Divertor Design & Materials

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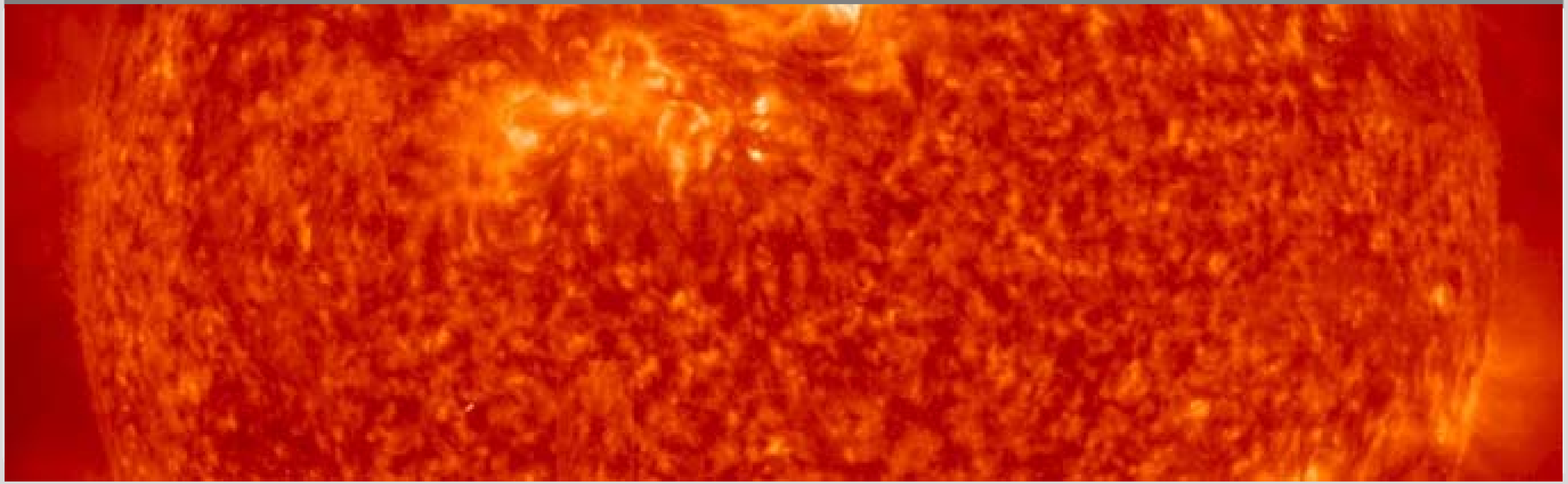
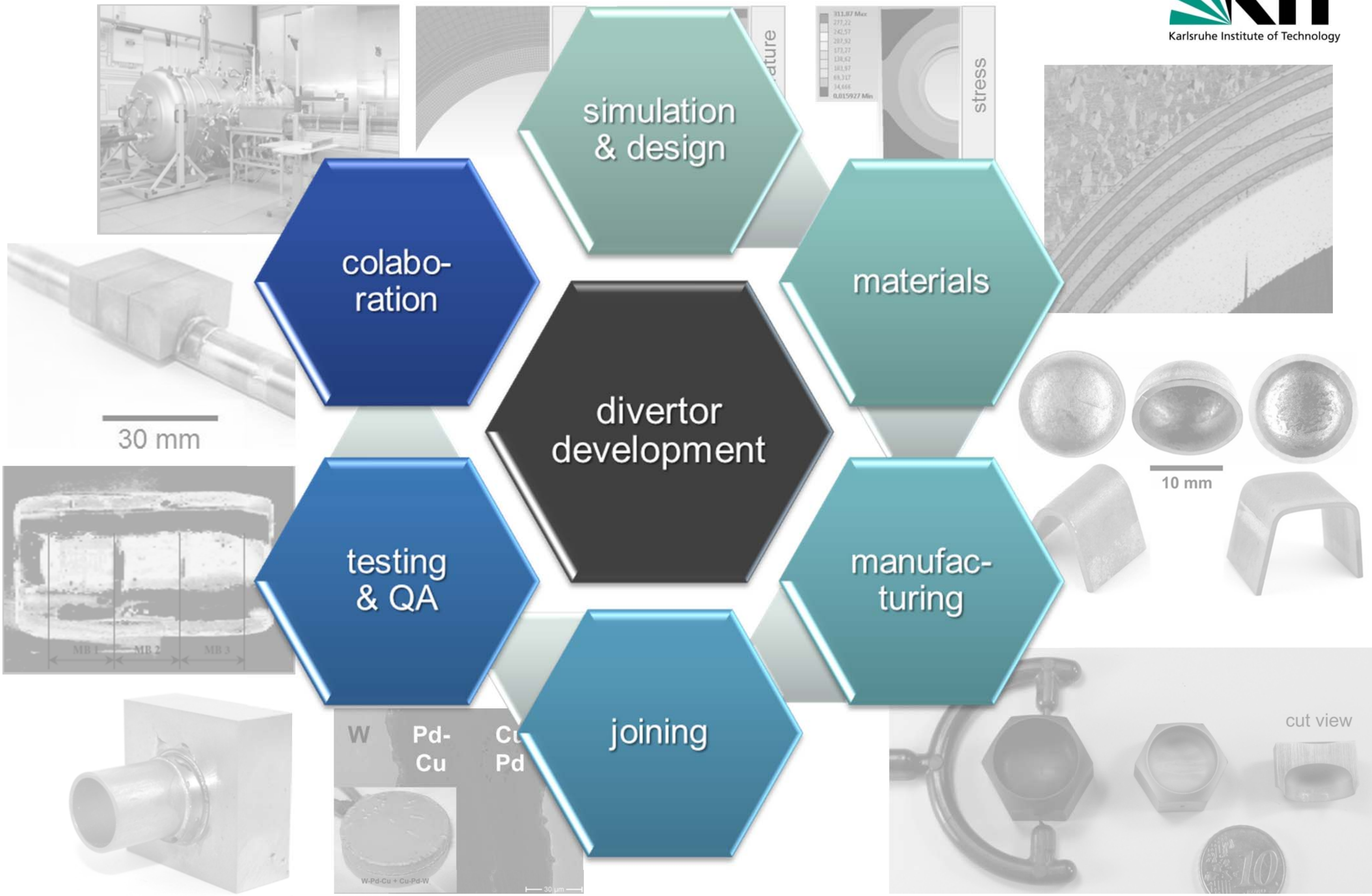


Overview


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

INTRODUCTION

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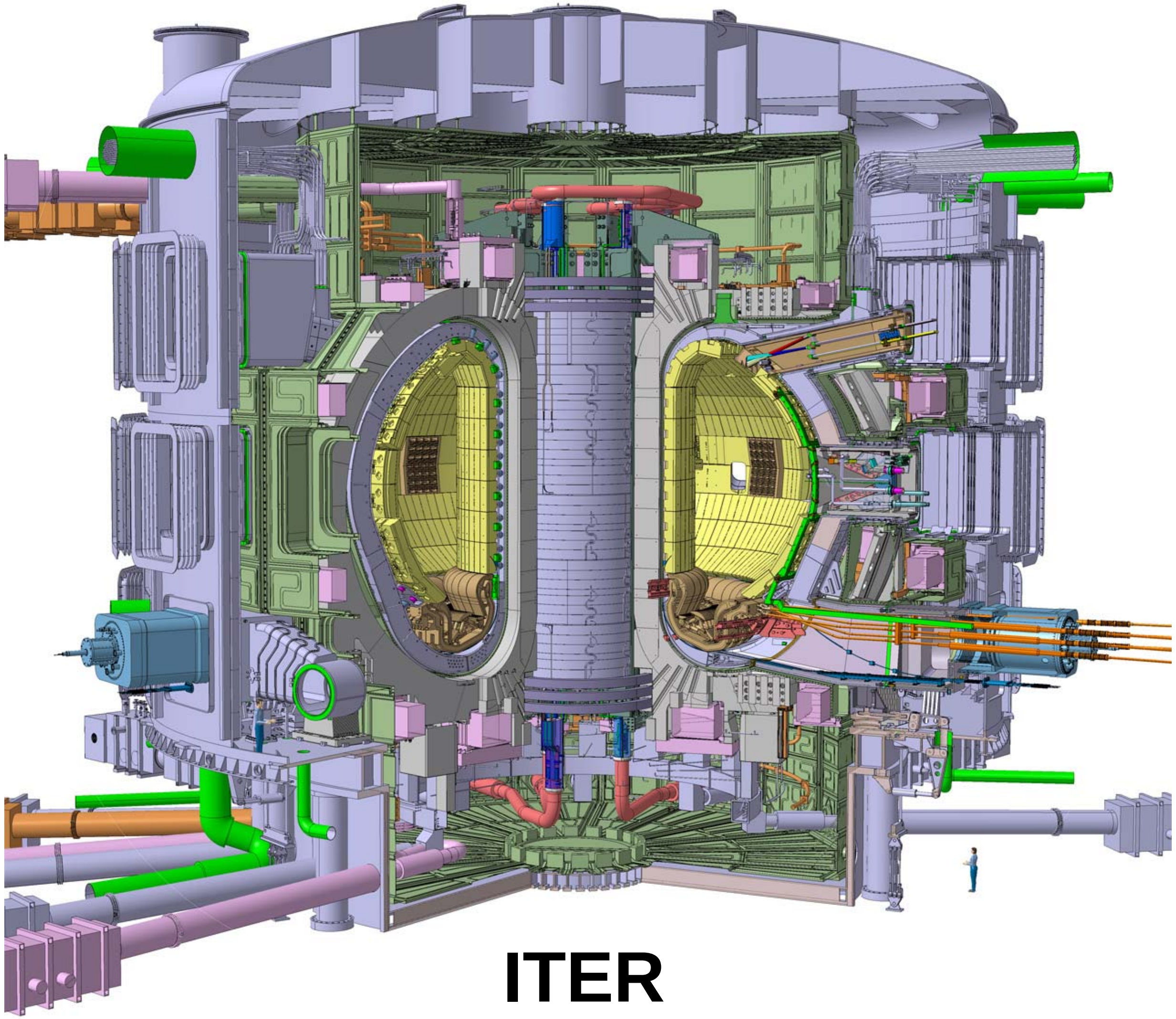
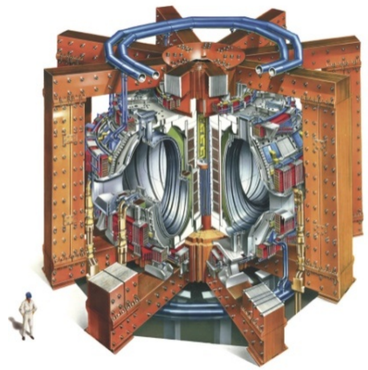


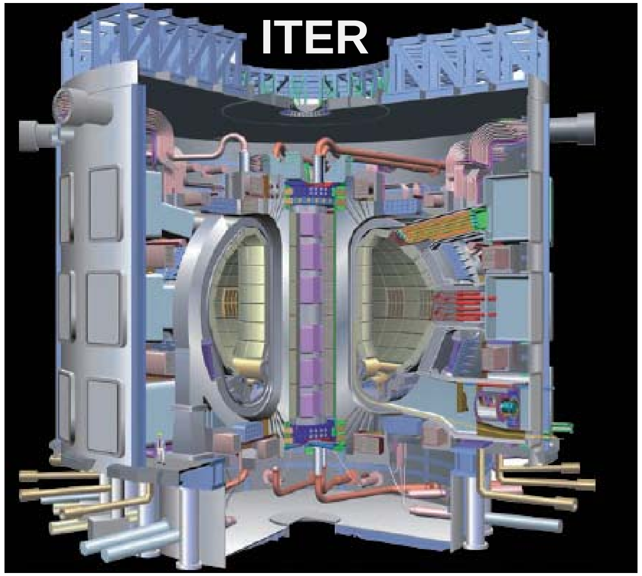
ITER

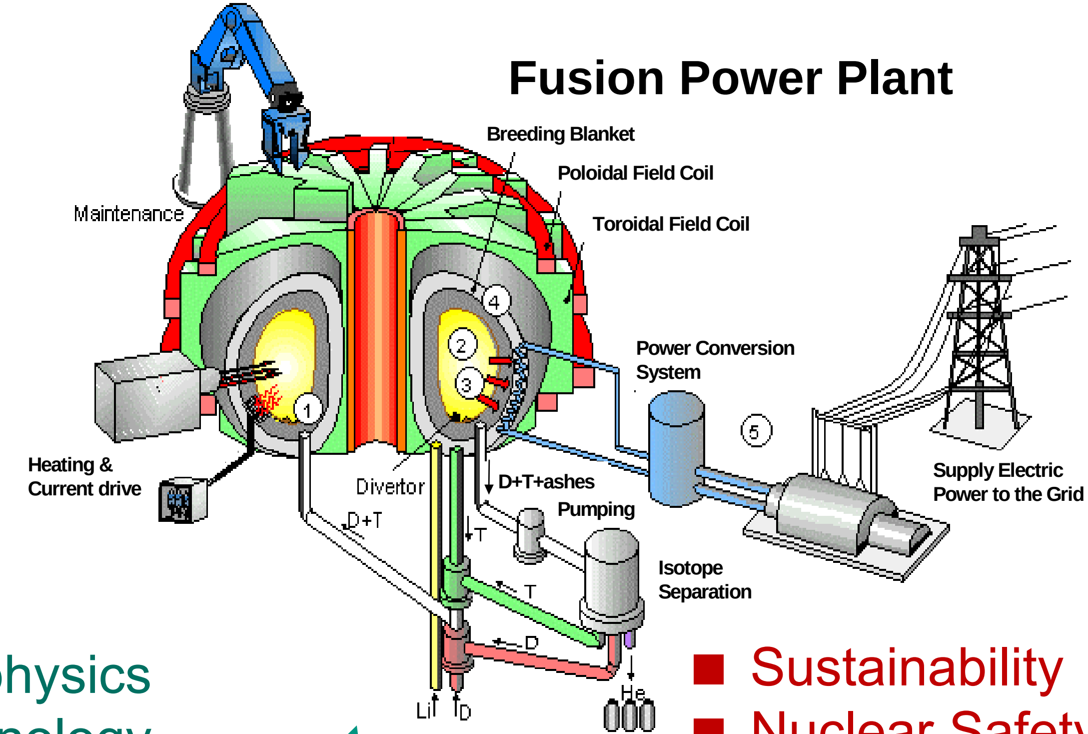
Nuclear fusion is relatively easy to accomplish. The trick is to gain energy out of it!

JET



WHERE IS THE CHALLENGE?





- Test device for plasma physics
- Safety → Standard technology

- Sustainability
- Nuclear Safety
- Economy

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

DEMO – THE STEP IN BETWEEN

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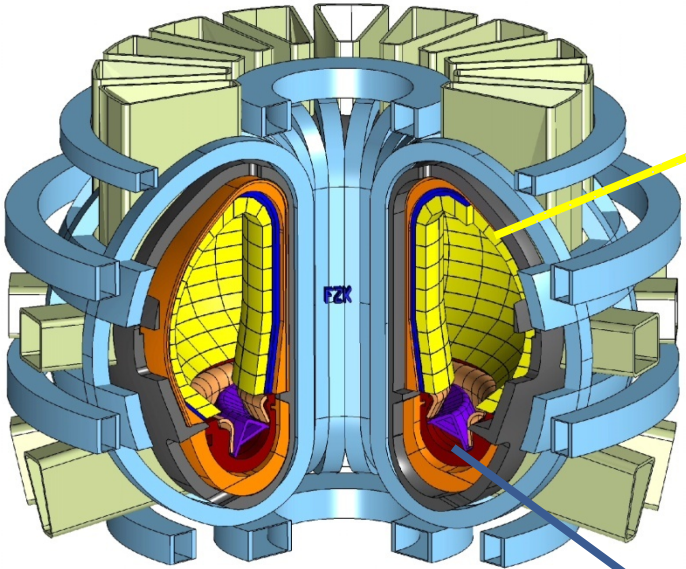
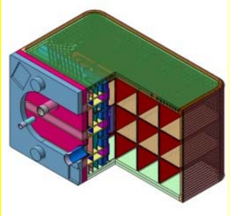


DEMO 2011

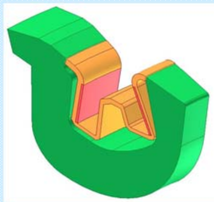


Blanket: ≤150 dpa/5 years, 2.5 MW/m^2

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

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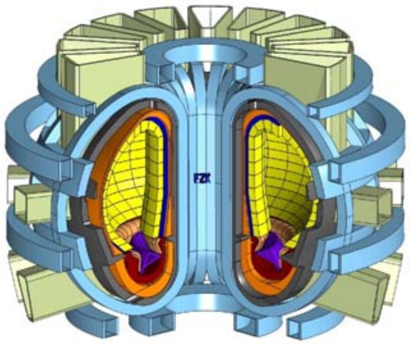
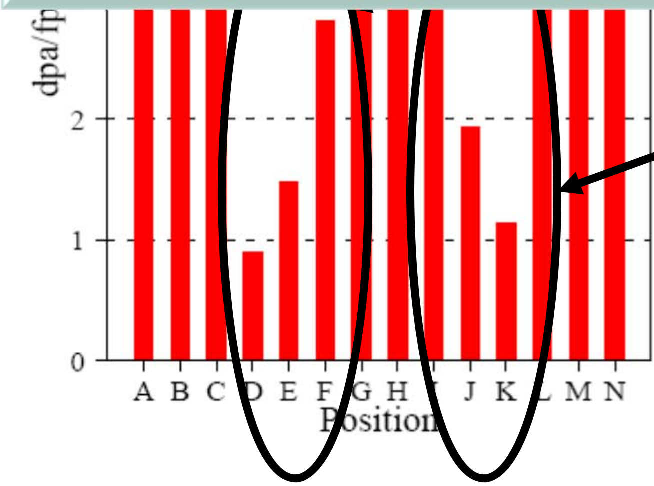


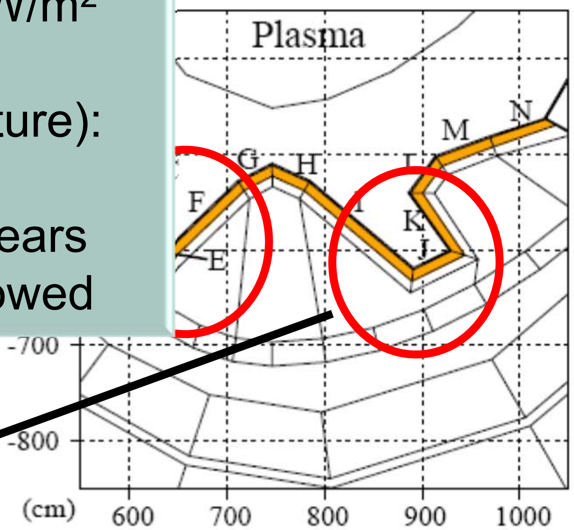
DEMO 2012

Early DEMO, DEMO-1, etc.

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





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

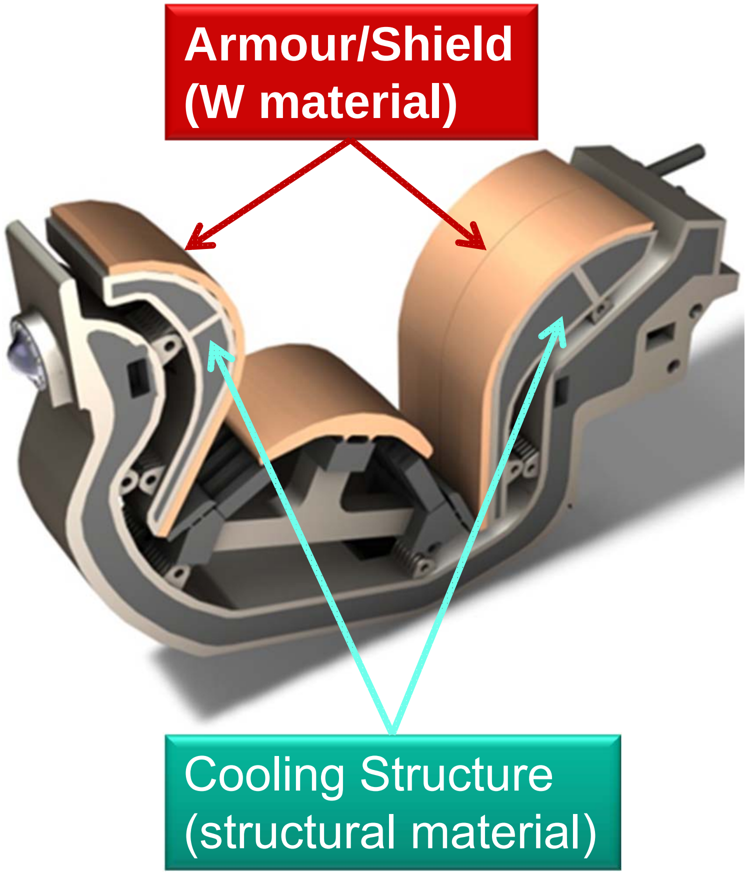
M. Gilbert, CCFE, 2012

DESIGNS

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

focus of this lecture

Conventional Divertor



HE-COOLED MODULAR DIVERTOR WITH JET COOLING (HEMJ) CONCEPT

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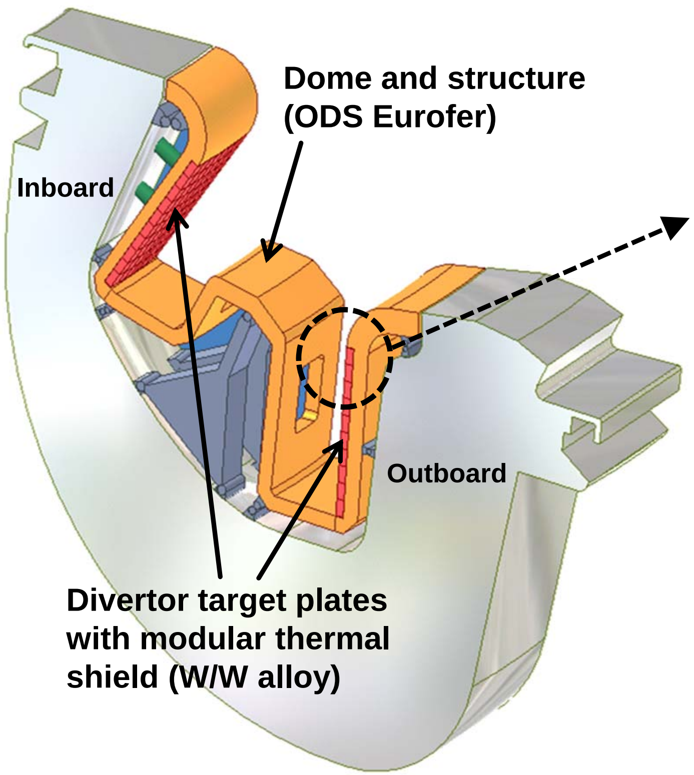
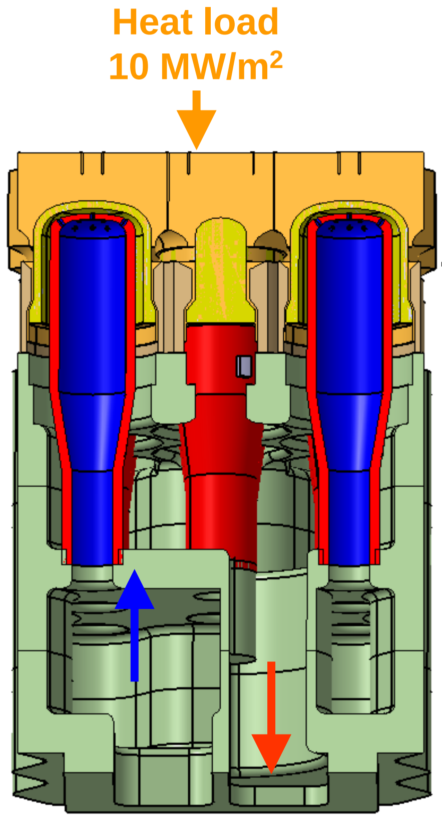
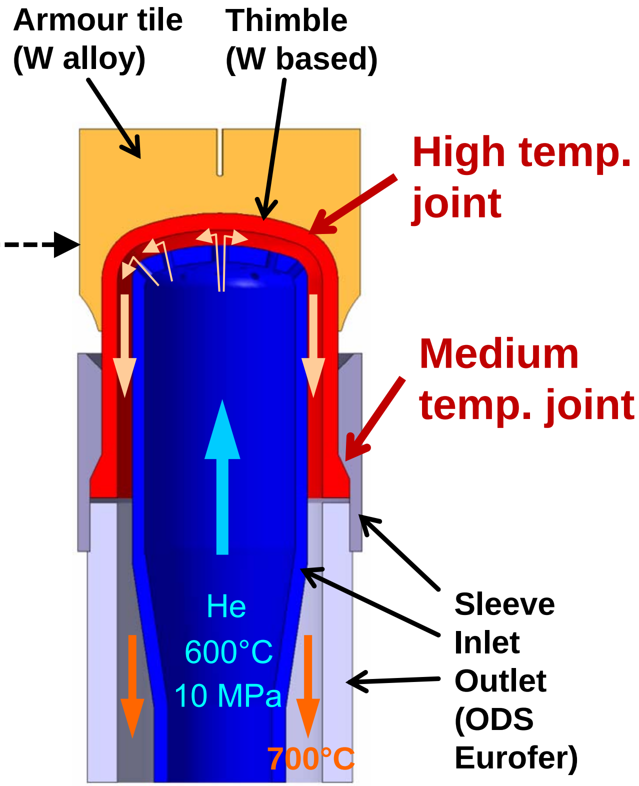


