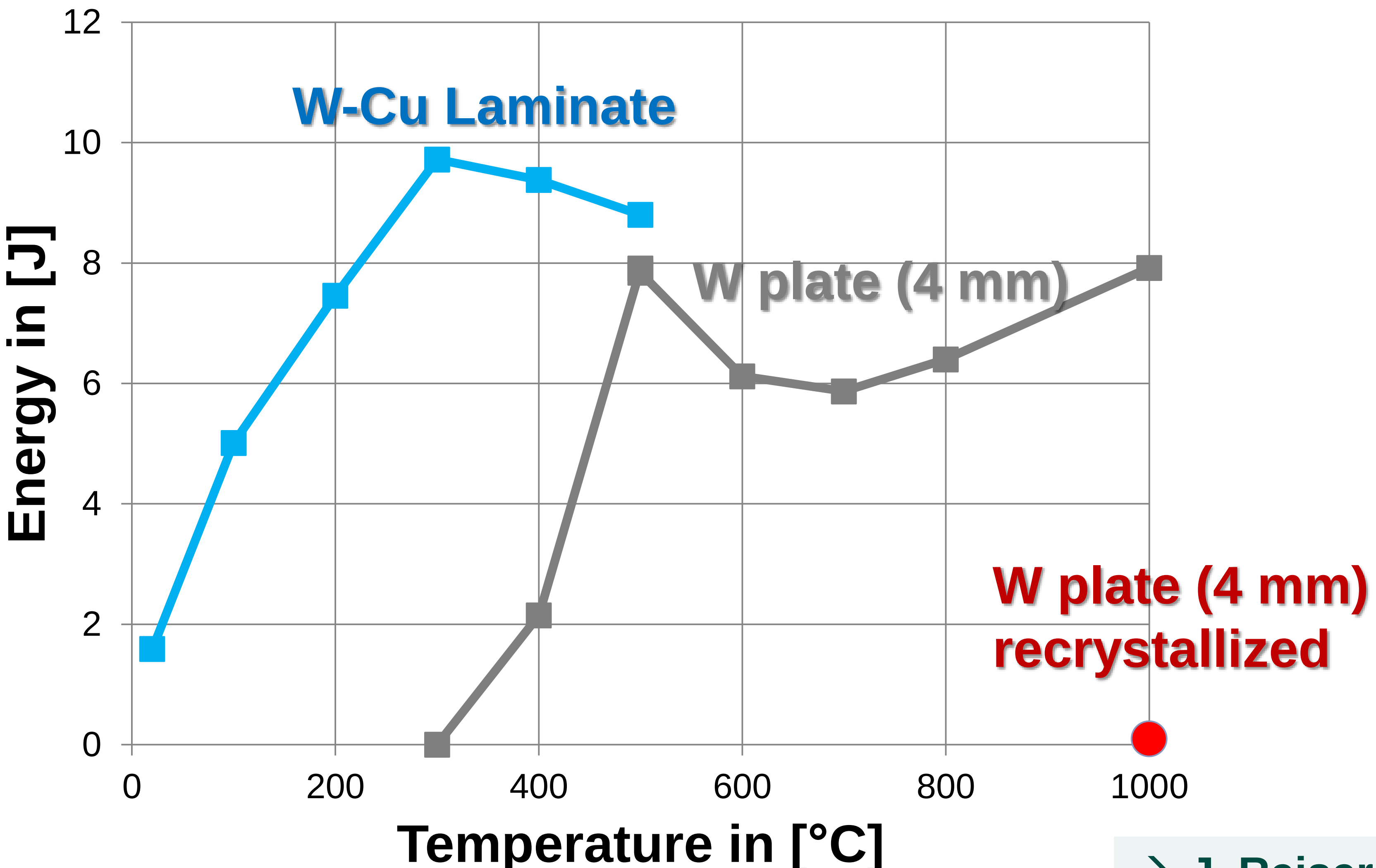