Divertor cassette



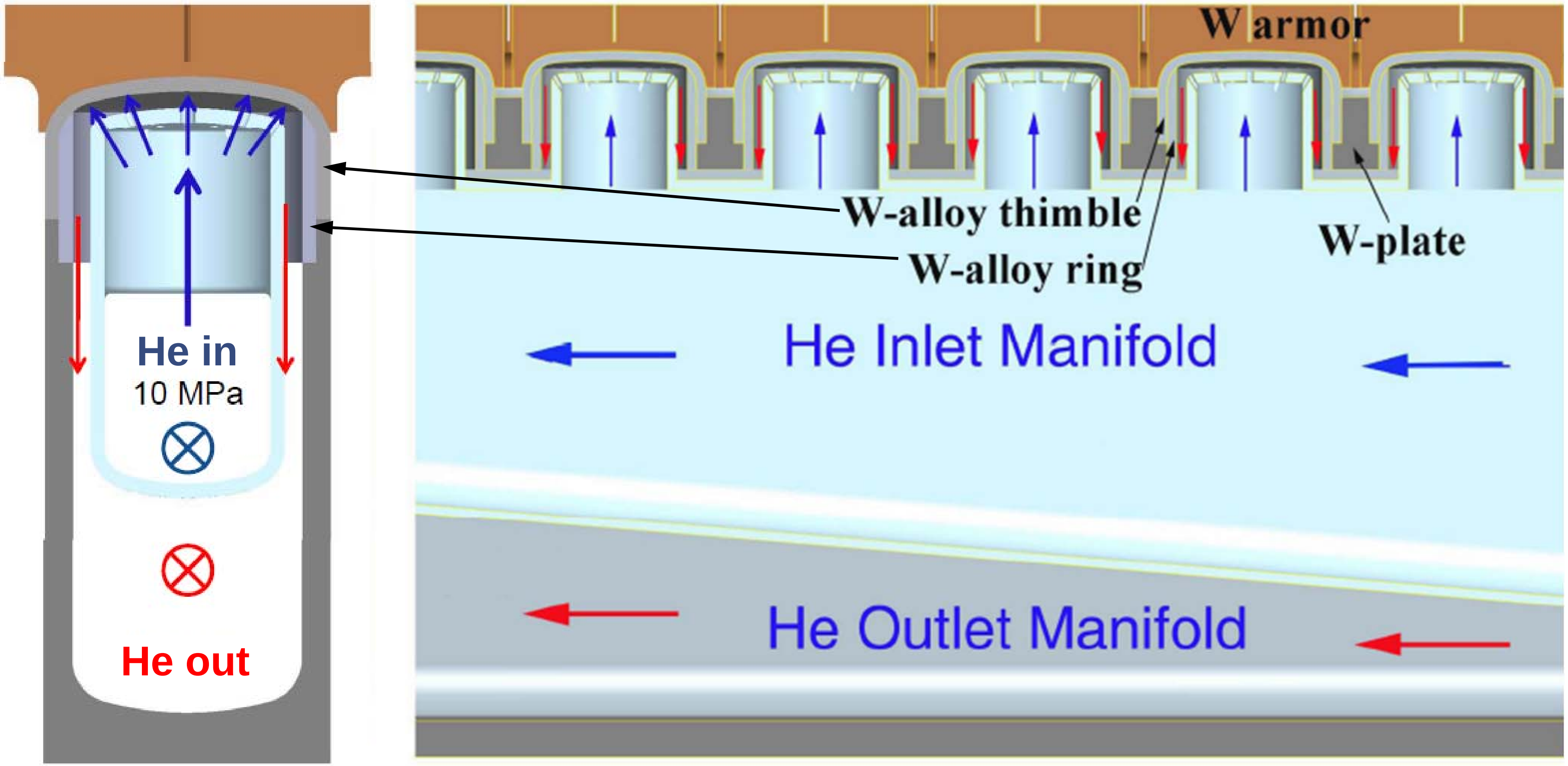
9-Finger module



1-Finger module

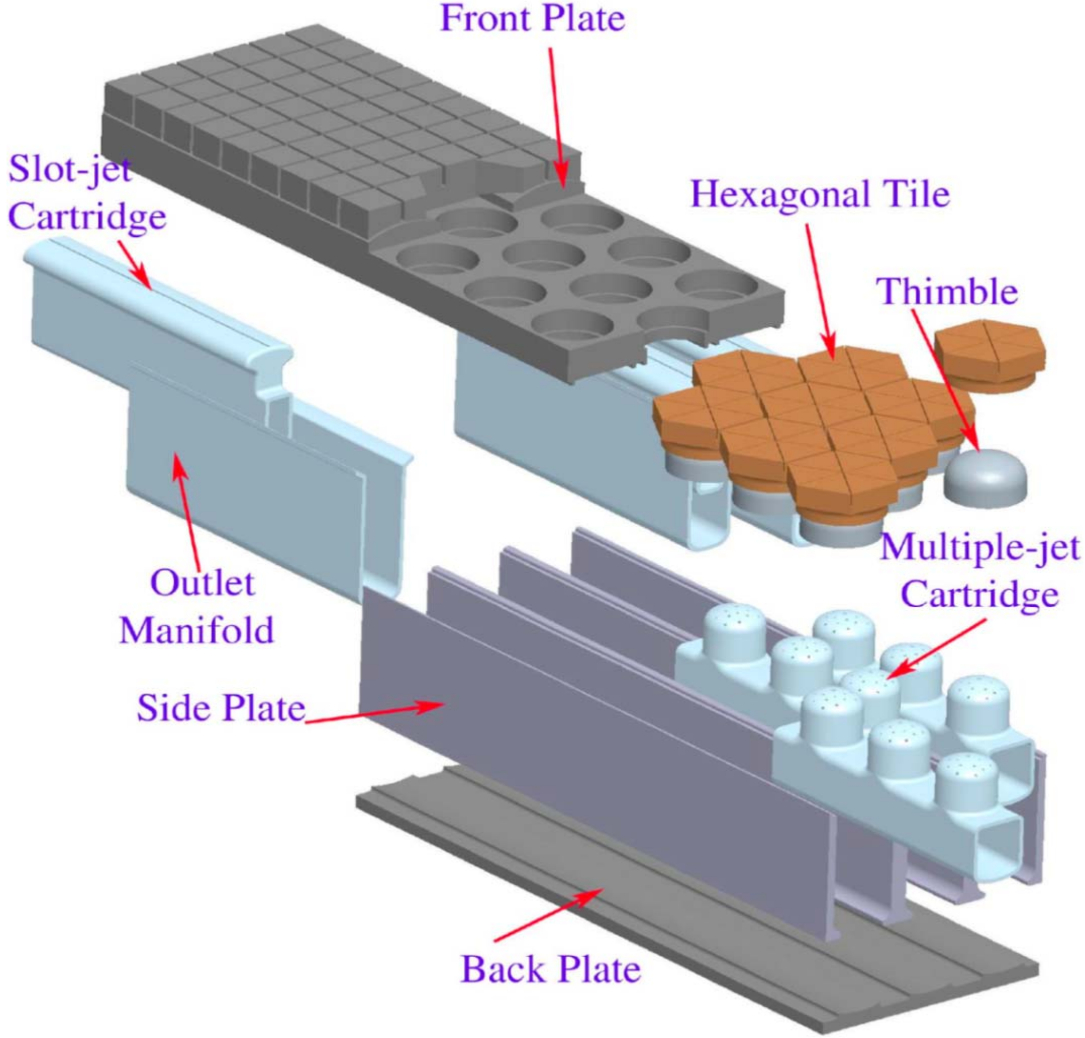
P. Norajitra *et al.*, KIT, 2003-2011

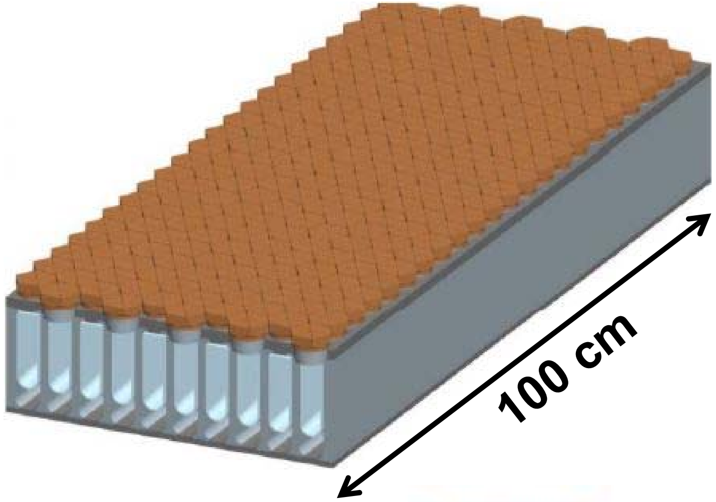
PLATE DESIGN (ARIES), JET COOLING



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

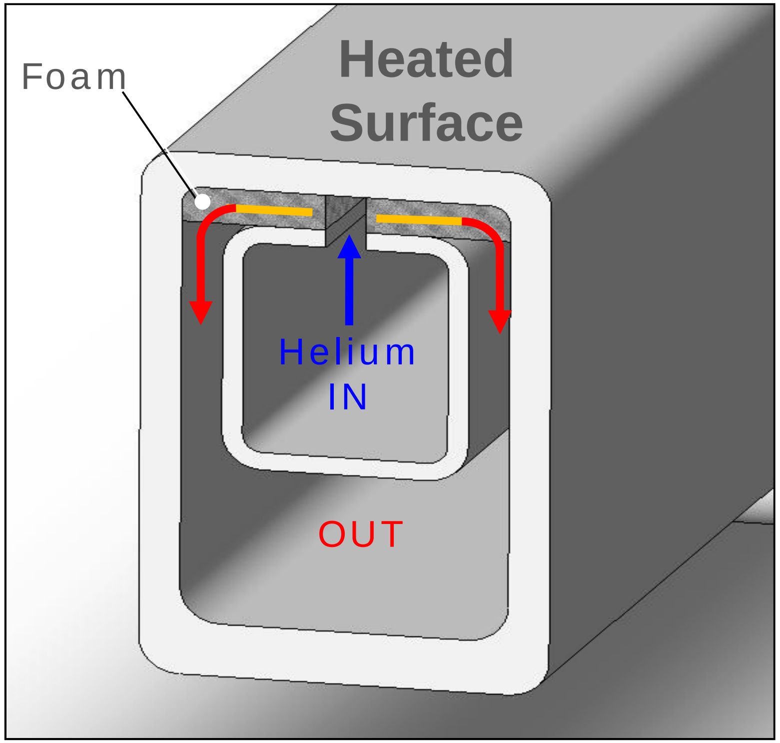
Plate Design (ARIES), Jet Cooling

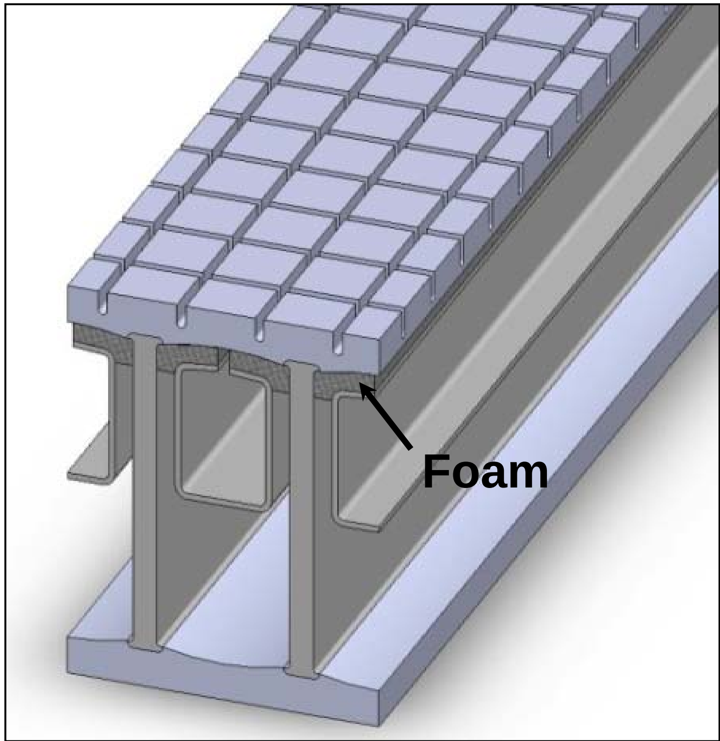


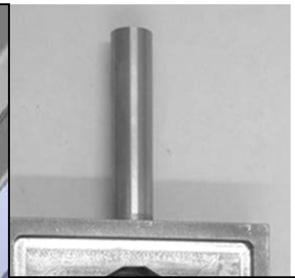


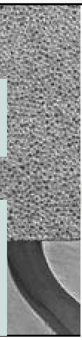
X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

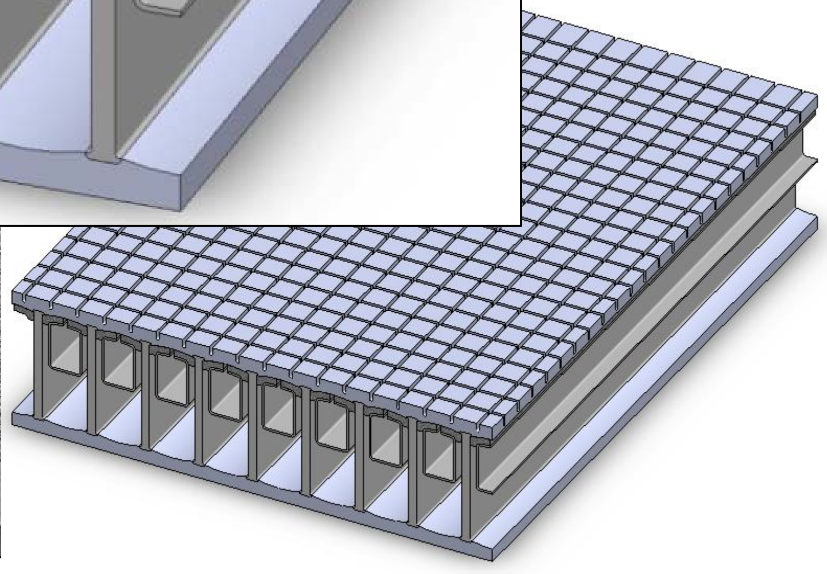
PLATE DESIGN, FOAM PROMOTER







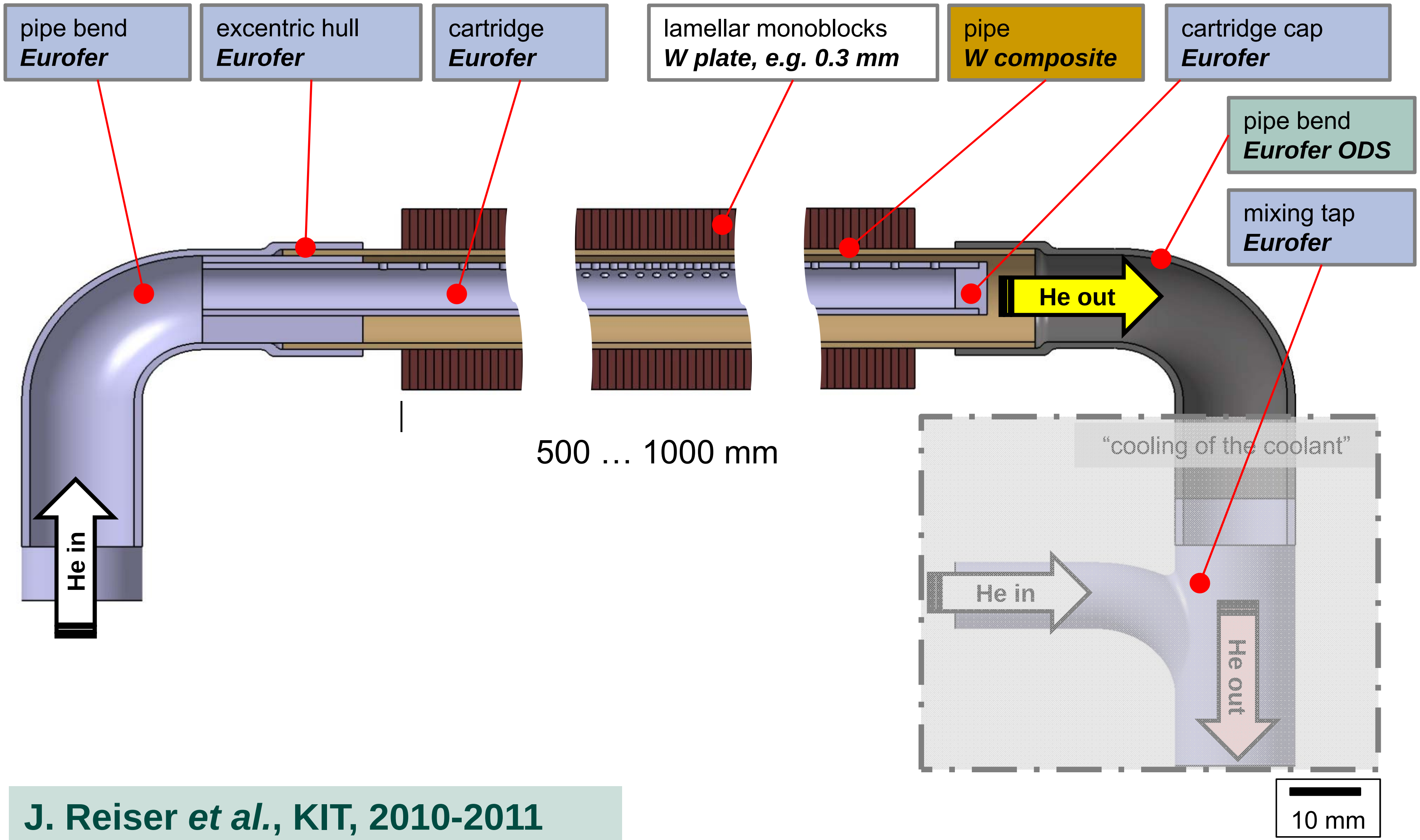




S. Sharafat *et al.*, UCLA, 2005-2009

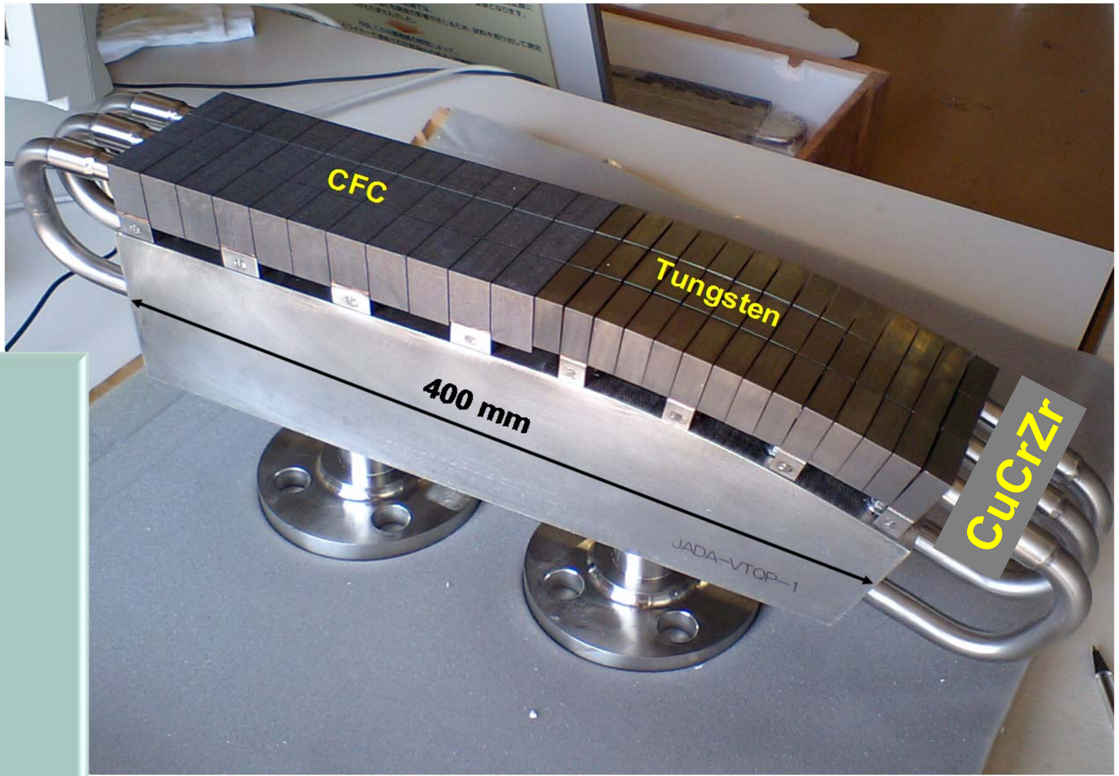
Mo, Nb, SiC Foam:
D. Youchison *et al.*, SNL,2011

Pipe/Monoblock Design, Jet Cooling



J. Reiser *et al.*, KIT, 2010-2011

ITER DESIGN, WATER COOLING

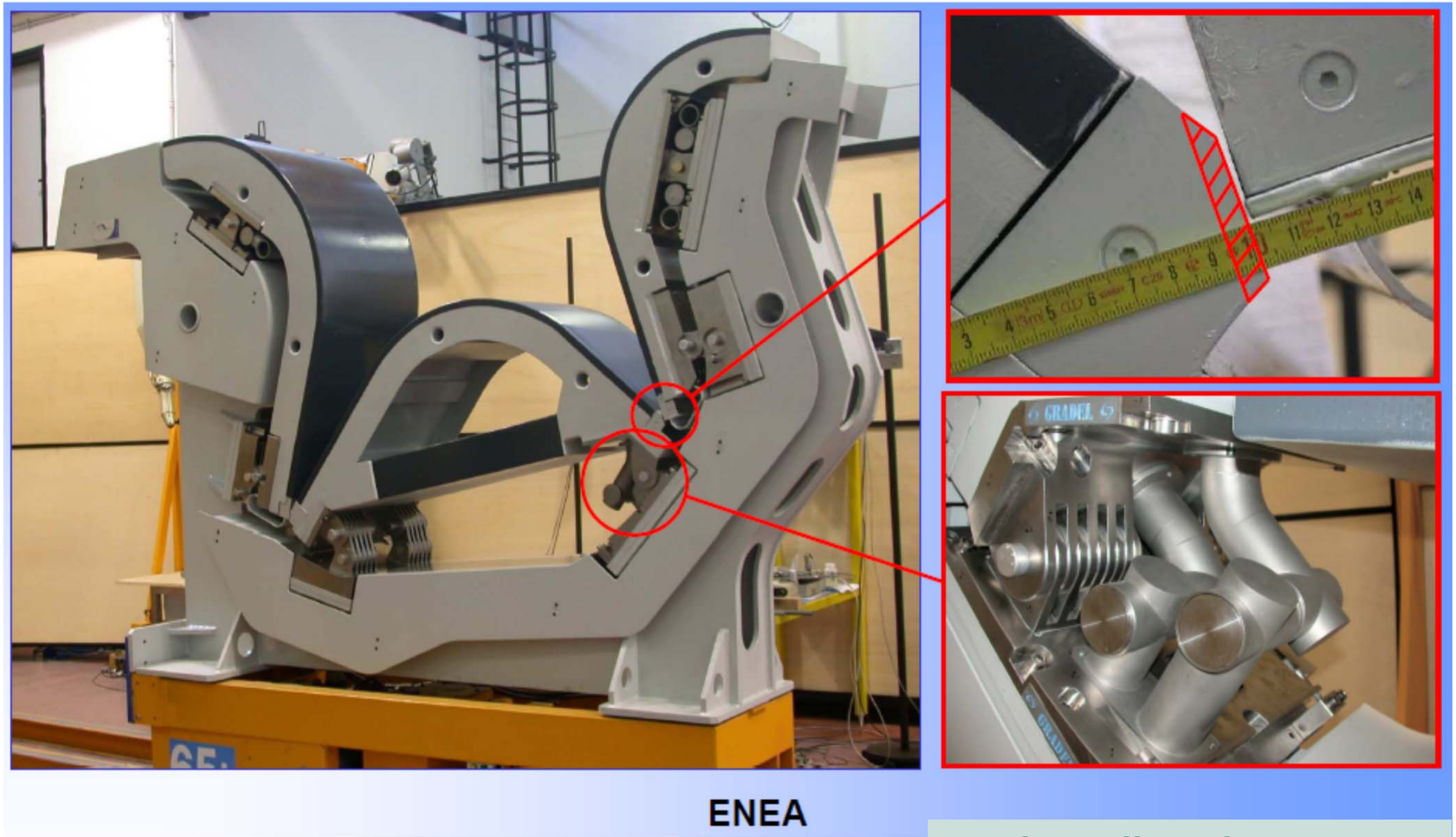


Coolant
- Pressure: 4 Mpa
- Temp.: 100-150 °C
- Flow: 9-11 m/s

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

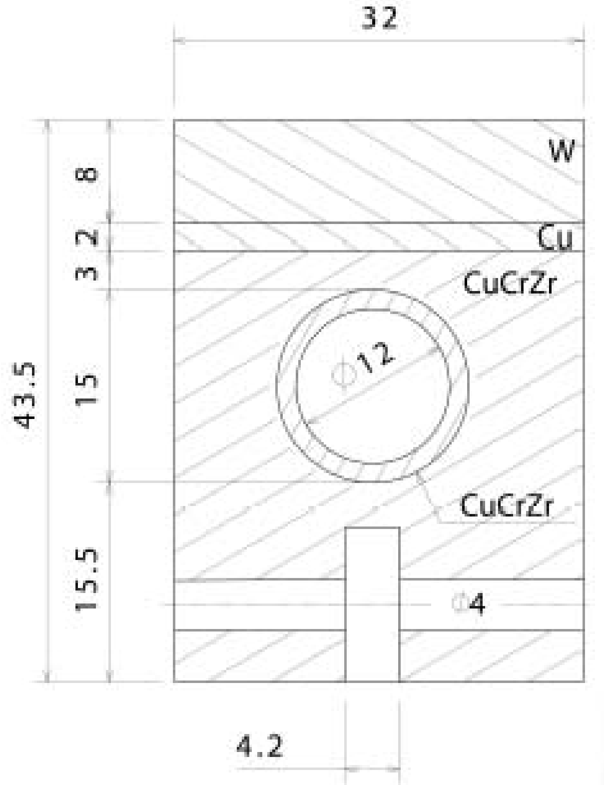
ITER DESIGN, WATER COOLING



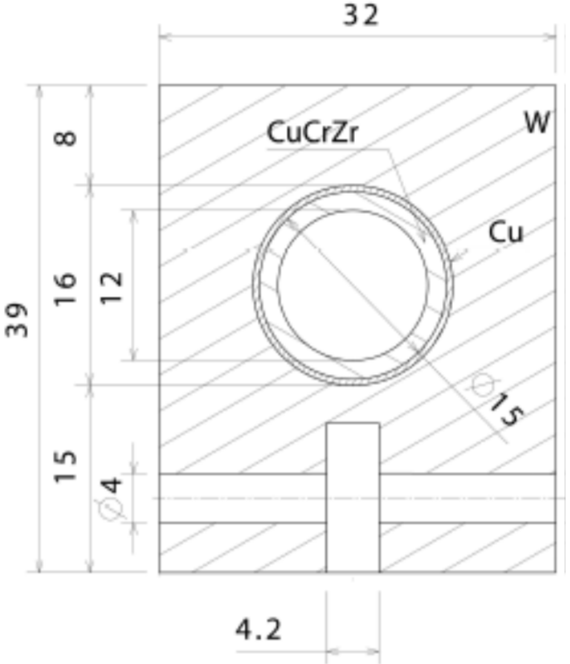
B. Riccardi *et al.*, F4E, 2008

ITER DESIGN, WATER COOLING

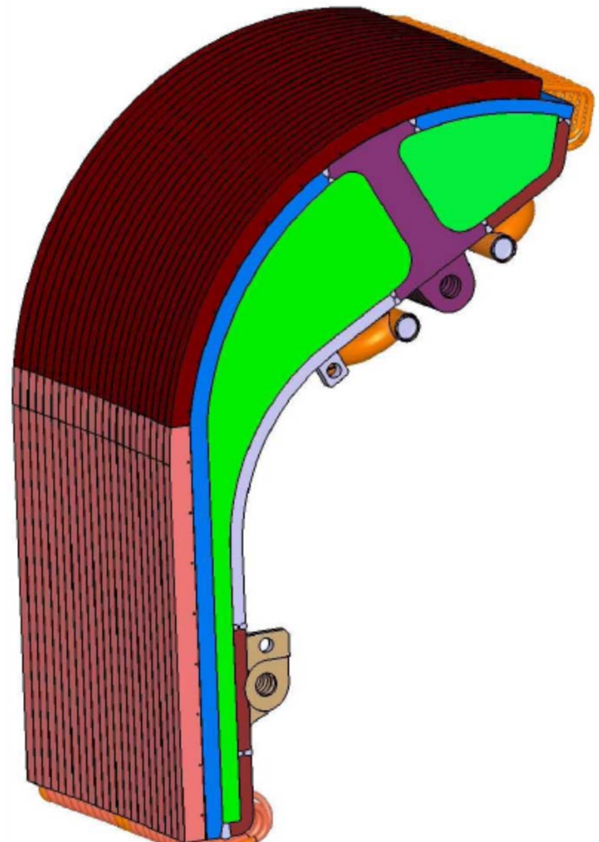
1. W Flat Tiles



2. W Monoblocks

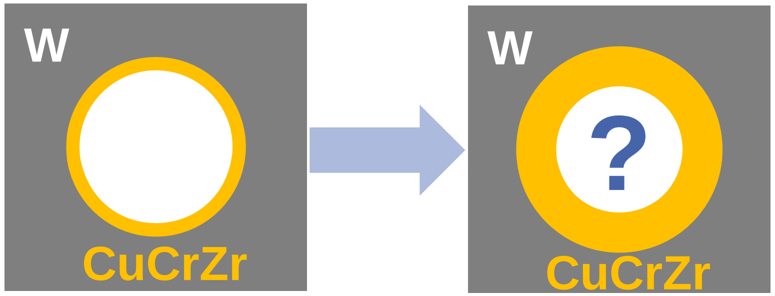


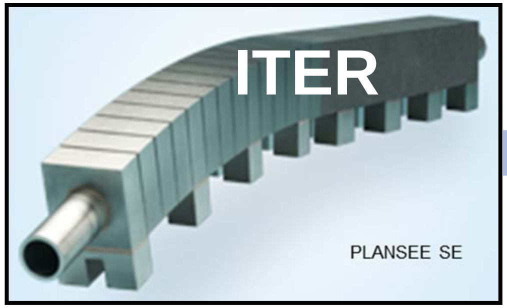
Vertical Target



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

DEMO Water Cooled Divertor





DEMO
?

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

Backup solutions are needed:
→ Development and use of composite materials

	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:	<0.1 dpa/y	3 dpa/fpy
Max. heat:	10-20 MW/m²	10-20 MW/m²

(Structural) Materials

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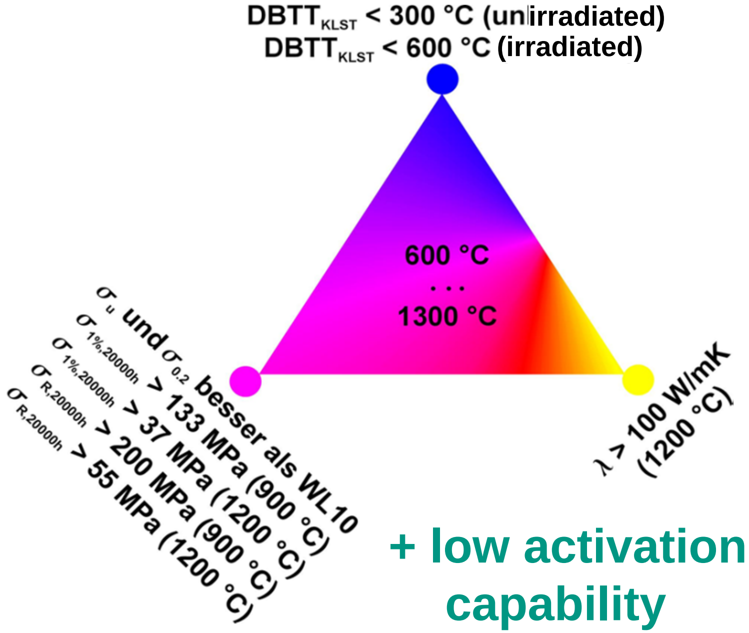
- During the last decade far too many and mutually exclusive design criteria have led to the following situation:
  - NONE of the divertor studies/candidates/concepts is convincing
  - Even worse: there is NO hope for a DEMO divertor at all
  - Examples for He cooling:

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**
- **…**

“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
- Irradiation limits: ~20 dpa

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

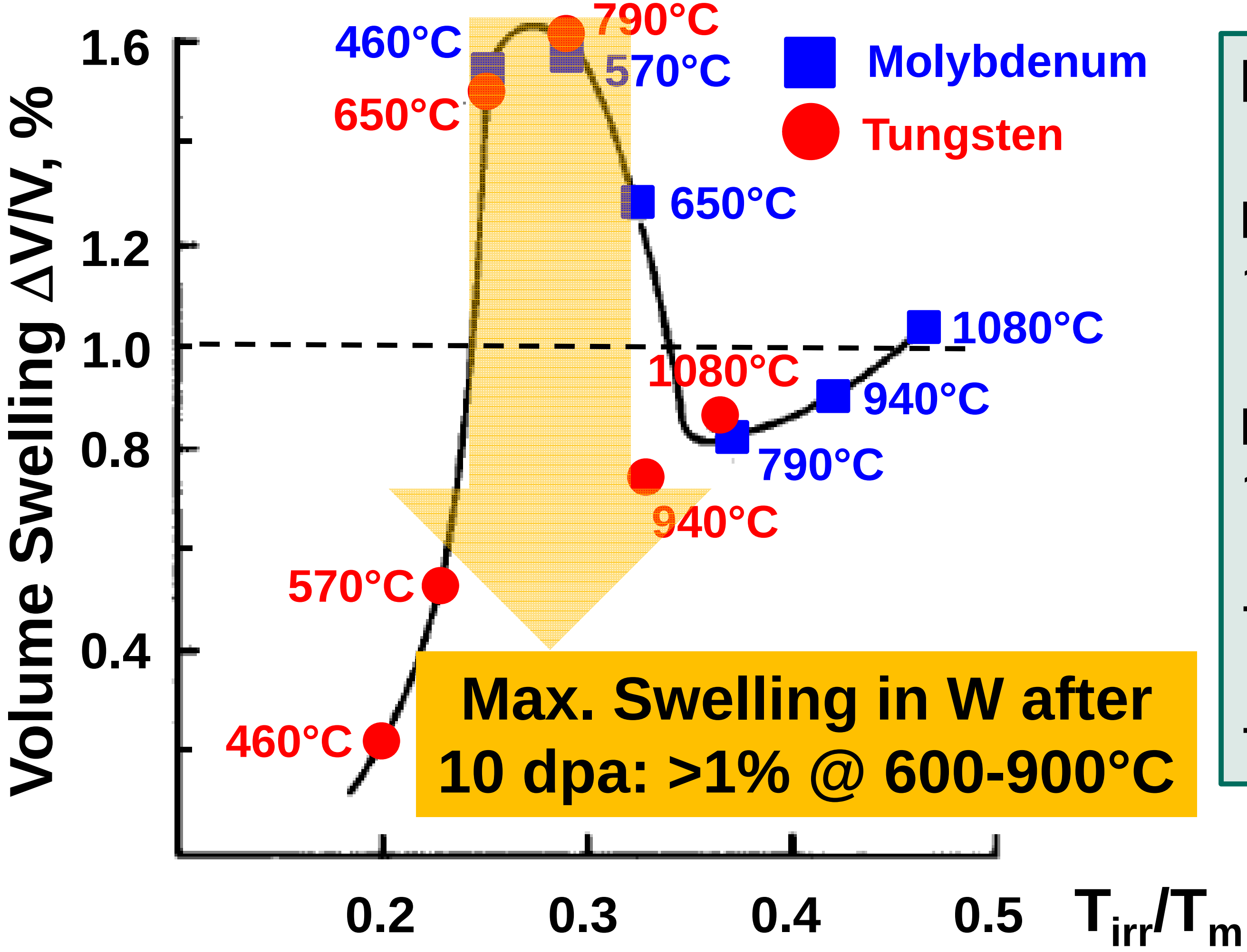
W

- 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

IRRADIATION EFFECTS → SWELLING



EBR-II

E_n > 1 MeV
1 x 10^{22} n/cm²

E_n > 0.1 MeV
1.6 x 10^{22} n/cm²

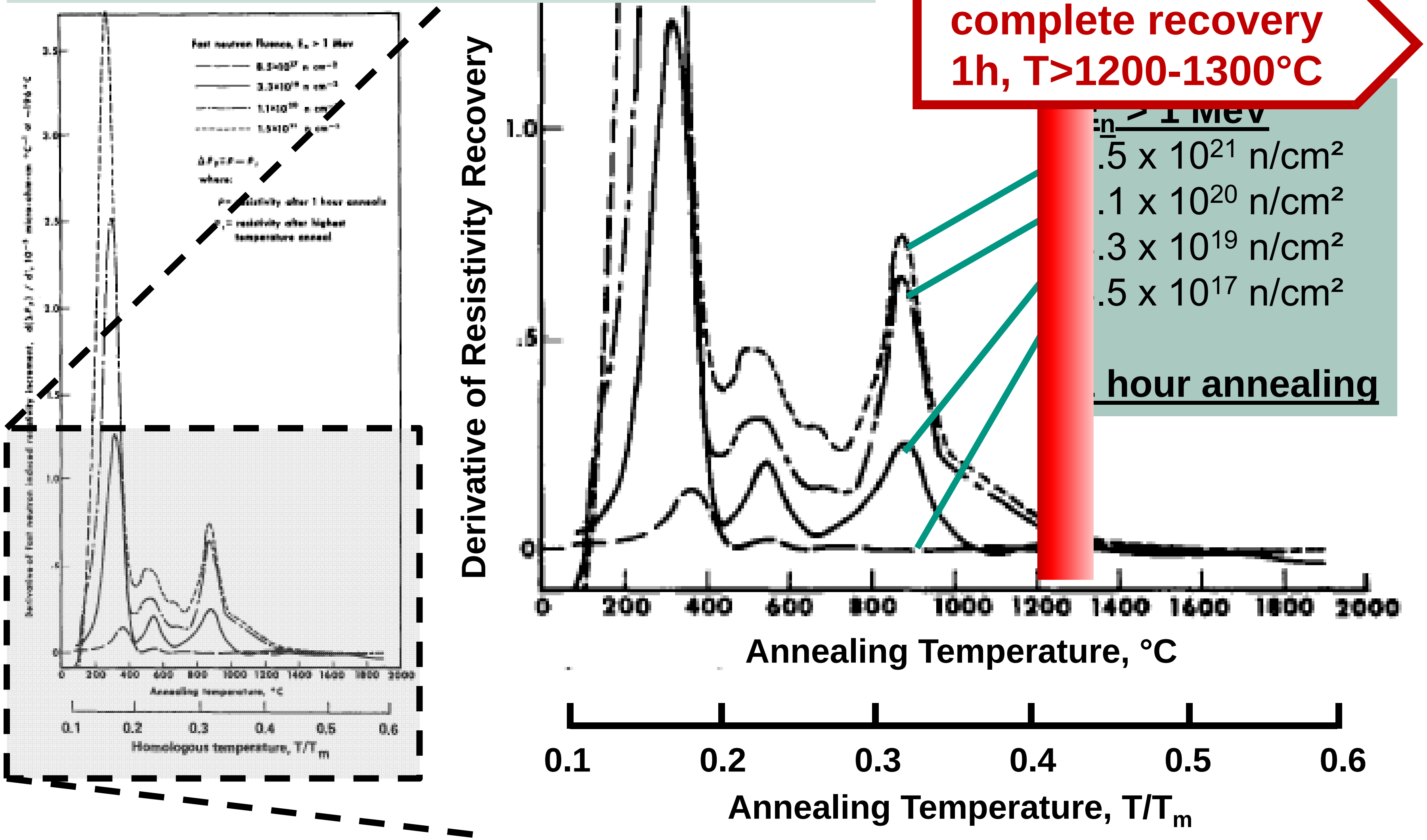
→ **29 dpa in Mo**

→ **9.6 dpa in W**

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

IRRADIATION EFFECTS → RECOVERY

→ L.K. Keys, J. Moteff, JNM 34 (1970) 260-280



IRRADIATION EFFECTS → EMBRITTLEMENT

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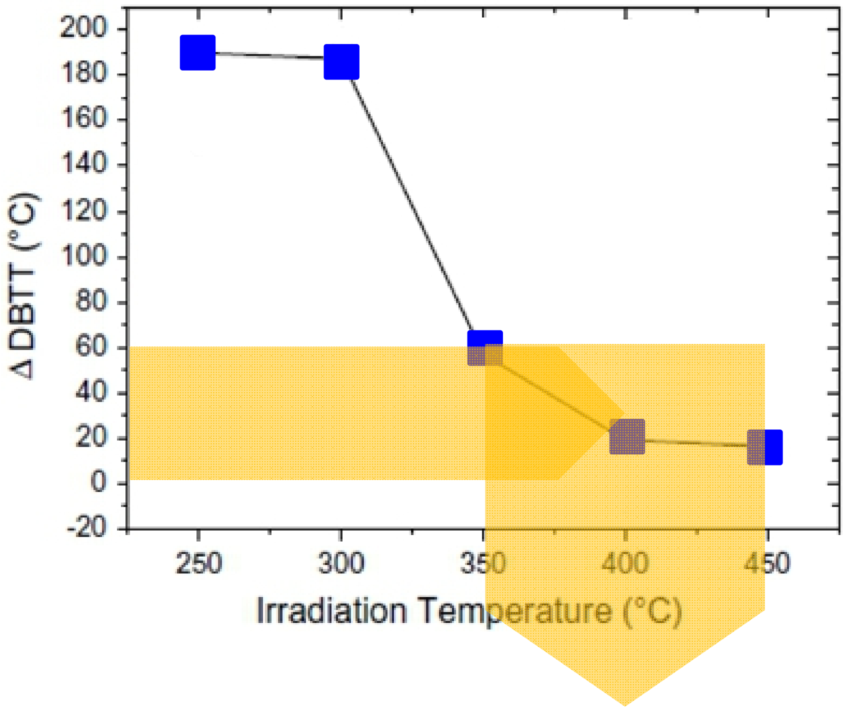
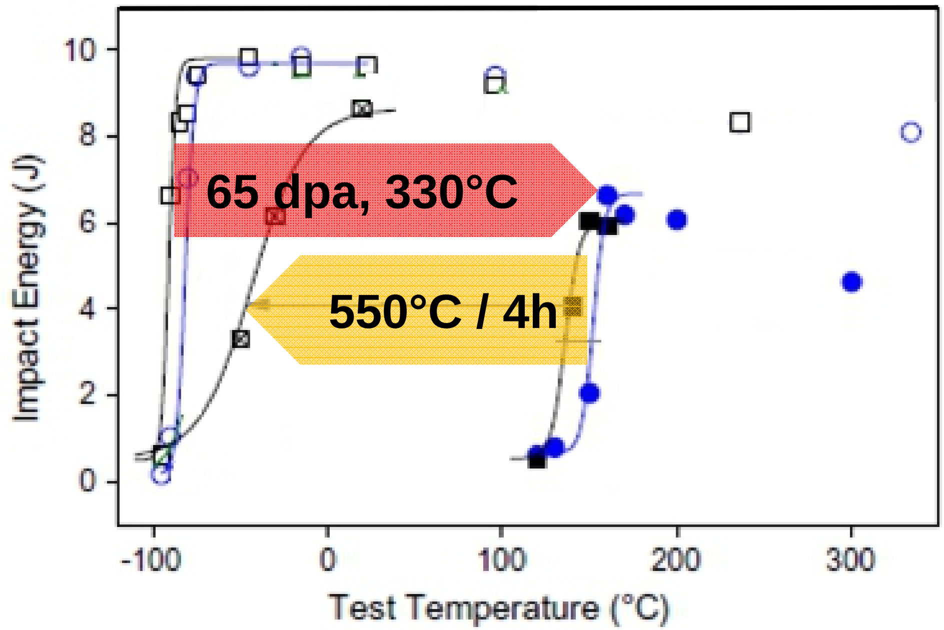
EUROFER: In-service irradiation embrittlement after ~10 dpa