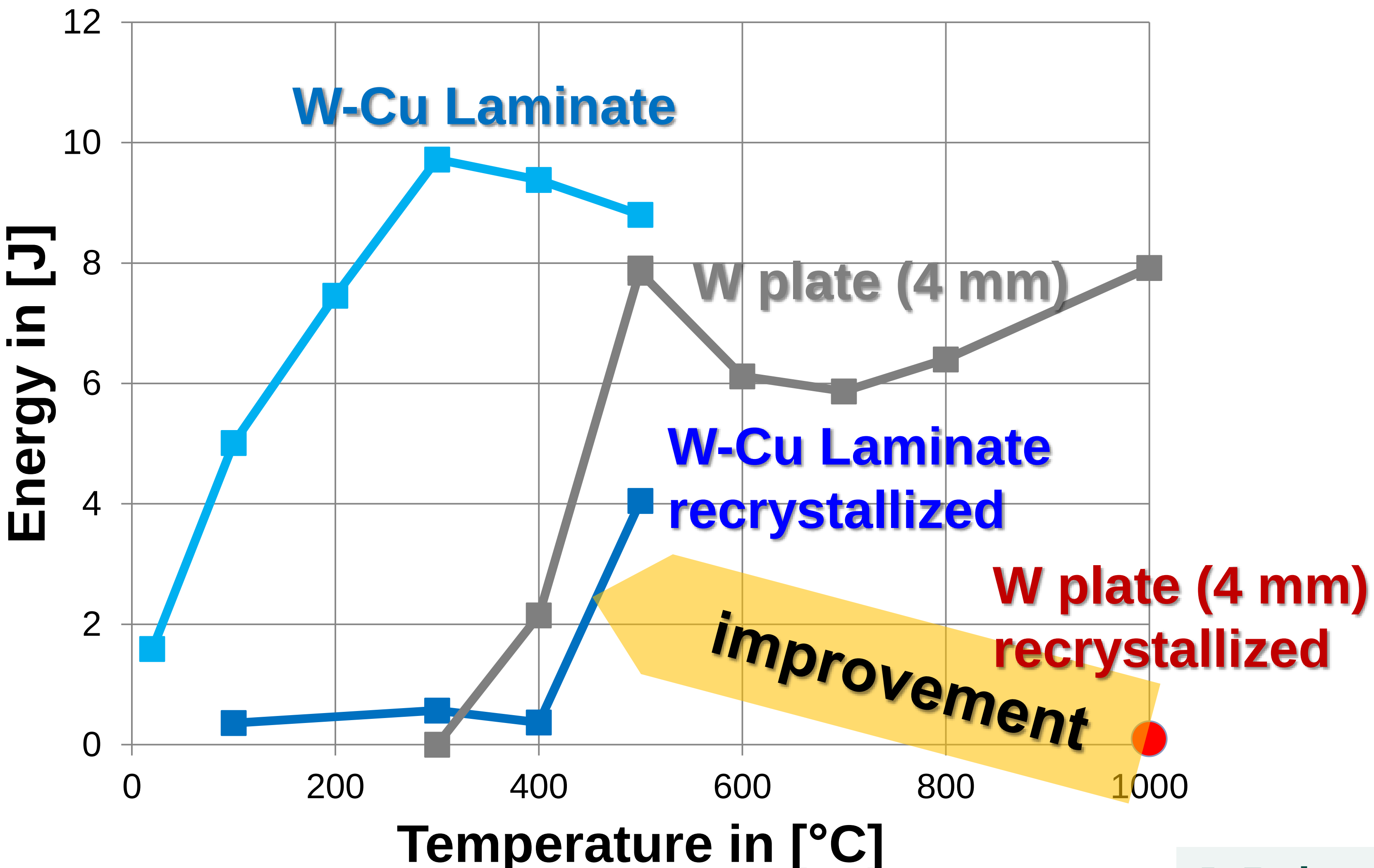
PATH FORWARD → TUNGSTEN LAMINATES