Possible Operating Temperature T_{op} > 350°C

EUROFER: Recovery of 65 dpa irradiation embrittlement

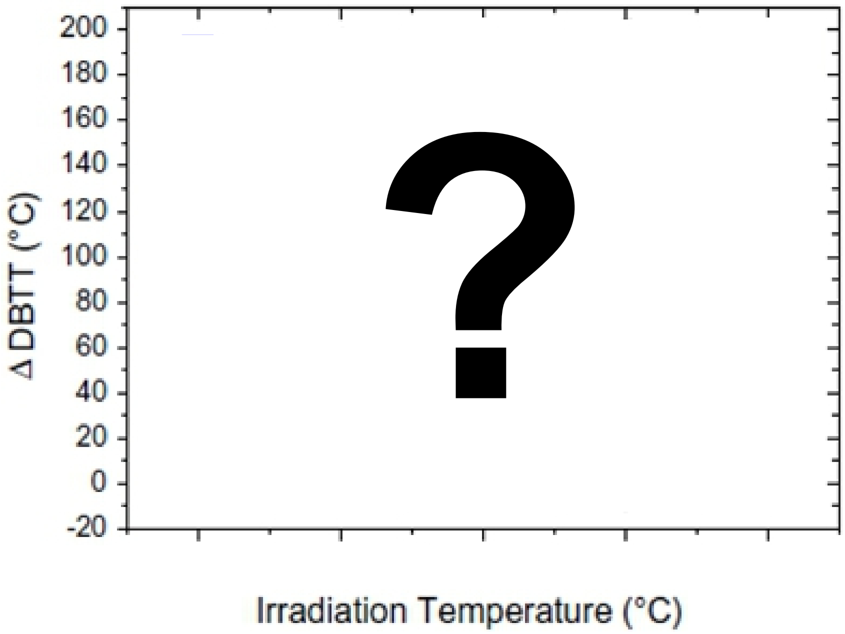


Possible Recovery Temp. T_{rec} > 550°C

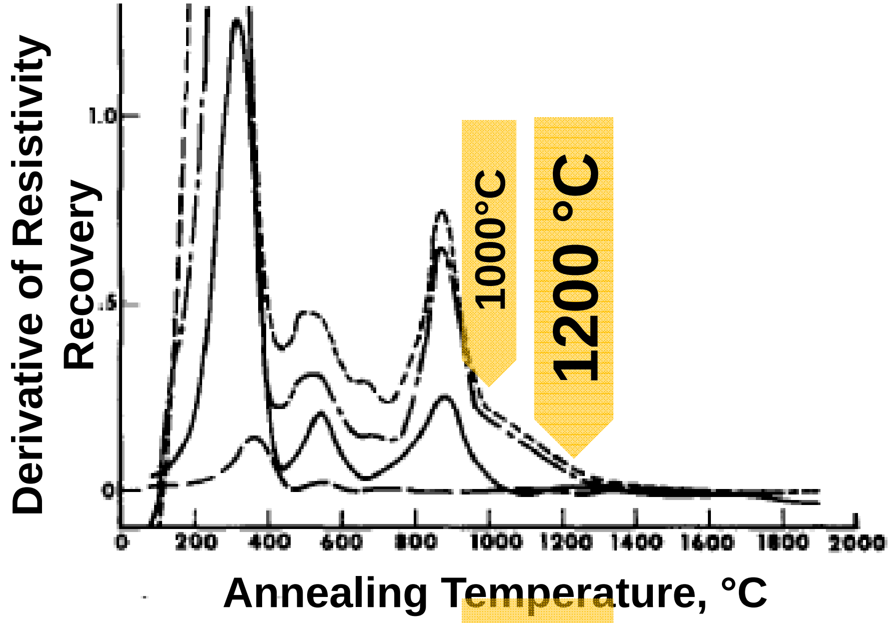
→ E. Gaganidze *et al.*, KIT

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

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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 Moldin
- Debindering/S ng
- HIP

- Ball Milling
- Encapsulati
- HIP/Hot Formin

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

s

Functional Applications

+ Mass ction
+ Ne ished
cts
ogenous
icrostructure

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

Still Under Investigation

+ Na cture
+ y

all Scale
roduction Route

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

COMMERCIAL SEMI-FINISHED W PRODUCTS

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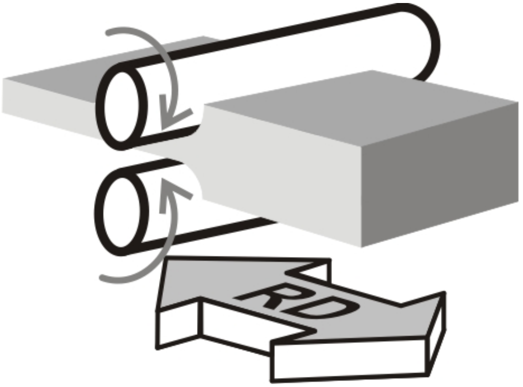
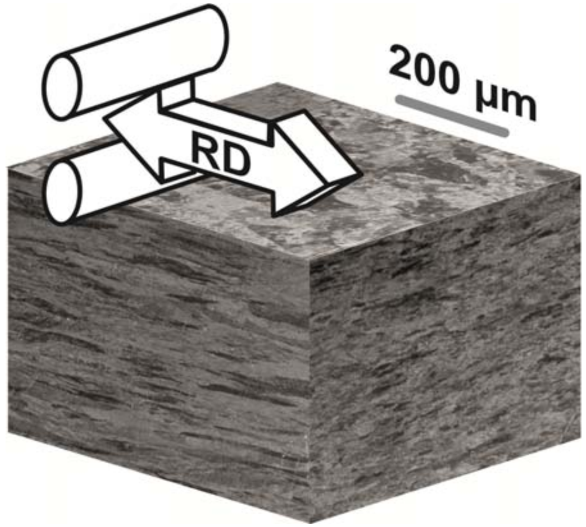
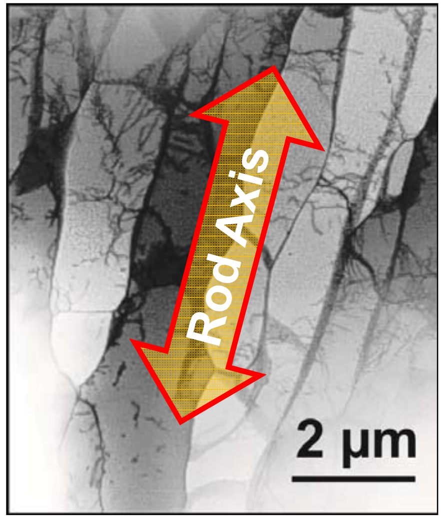
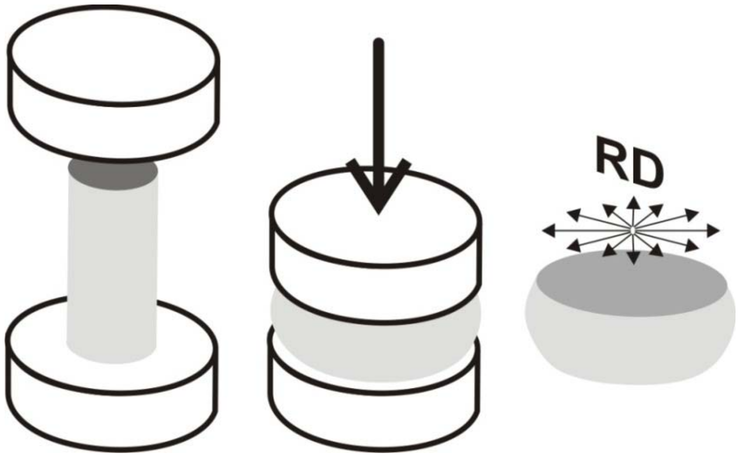
Rolling Plates



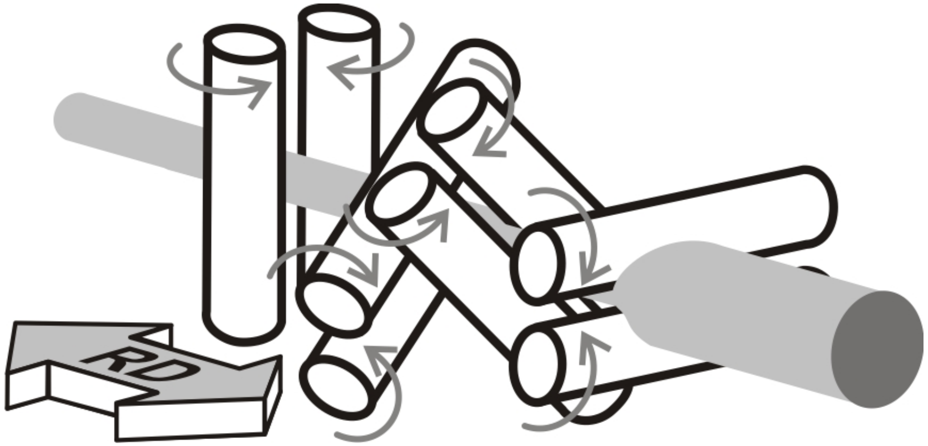




Forging Round Blanks

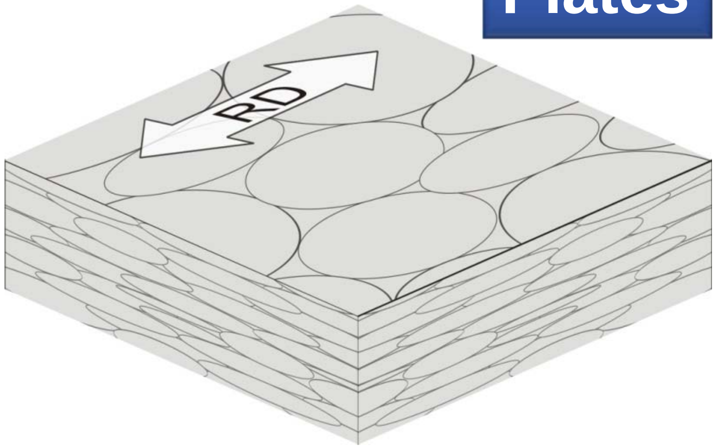


Rolling/Swaging Rods

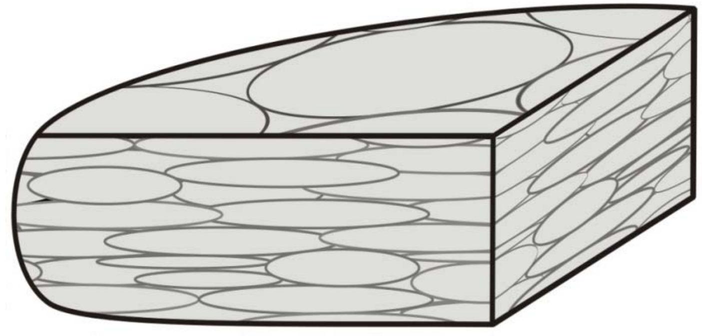


Microstructure: Simplification

Plates

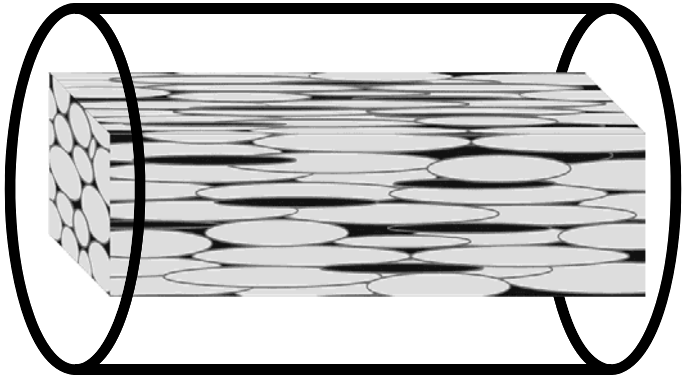


Round Blanks



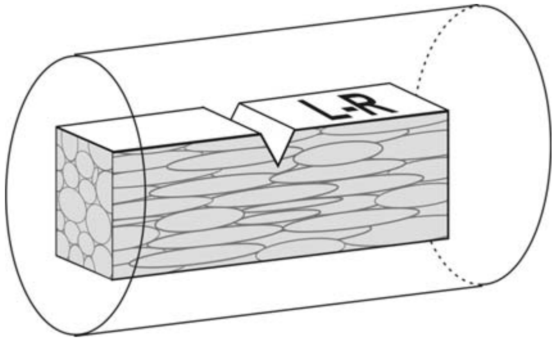
Stack of „Pancakes“

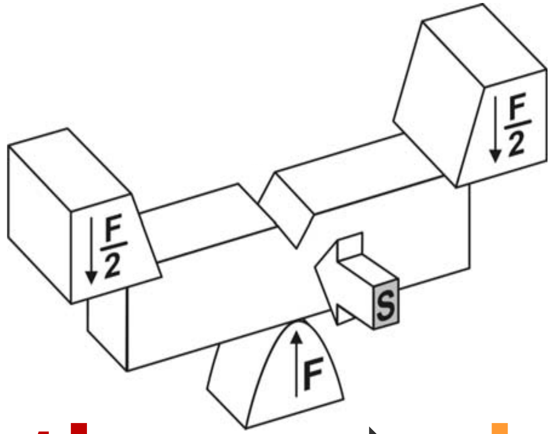
Rods



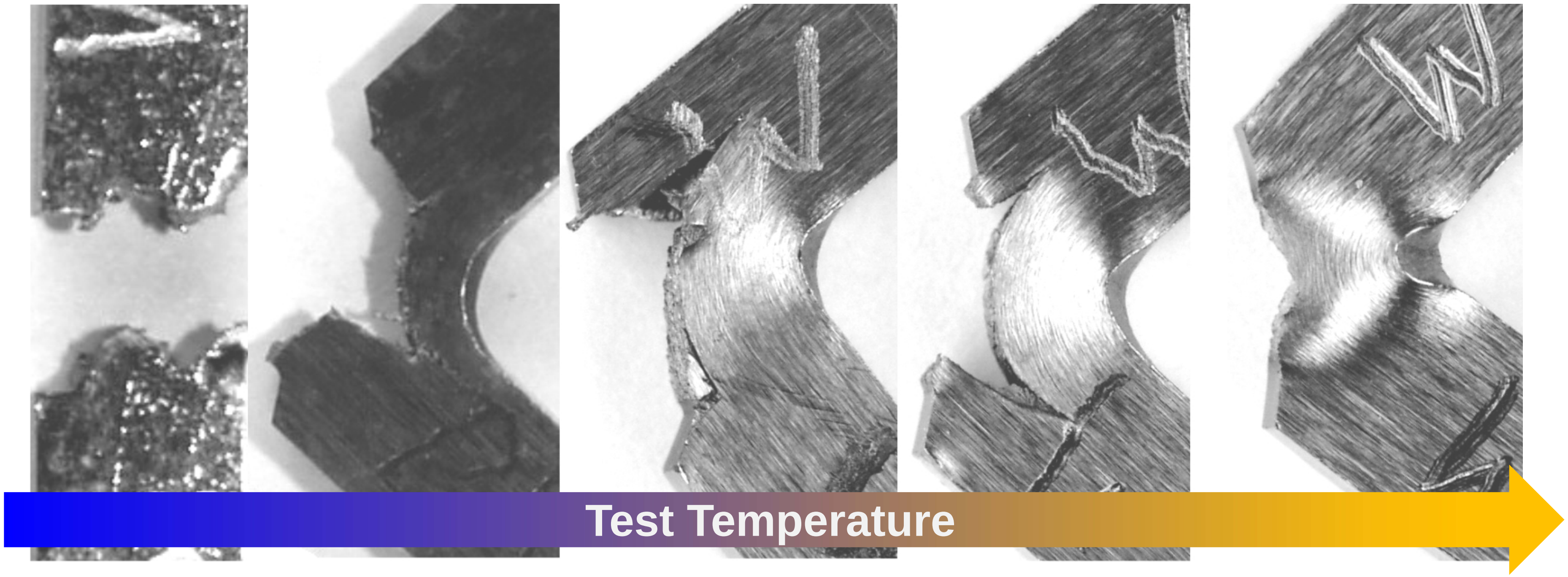
Bundle of „Fibres“

Rods: Dynamic Fracture

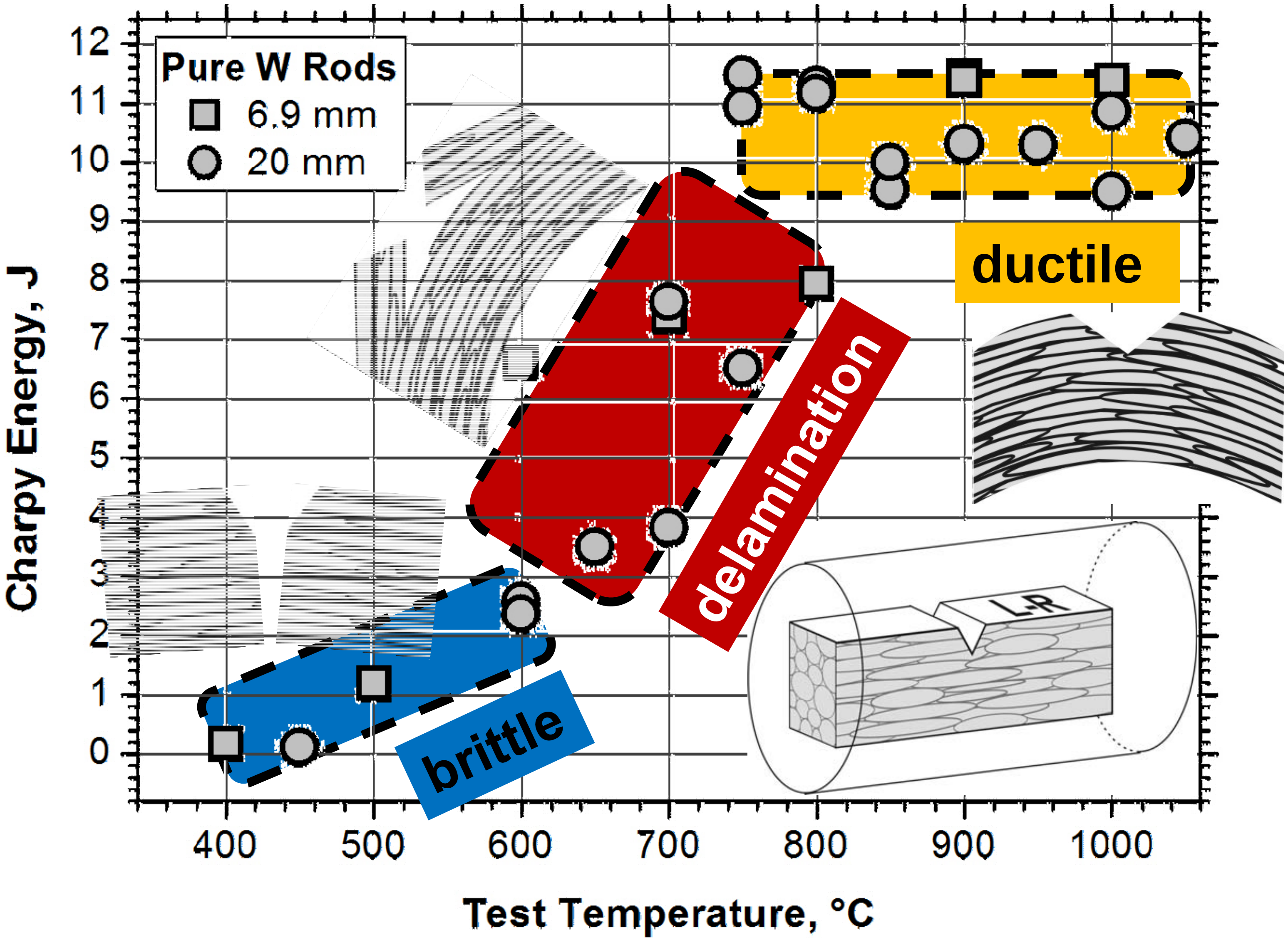




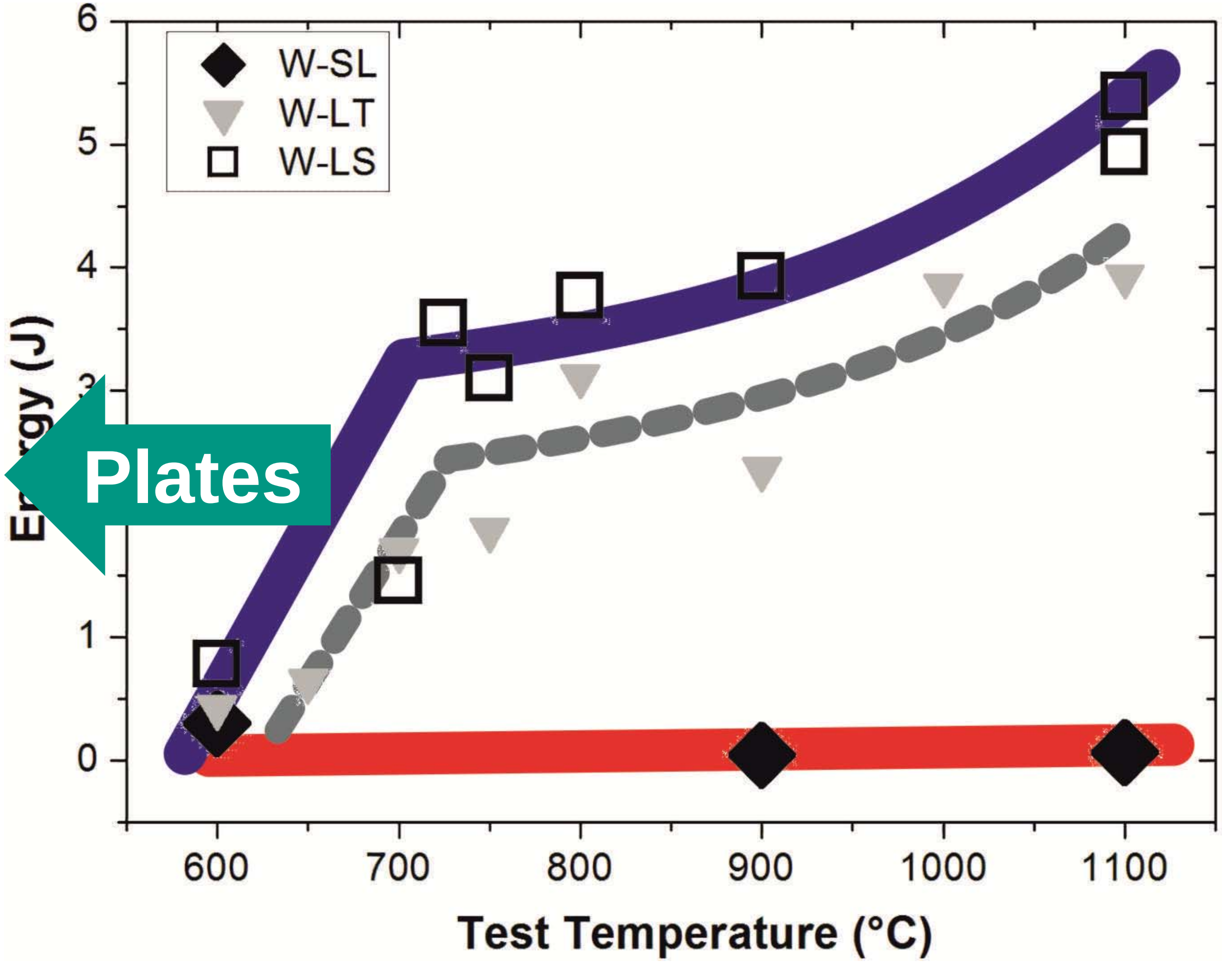
brittle → delamination → ductile

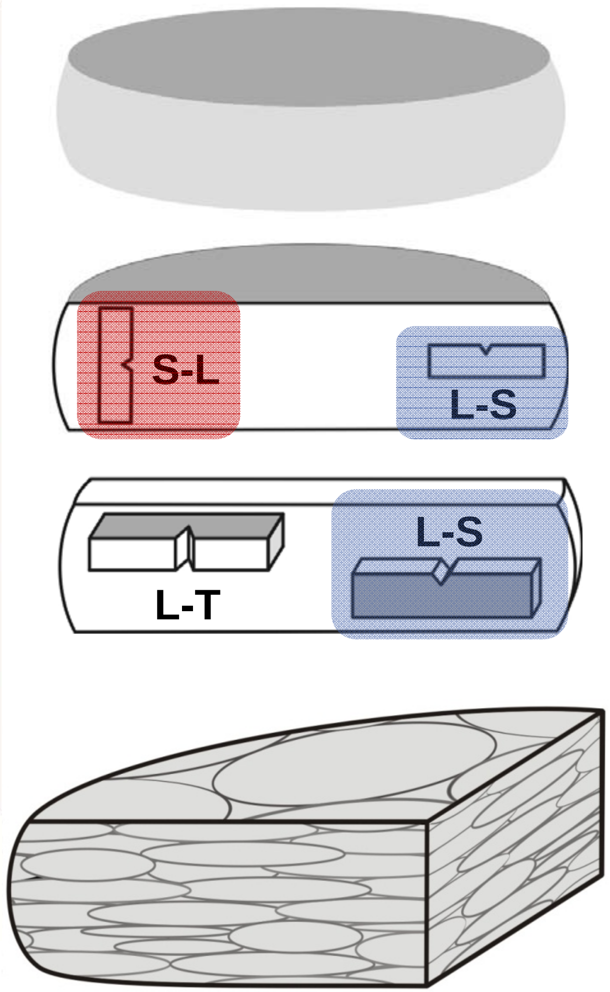


Rods: Fracture Mode Transitions

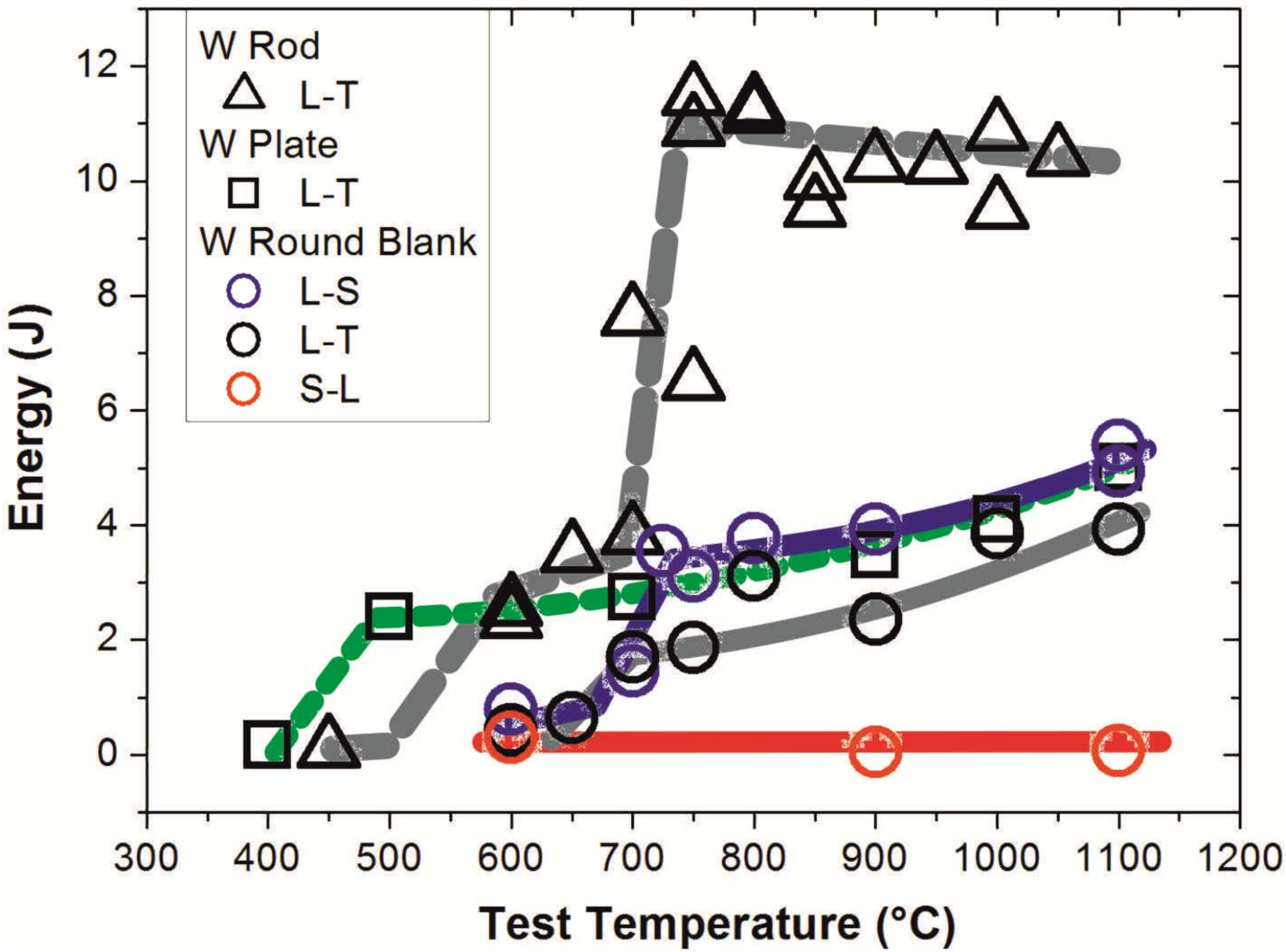


Plates/Blanks: Fracture Behavior





Pure W - Overview



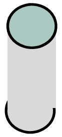
DELAMINATION DUCTILE

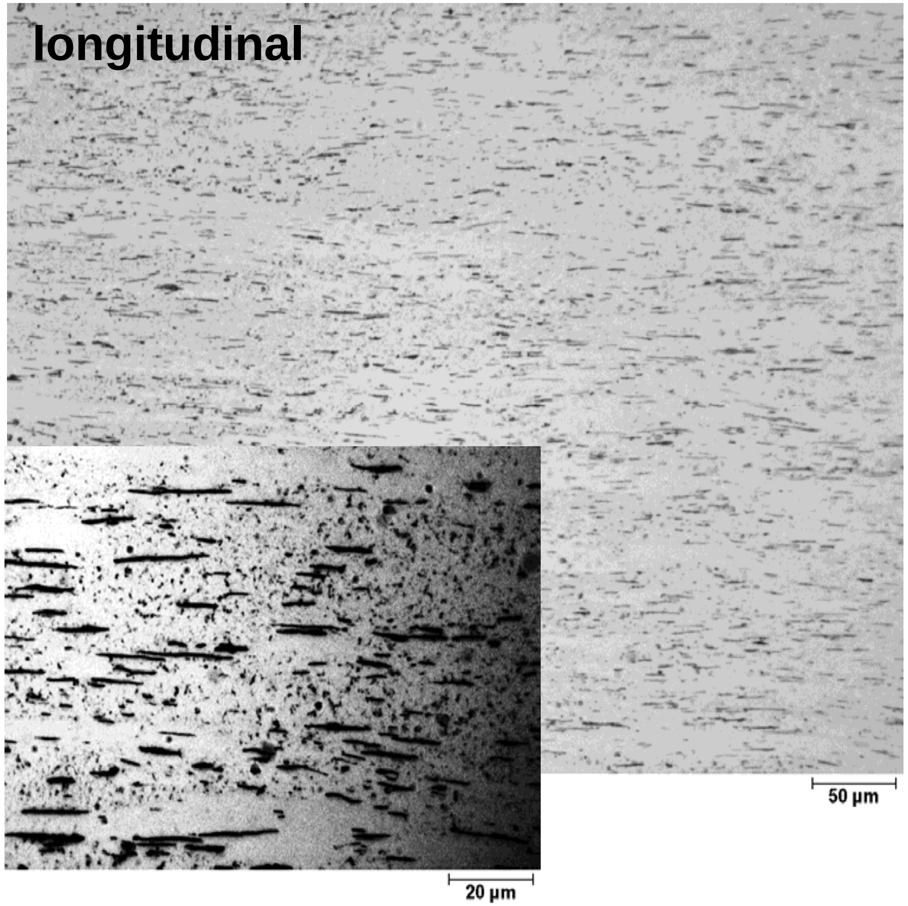
Effect of ODS particles in W

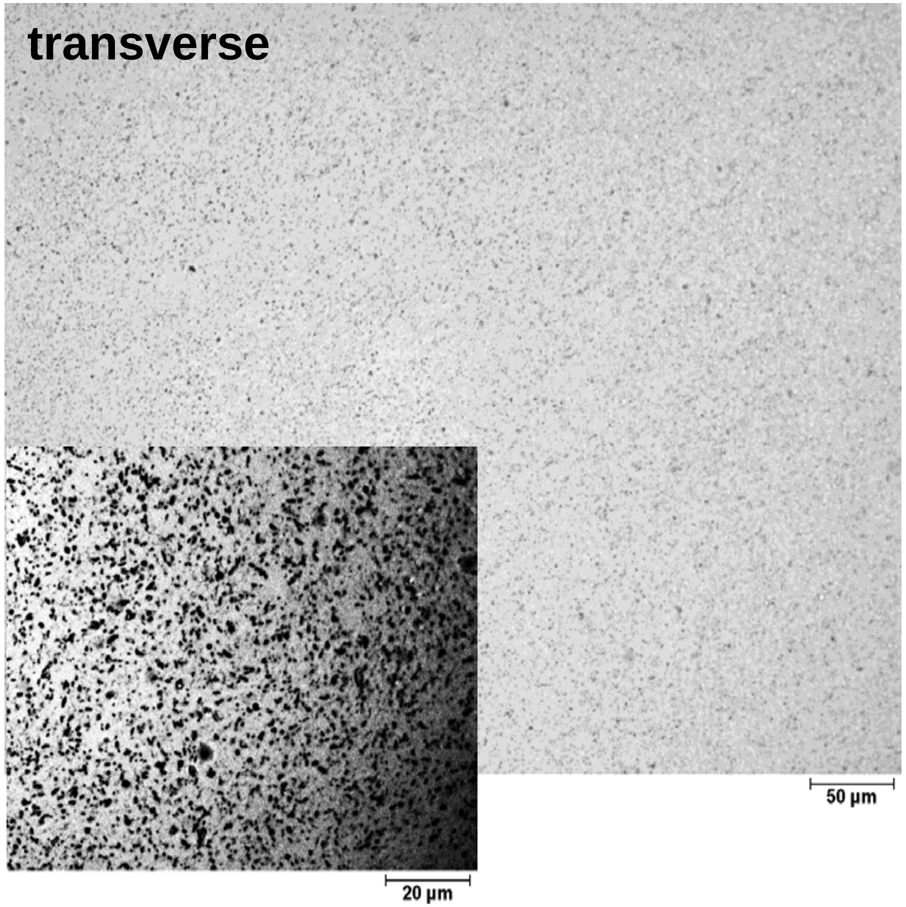
Karlsruhe Institute of Technology

WL10 Rod, Ø7 mm

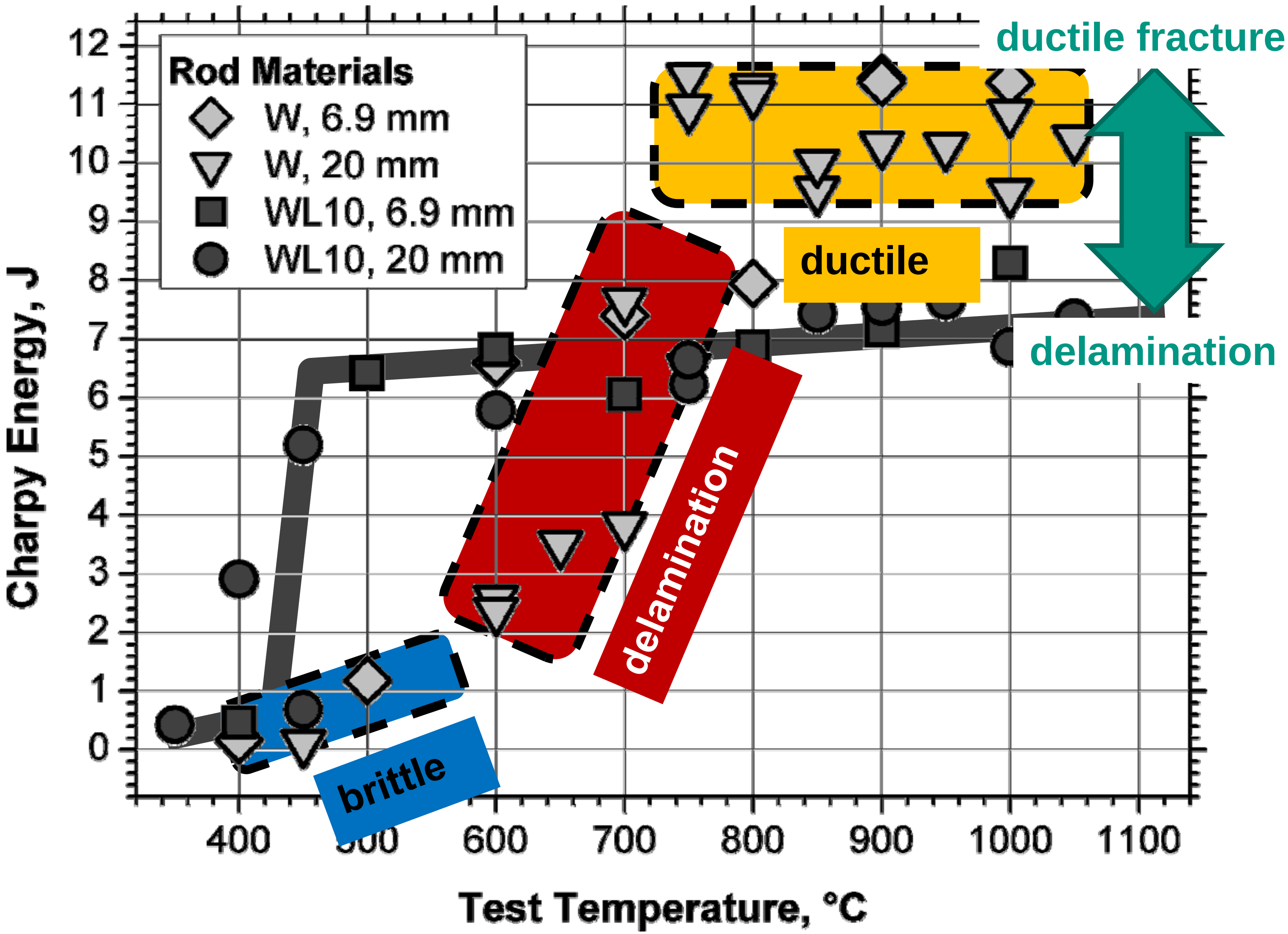
Rods: Metallography







Effect of ODS particles in W



"REASONABLE" ALLOYING ELEMENTS FOR W

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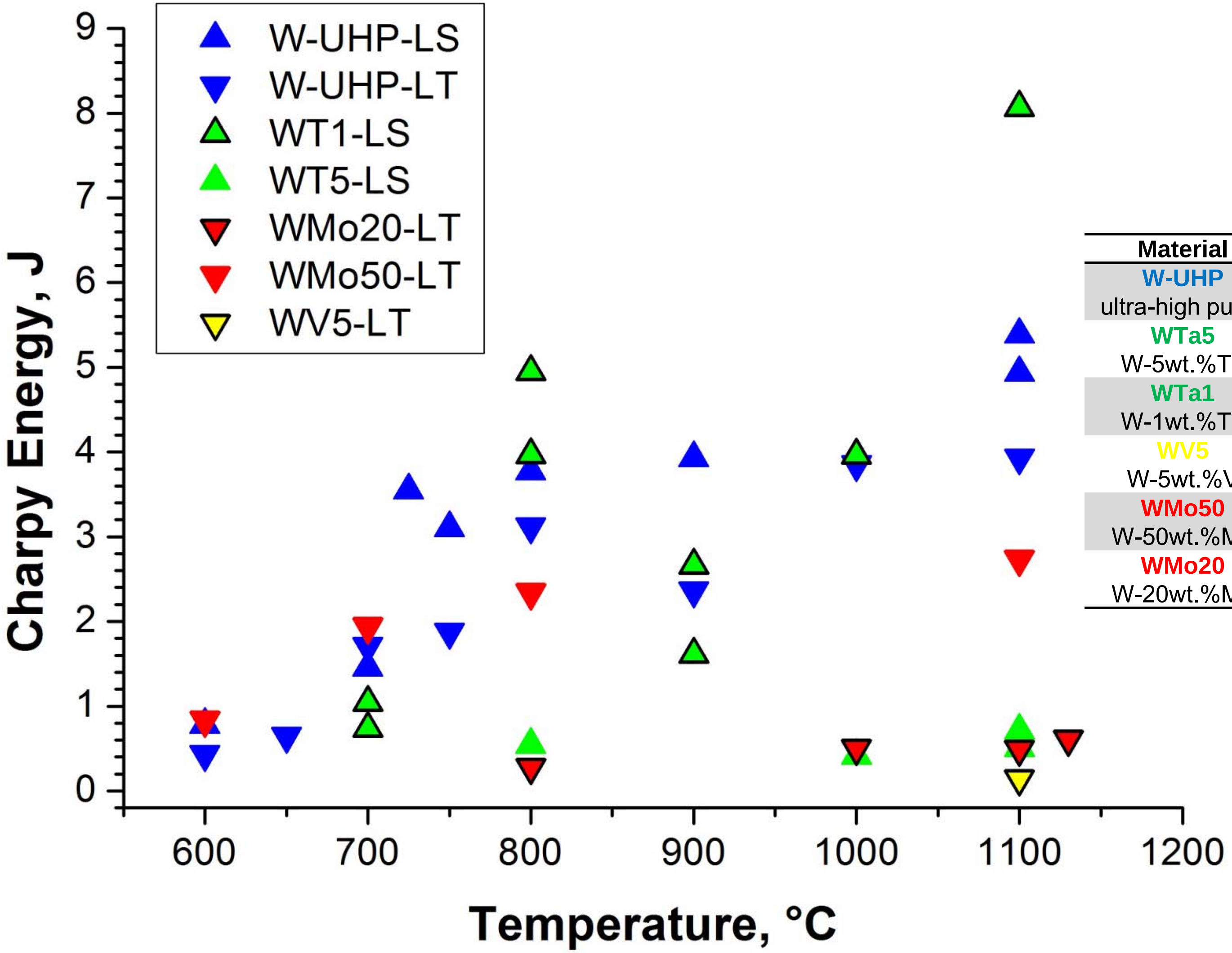
M_2W Be	Mg	MW B	MW_2 C $M_{1-x}W$	M_4W Al		Y	La	
Ti >3wt.% >300°C	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu	
MW_2 Zr	Nb	Mo		Ru < 3 wt. %	Rh < 2 wt. %	M_3W Pd	Ag	Cd
MW_2 Hf	Ta		MW Re < 26 %	Os < 5 %	MW Ir	MW Pt	Au	