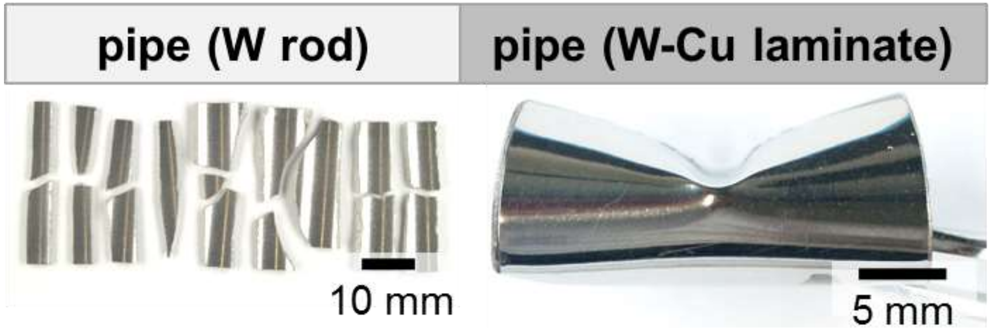
→ J. Reiser, KIT

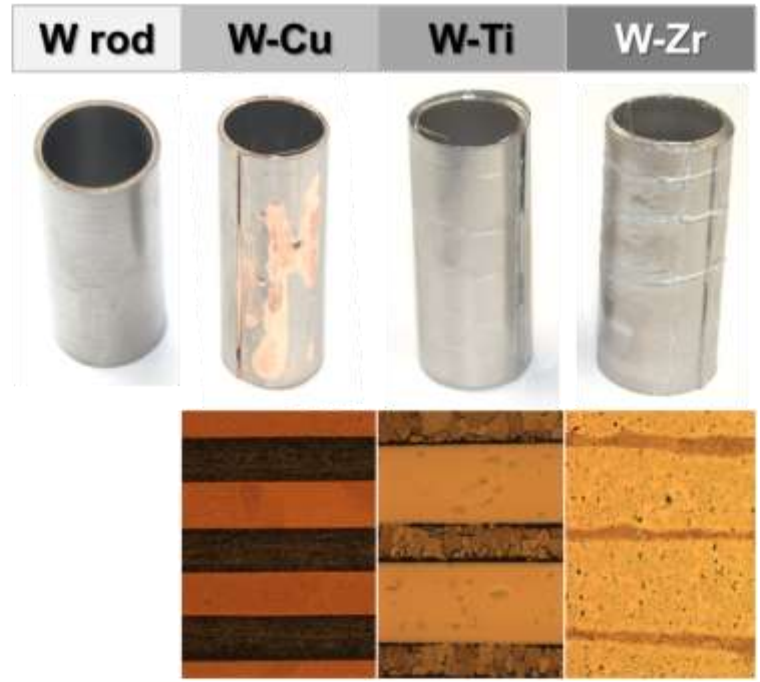
PATH FORWARD → TUNGSTEN LAMINATES



J. Reiser, KIT

Pipe Fabrication



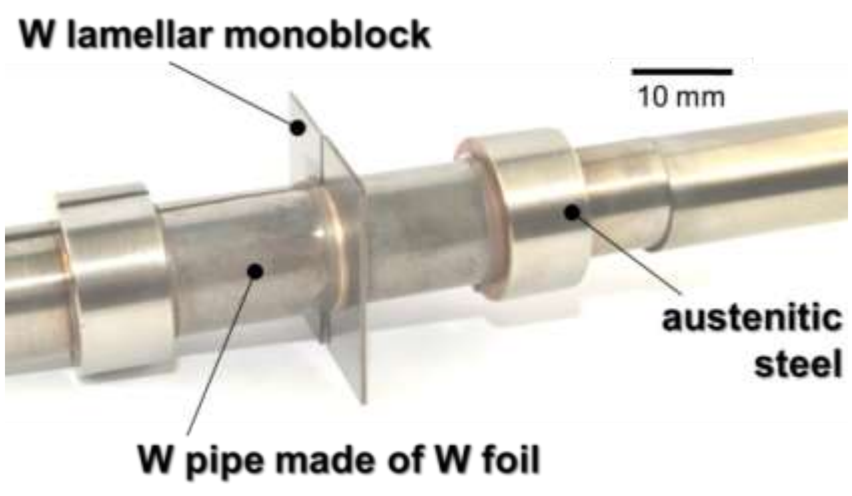


- Pipe fabrication with W laminates
  - Wrapping under investigation
  - Possible alternatives identified
- Pipe characterization
  - Impact tests
  - Pressurized tests (static, cyclic) in preparation
- Irradiation performance → first results in 2013 (ORNL)