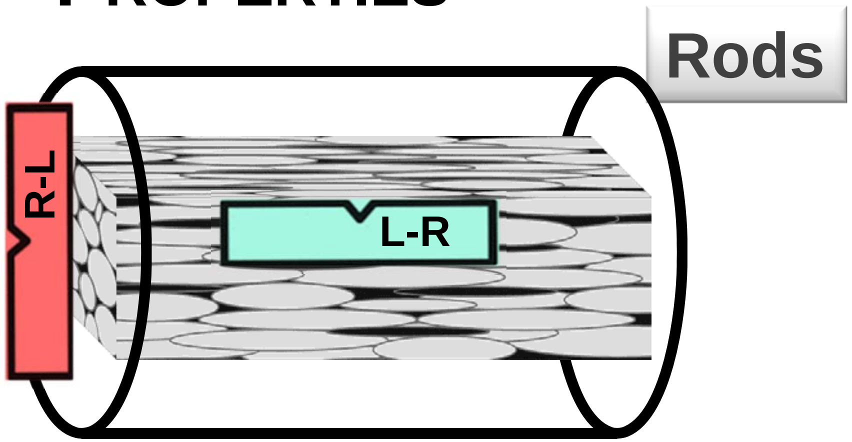
Insoluble **Intermetallic Phases** **Line Compounds** **Solid Solution**

Effect of Alloying Elements in W

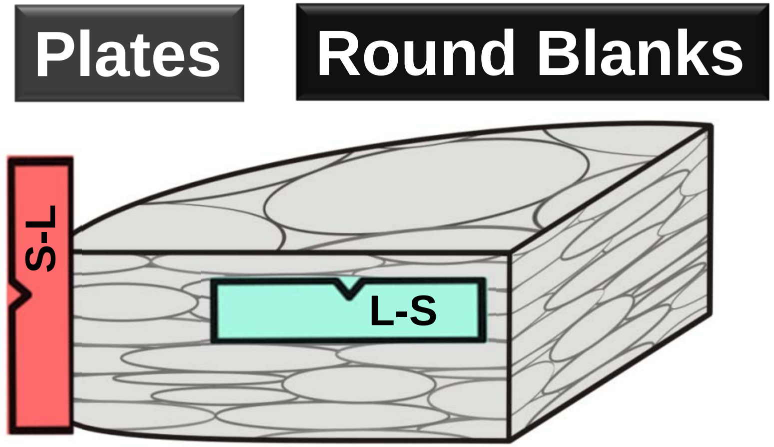


Material	Form	Size
W-UHP ultra-high purity	round blank	Ø180 mm, thickness 30 mm
WTa5 W-5wt.%Ta	round blank	Ø180 mm, thickness 30 mm
WTa1 W-1wt.%Ta	round blank	Ø180 mm, thickness 30 mm
WV5 W-5wt.%V	round blank	Ø95 mm, thickness 20 mm
WMo50 W-50wt.%Mo	round blank	Ø95 mm, thickness 20 mm
WMo20 W-20wt.%Mo	round blank	Ø95 mm, thickness 20 mm

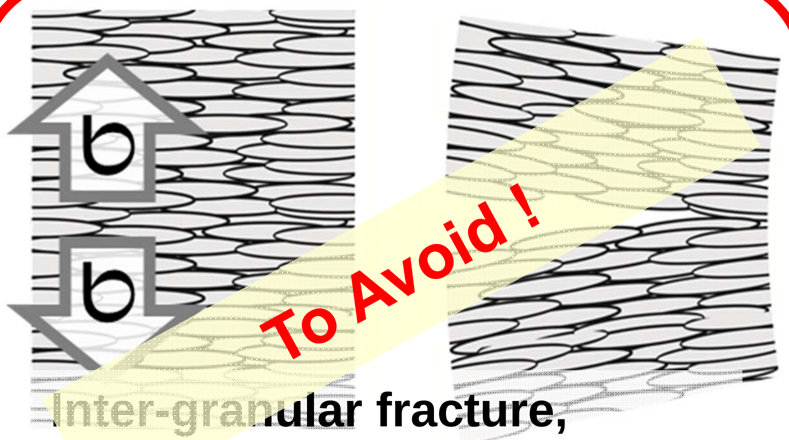
MICROSTRUCTURE AND RELATED PROPERTIES



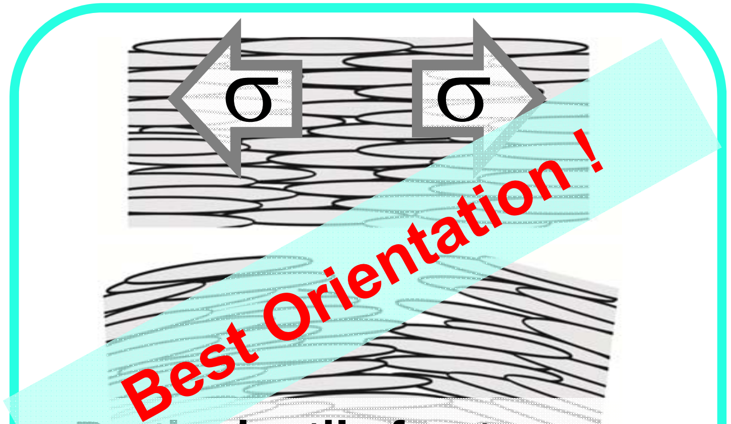
Bundle of „Fibres“



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

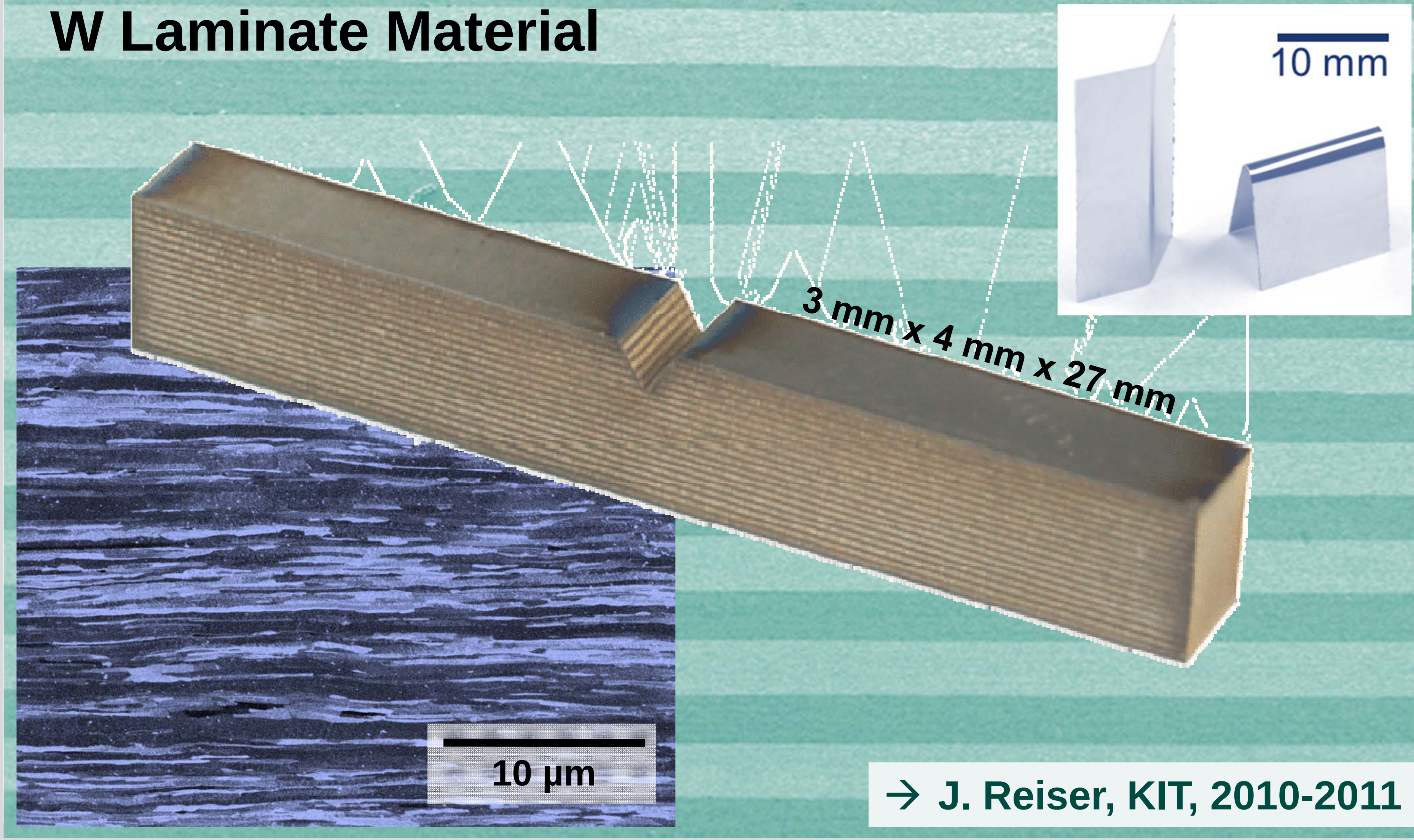
Pure Tungsten (maybe small amounts of grain stabilizers, like La_2O_3)

Costs for 500 t → over 100 Mio. US $

based on PLANSEE online catalogue, September 2011, including discount

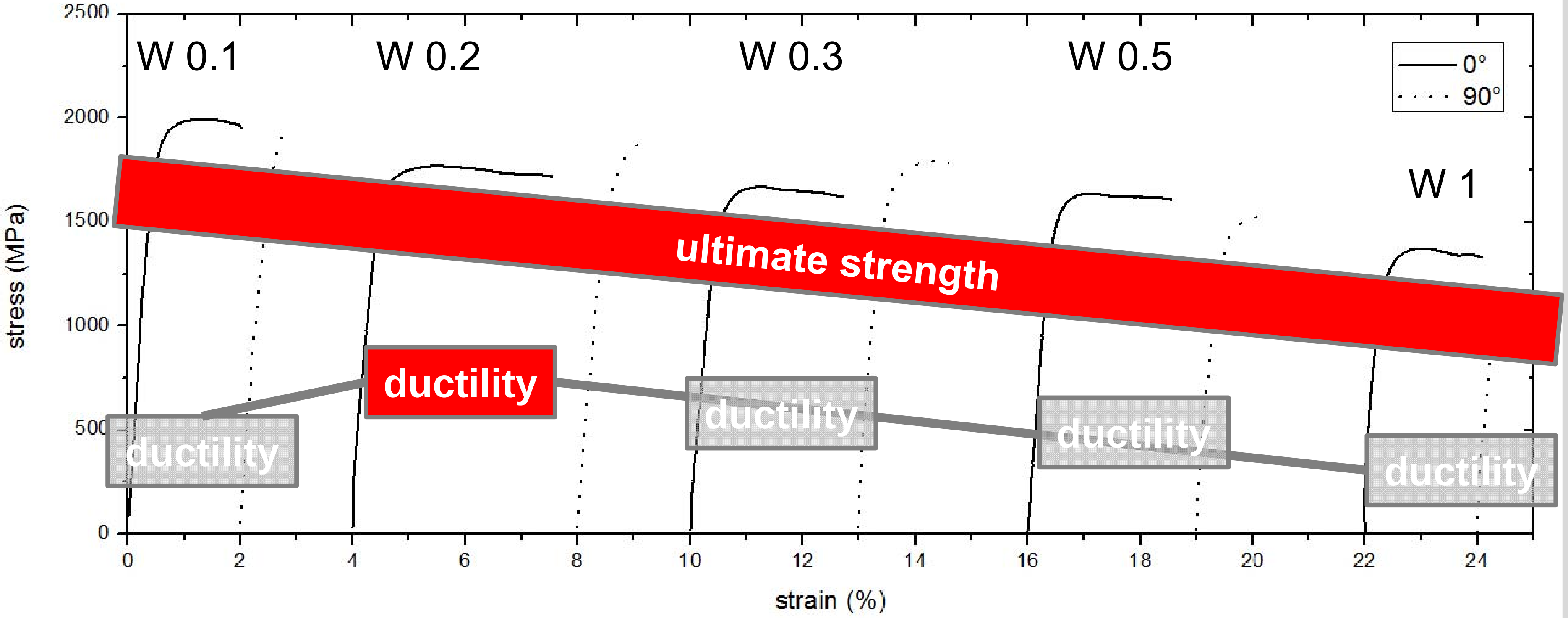
TUNGSTEN COMPOSITES (LAMINATES)

W Laminate Material



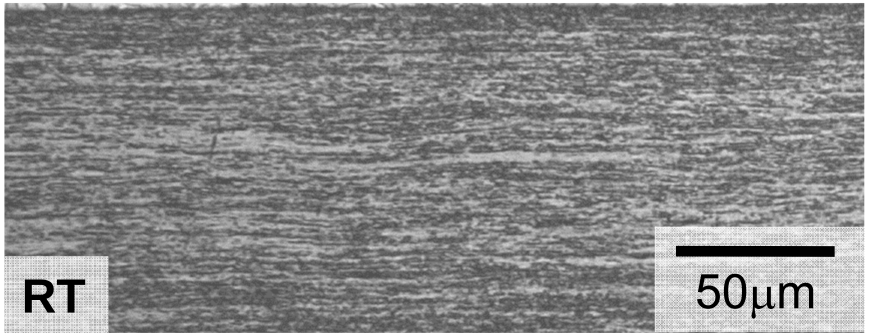
→ **J. Reiser, KIT, 2010-2011**

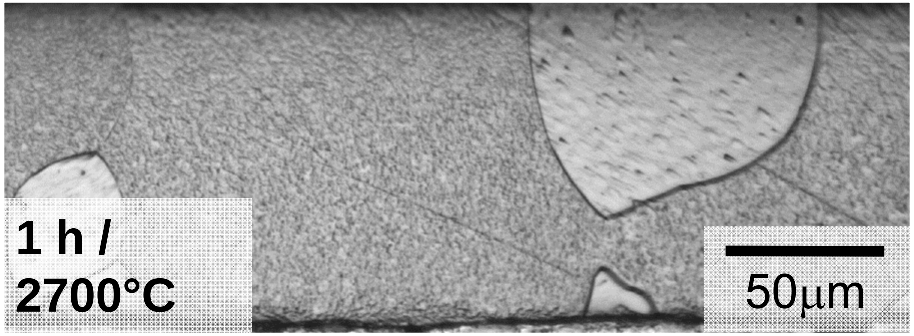
TENSILE TEST PROPERTIES: W



- assumption: optimum ductility at 0.2 mm thickness

MICROSTRUCTURE OF W-FOIL, 0.1 MM





W 0.1 mm, as-received

texture: {100} <011>

grain size: 0.5 x 3 x 15 μm^3

disl. density: high

ductility: **edge,**
small grains

W 0.1 mm, annealed

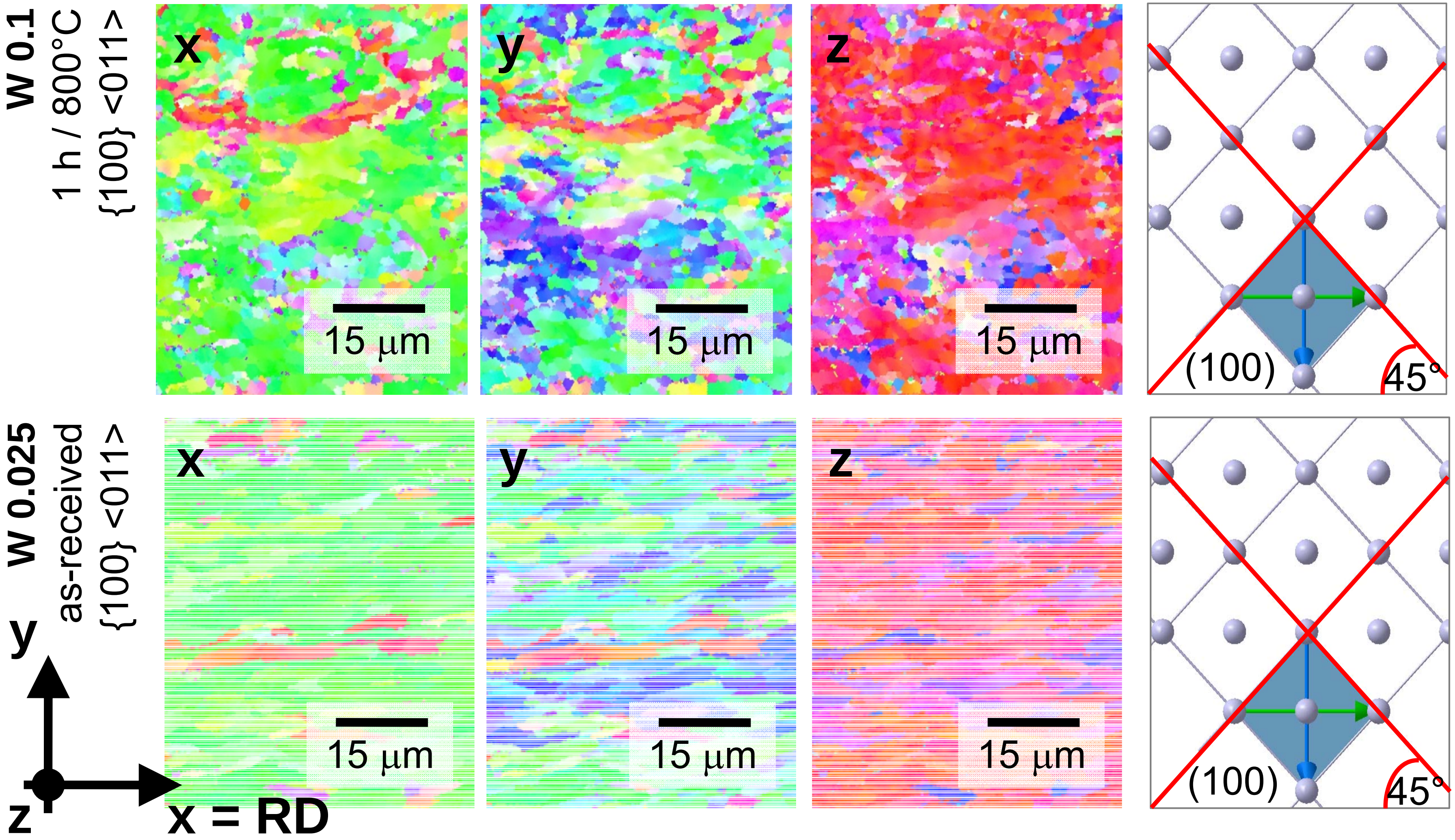
texture: {100} <011>

grain size: 100 x 100 x 100 μm^3

disl. density: low

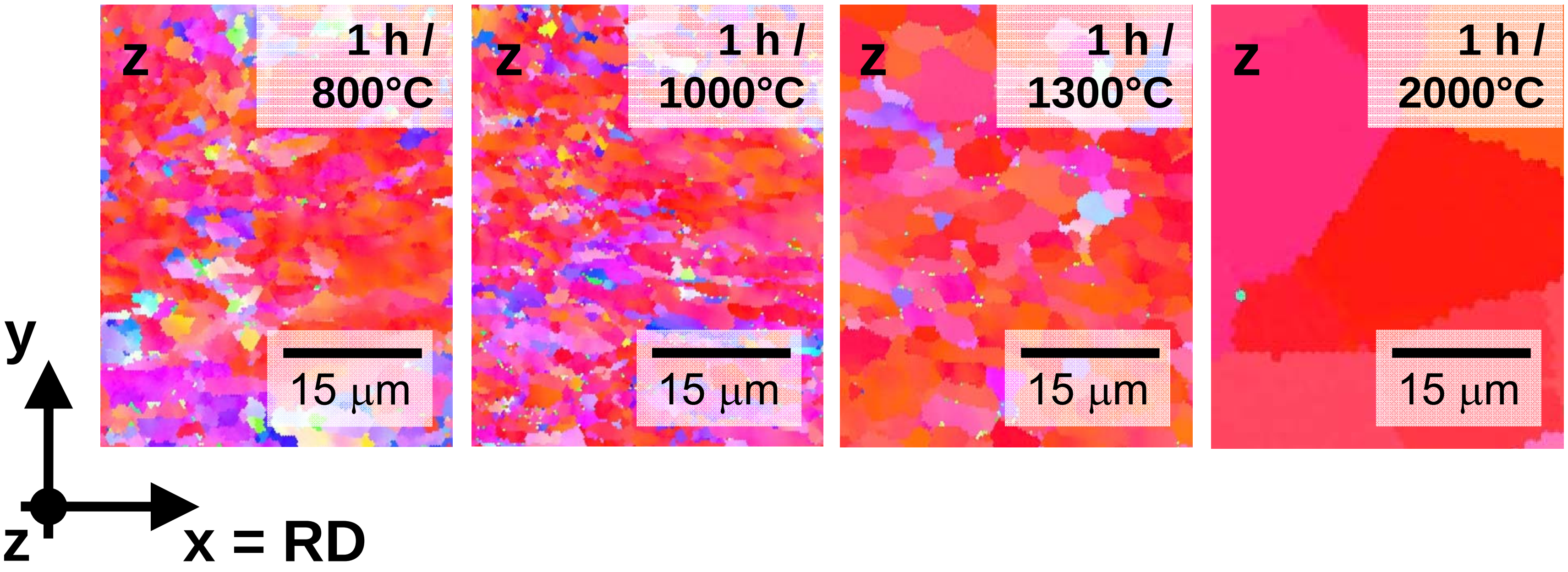
ductility: **screw,**
disl. annihil.

TEXTURE ANALYSIS: W FOIL AS RECEIVED



David Armstrong, Oxford, 2011

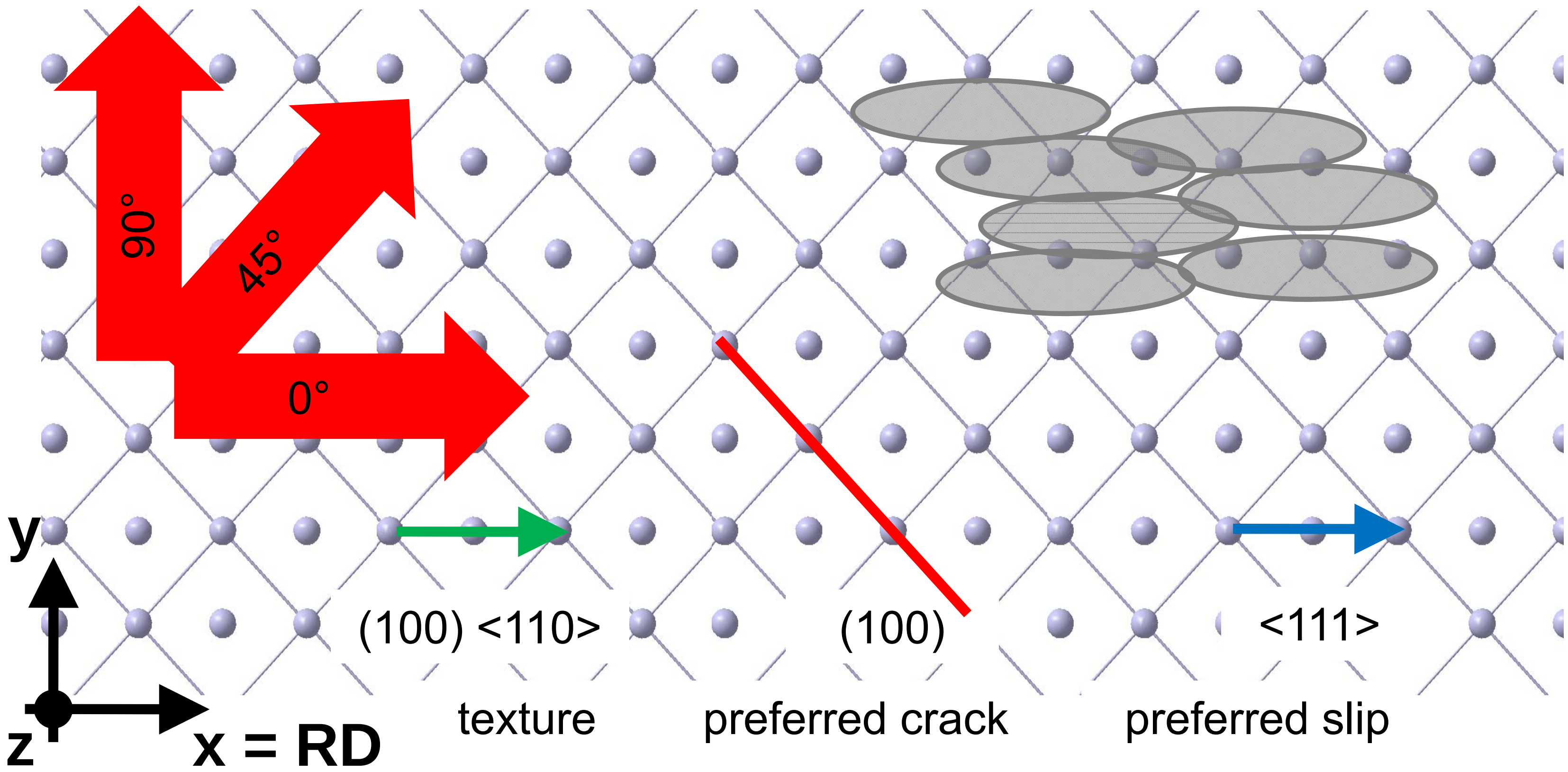
TEXTURE ANALYSIS: W FOIL AFTER HT



D. E. J. Armstrong, Oxford, 2011

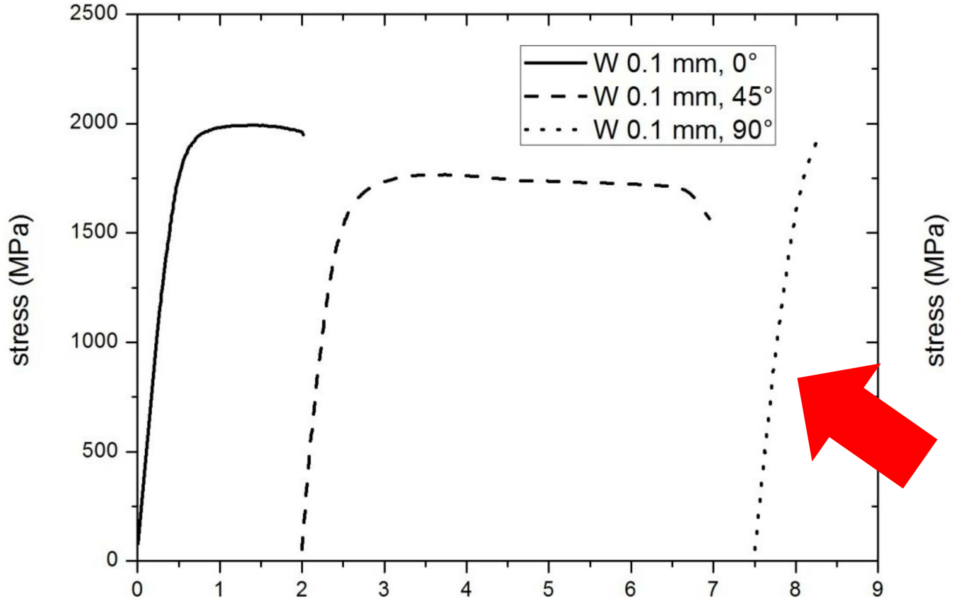
TENSILE TEST PROPERTIES: W 0.1 MM

- texture: (100) <110>
- preferred slip: <111>
- W foil, 0.1 mm, grain size: 0.5 x 3 x 15 μm^3

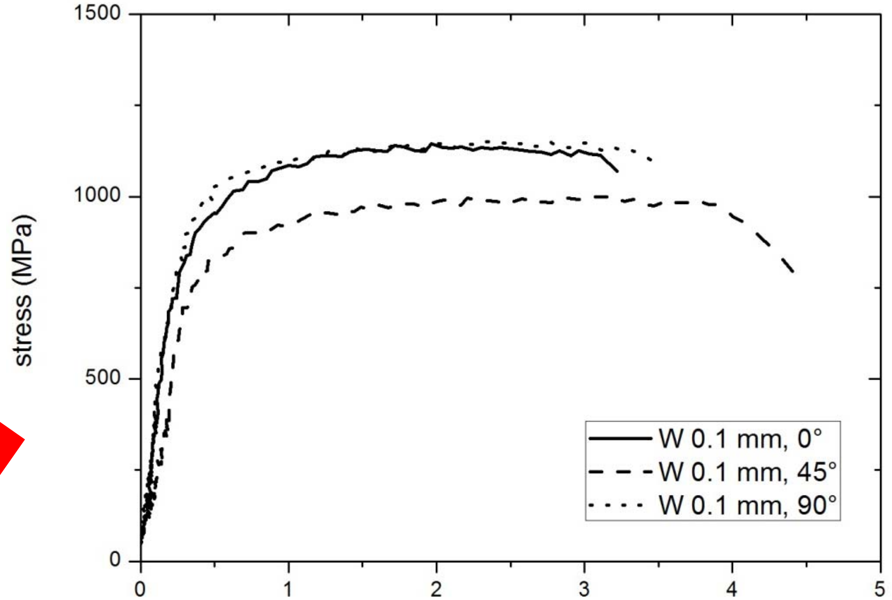


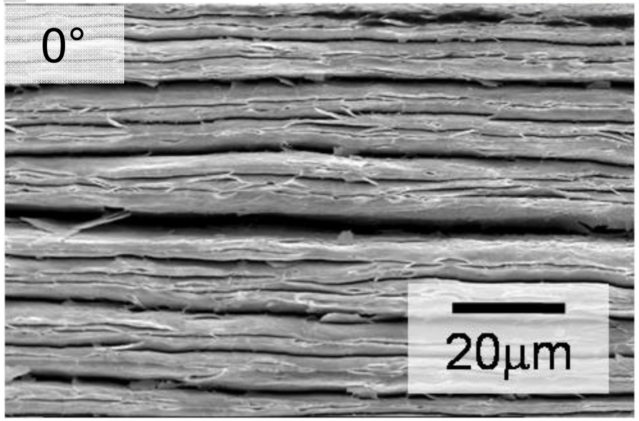
TENSILE TEST PROPERTIES: W 0.1 MM

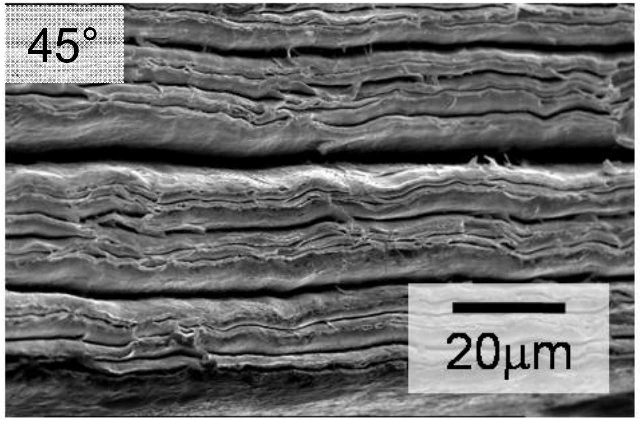
W foil, 0.1 mm, RT

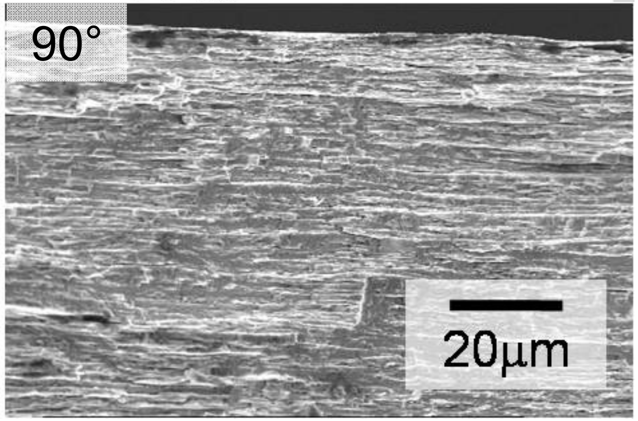


W foil, 0.1 mm, 600°C

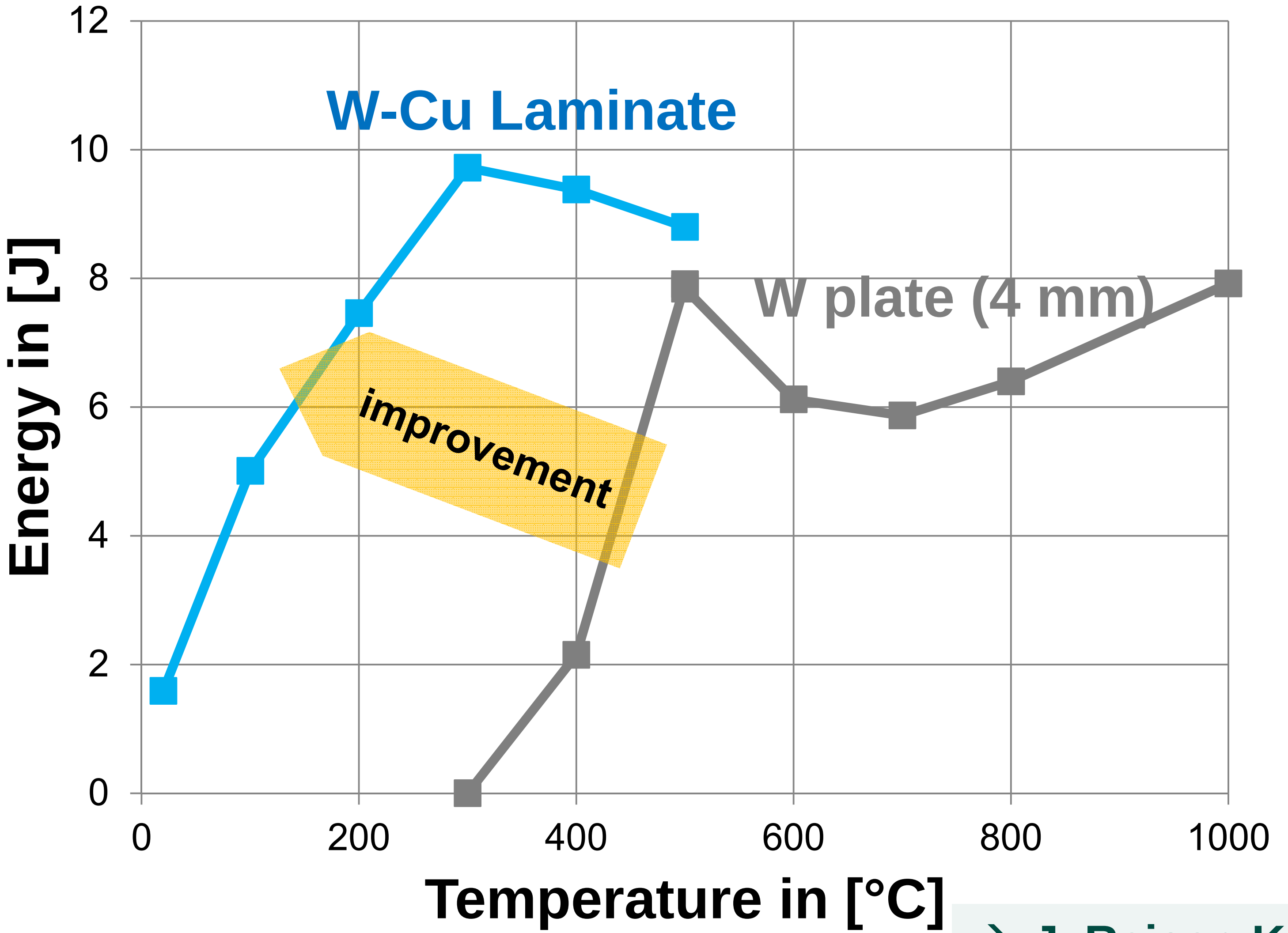






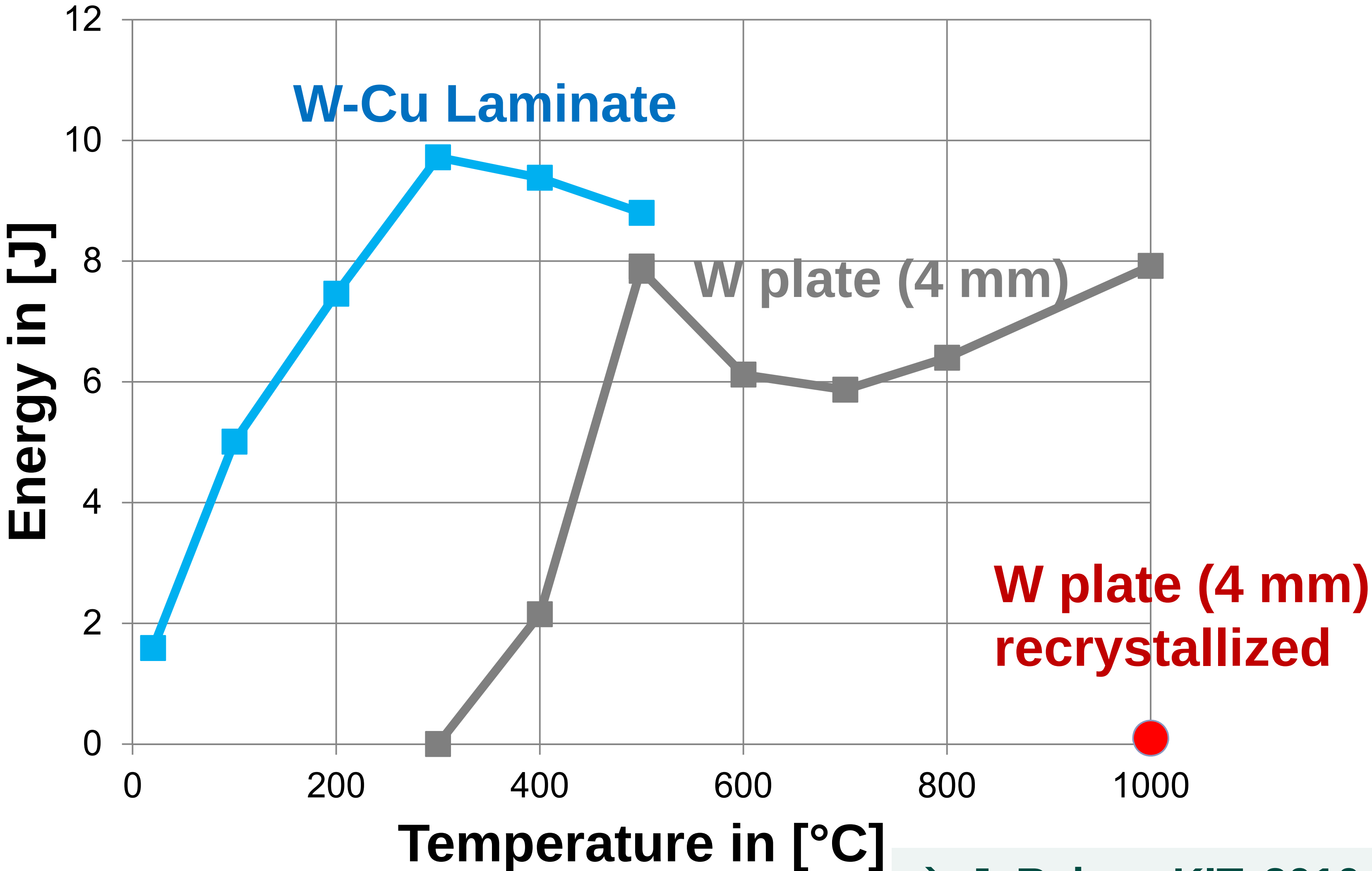


PATH FORWARD → TUNGSTEN LAMINATES



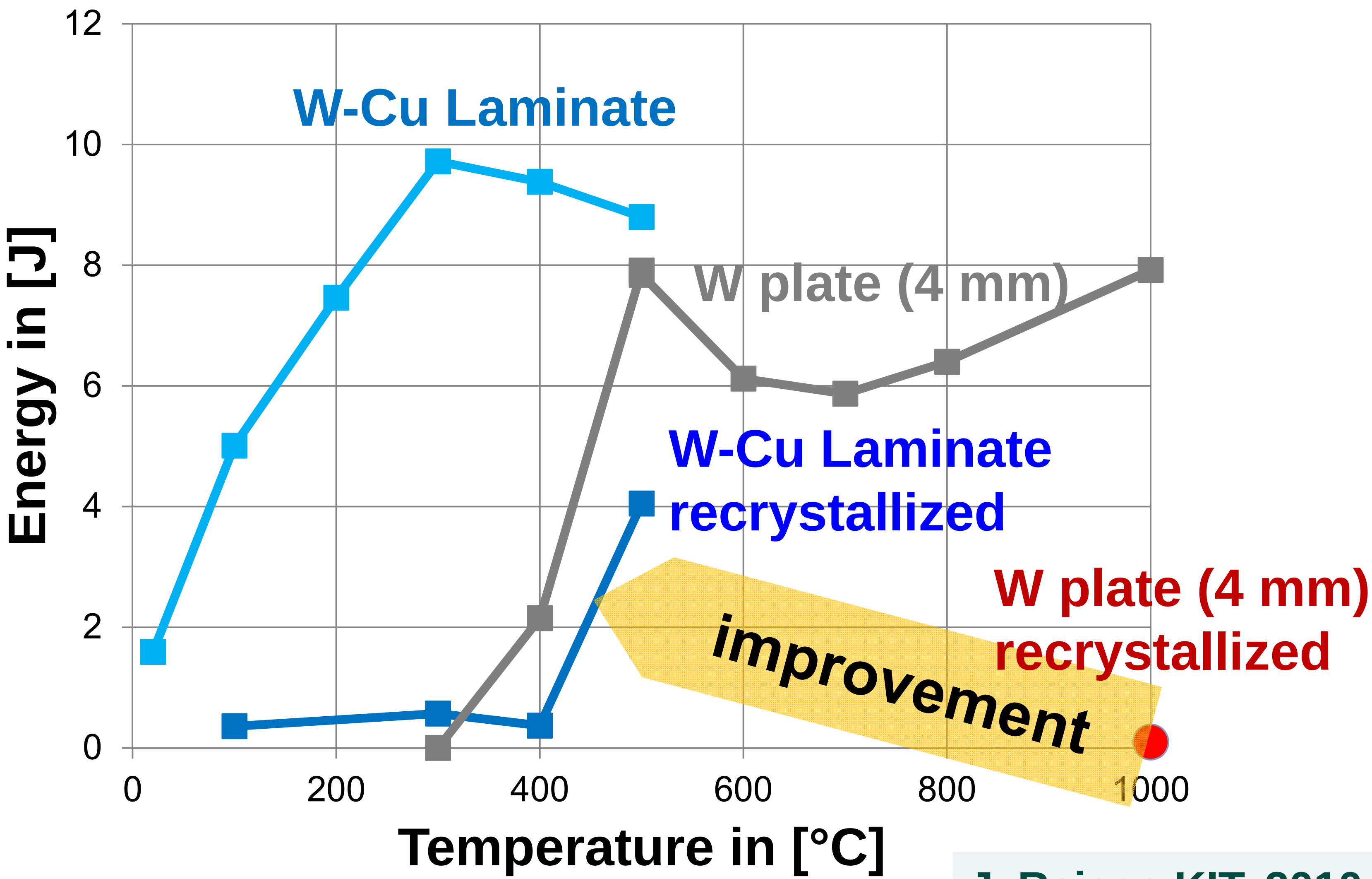
→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN LAMINATES



→ J. Reiser, KIT, 2010-2011

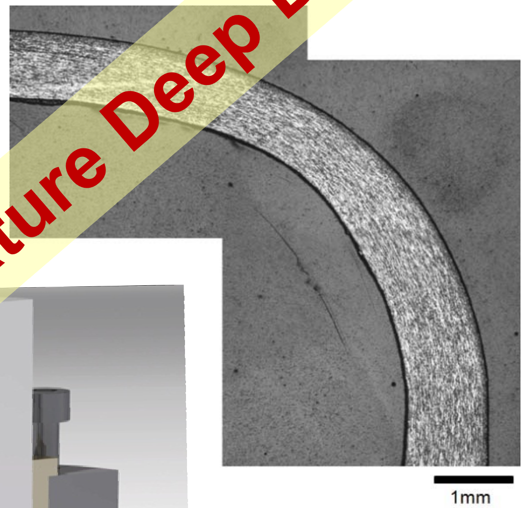
Path Forward → Tungsten Laminates

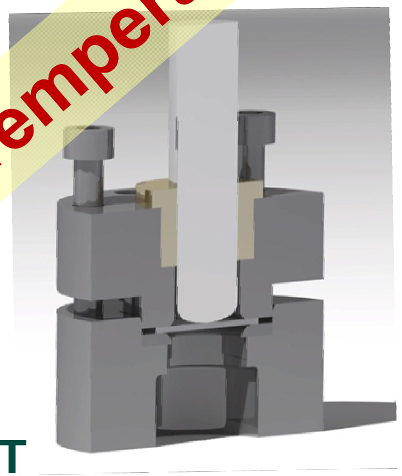


J. Reiser, KIT, 2010-2011

MANUFACTURING

Machining: Turning, Milling, Grinding, ...