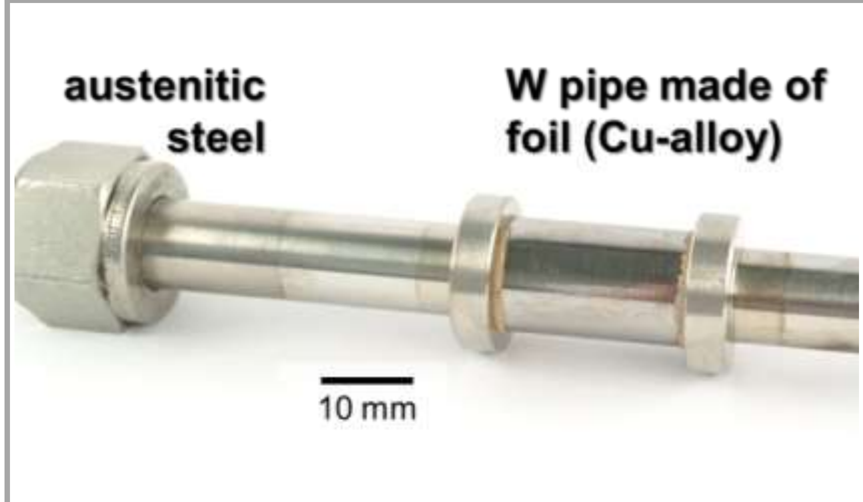
J. Reiser *et al.*, KIT

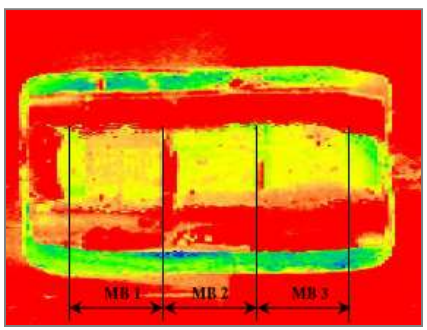
W Laminate Pipe Testing

Fabrication studies



Pressurized pipe tests

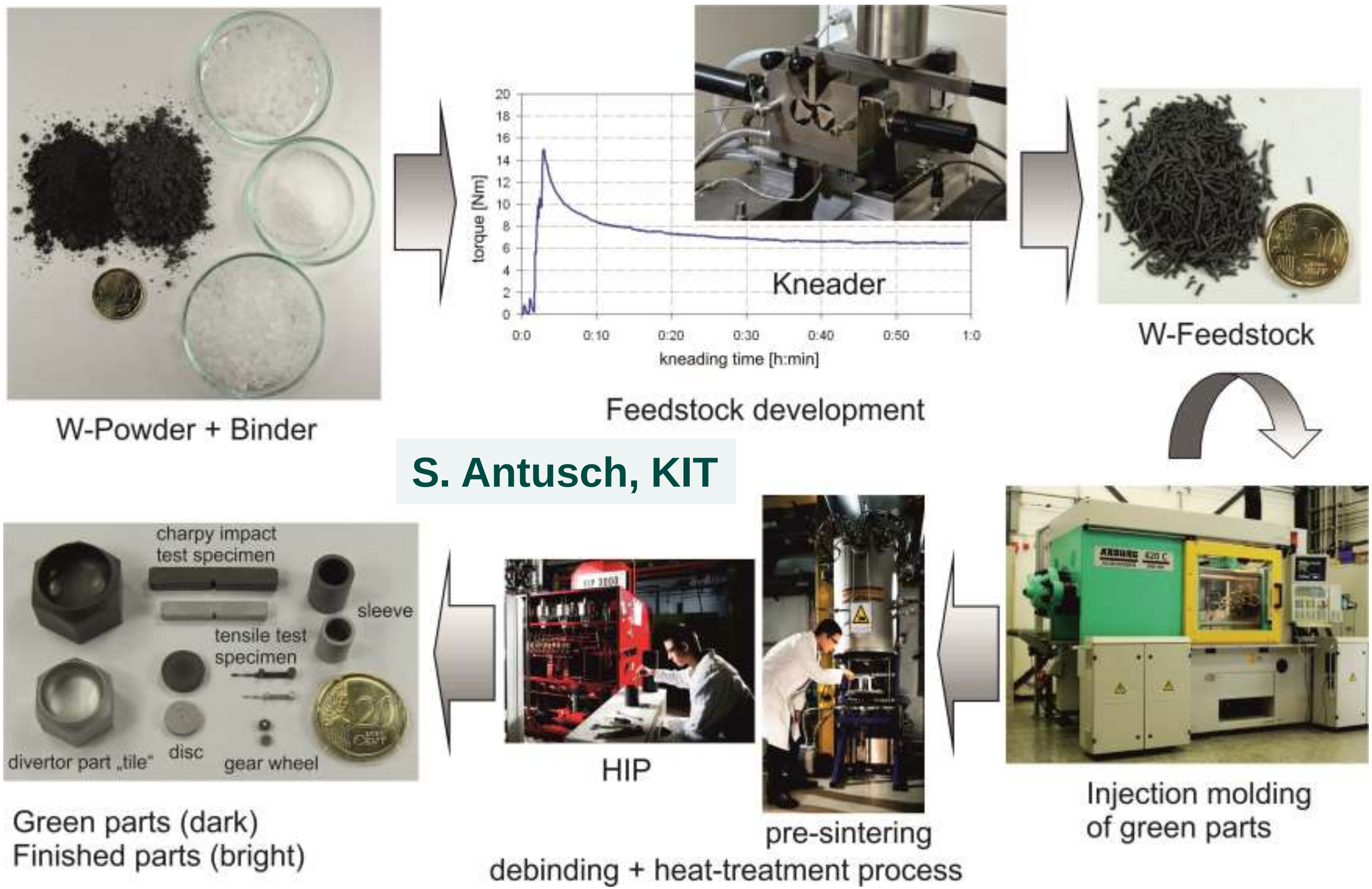




non-destructive testing,
PLANSEE SE

GLADIS, IPP, Garching

POWDER INJECTION MOULDING (PIM)



PIM Process for Tungsten Parts

→ near net-shape mass fabrication of tungsten parts

green parts

debinding +
heat-treatment-process

finished parts

S. Antusch, KIT

Outlook – KIT divertor R&D programme

DECISION POINT

2016 · 2015 · 2014 · 2013

Liquid Metal

Evaluation of promising approaches

- Design Studies
- Heat transfer capability and limits
- Magnetohydro-dynamic (MHD) behaviour
- Corrosion
- Tritium retention

Water

Identification and investigation of promising designs which are based on Cu alloys and stainless steel (as structural materials)

- Small-scale mock-up design/fabrication/testing/ optimisation campaign
- Technology improvement
- Materials development

Helium

Addressing Critical Issues

- W irradiation limits
- Design rules for brittle materials
- Risk/failure analysis of multi-component design

Alternative Design/Material Combinations

- W-laminate materials
- Fabrication processes

Mock-up Testing (KATHELO)

- 1-Finger modules
- Pipes of W-laminate