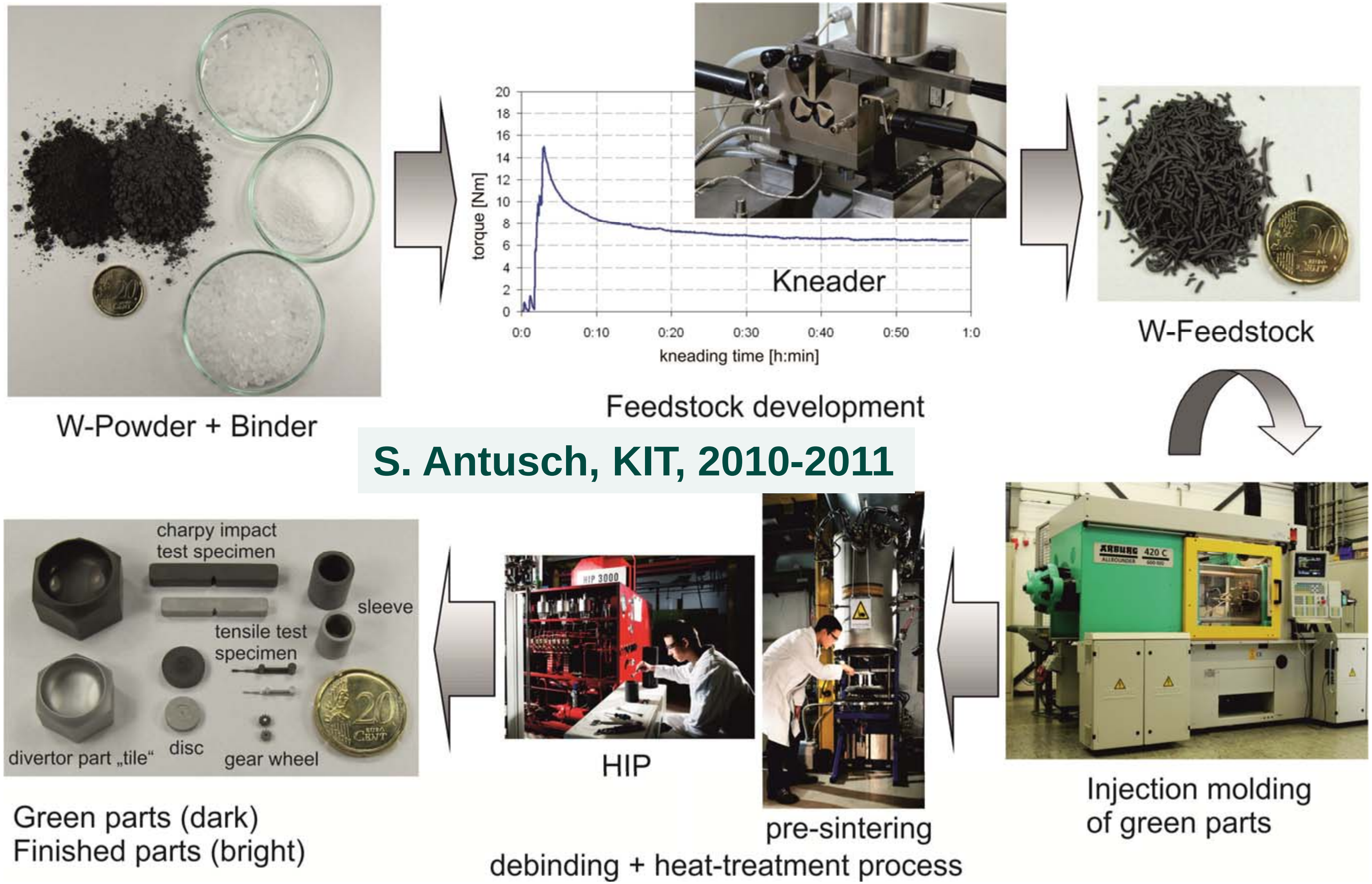




High Temperature Deep Drawing

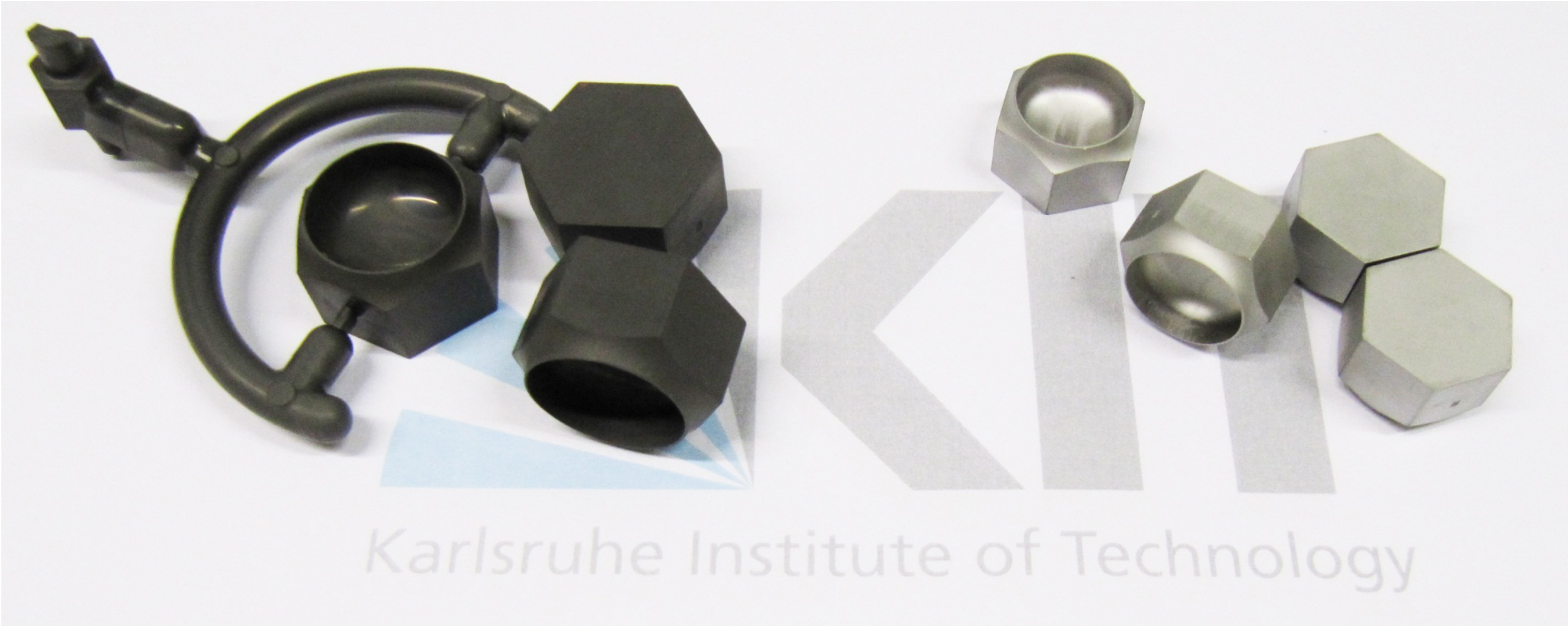
P. Norajitra, J. Reiser, S. Baumgärtner *et al.*, KIT

POWDER INJECTION MOULDING (PIM)



PIM Process for Tungsten Parts

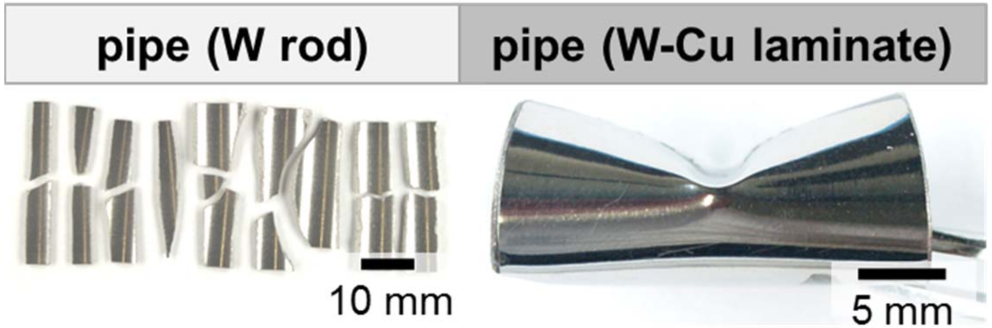
→ near net-shape mass fabrication of tungsten parts

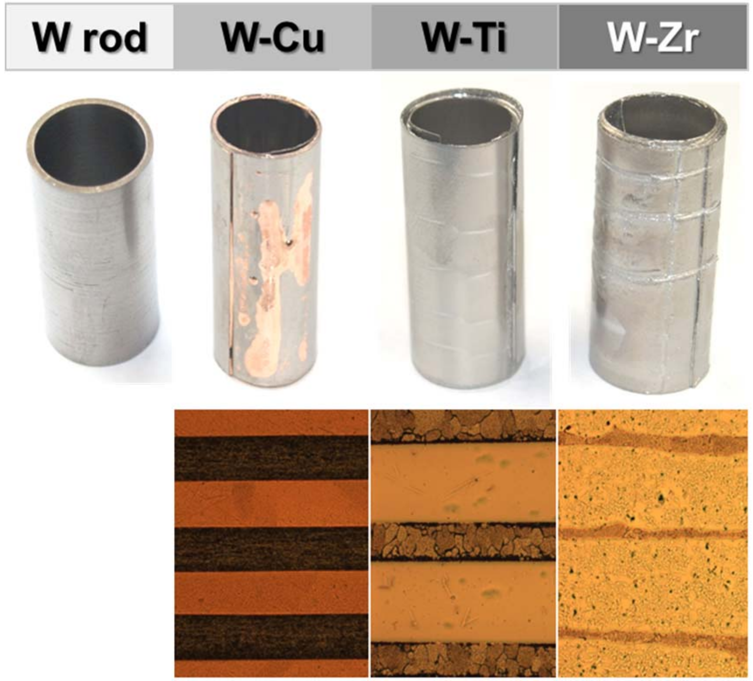


green parts → **debinding + heat-treatment-process** → **finished parts**

S. Antusch, KIT, 2010-2011

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

J. Reiser *et al.*, KIT, 2011

JOINING

IMPORTANT: We have to consider joints for STRUCTURAL applications!!!
Joining W tiles to W timbles is NOT considered as structural application!

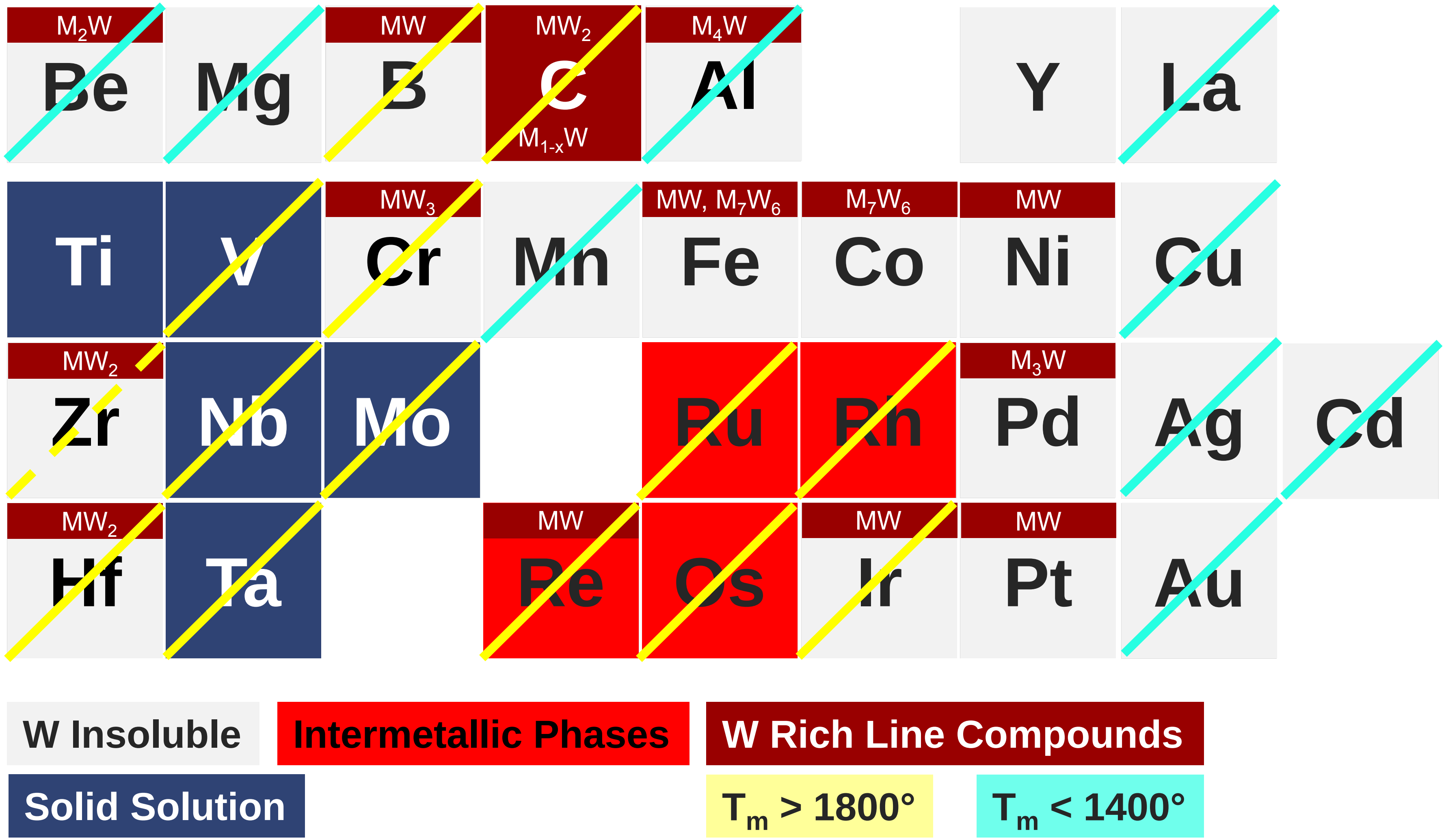
Brazing Material for W-W Joints

- Brazing temperature must be >>900-1200 °C (operating temp.)
- Brazing temperature must be <1800 °C → Grain growth
- Formation of brittle compounds cannot be tolerated

Brazing Material for W-Steel Joints

- Brazing temperature <1100 °C → Grain growth (in steel)
- Brazing temperature must be >>550-750 °C (operating temp.)
- Formation of brittle compounds cannot be tolerated

BRAZING W→W



M2W
Be
Mg
MW
B
MW2
C
M1-xW
M4W
Al
Y
La
Ti
V
MW3
Cr
Mn
MW, M7W6
Fe
M7W6
Co
MW
Ni
Cu
MW2
Zr
Nb
Mo
Ru
Rh
M3W
Pd
Ag
Cd
MW2
Hf
Ta
MW
Re
Os
MW
Ir
MW
Pt
Au
W Insoluble
Intermetallic Phases
W Rich Line Compounds
Solid Solution
Tm > 1800°
Tm < 1400°

BRAZING MATERIALS, W→W

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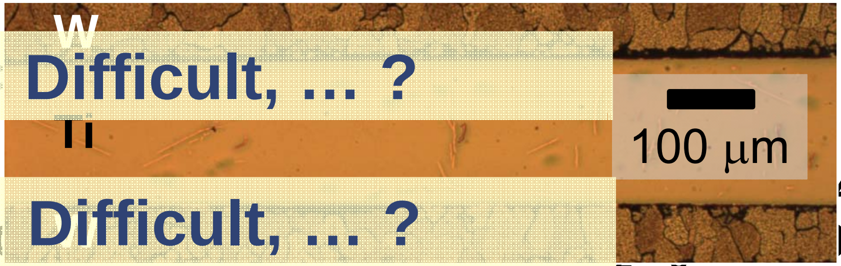
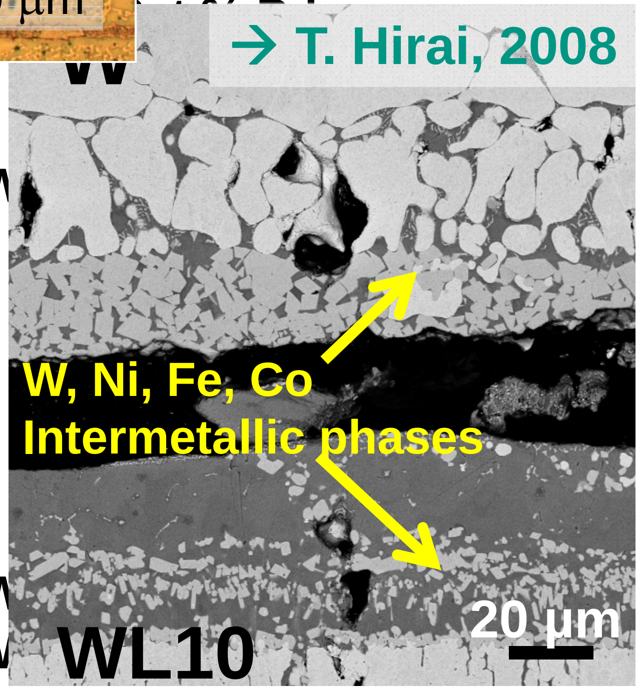
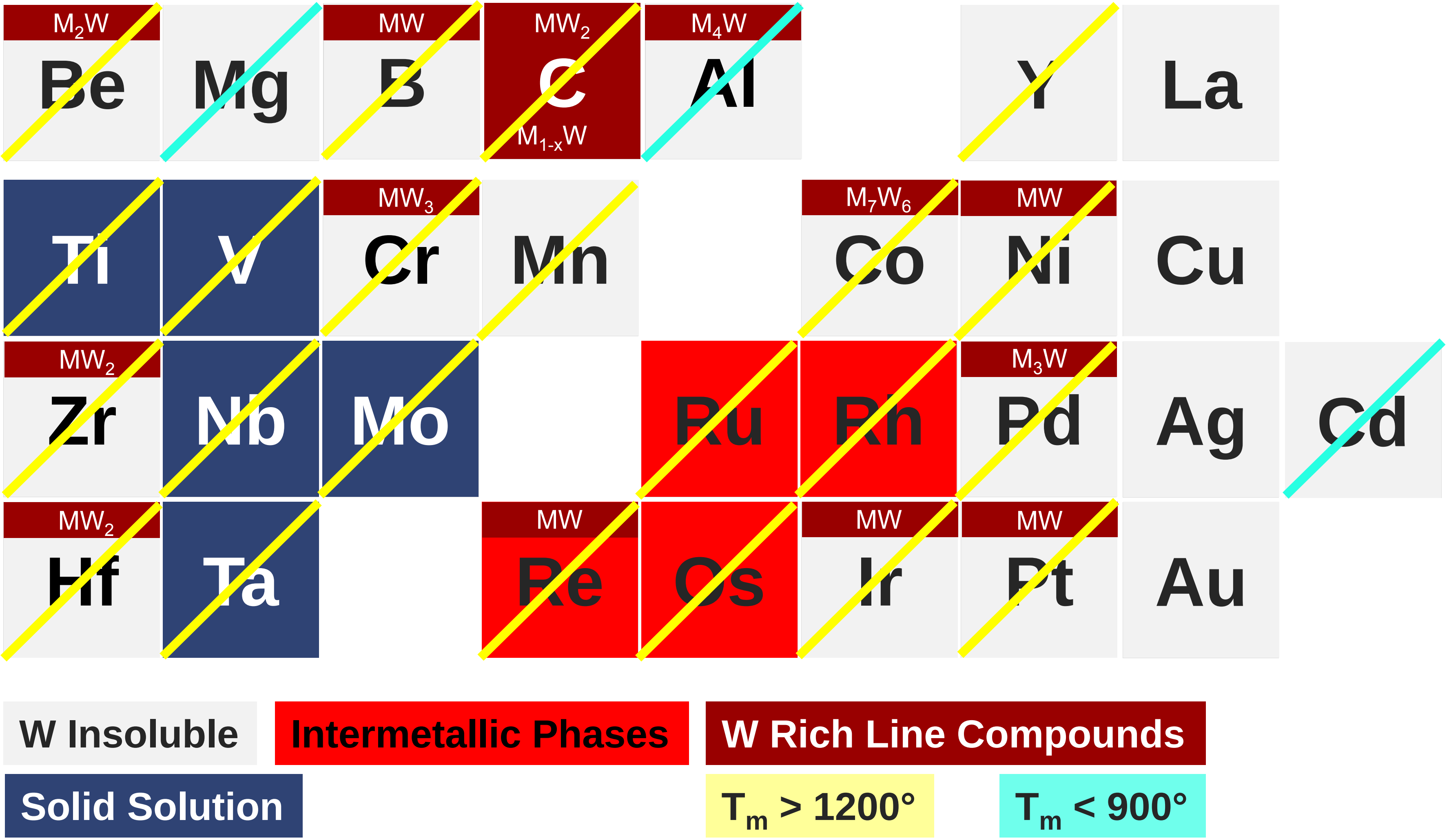
1670°C	Ti	<740°C	Difficult, … ?
1520°C	Y	Strong … <1570°C … 40°C / …00°C: alpha-Y + Y_2O_3	Difficult, … ?
1850°C	Zr	<2160°C W→ ZrW_2 / <1700°C … % intermetallic ZrW_2 / <860°C Zr→ ZrW_2 … tallic ZrW_2	Brittle Joint
1550°C	Pd	<1800°C W→ ZrW_2 / <900°C: intermetallic Pd_3W ???	Expensive, … ?
1770°C	Pt	<24…°C … phase Pt_3W	Very expensive, … ?
1540°C	Fe	<1700°C: µ phase $Fe_7W_6(Fe,W)_4$ <1000°C: Laves phase Fe_2W	
1500°C	Co	<1700°C: µ phase $Co_7W_6(Co,W)_4$ <1000°C: Laves phase Co_3W	
1450°C	Ni	<1000°C: peritectoid intermetallics NiW… <950°C: peritectoid intermetallic Ni_4W	

Brittle Joints



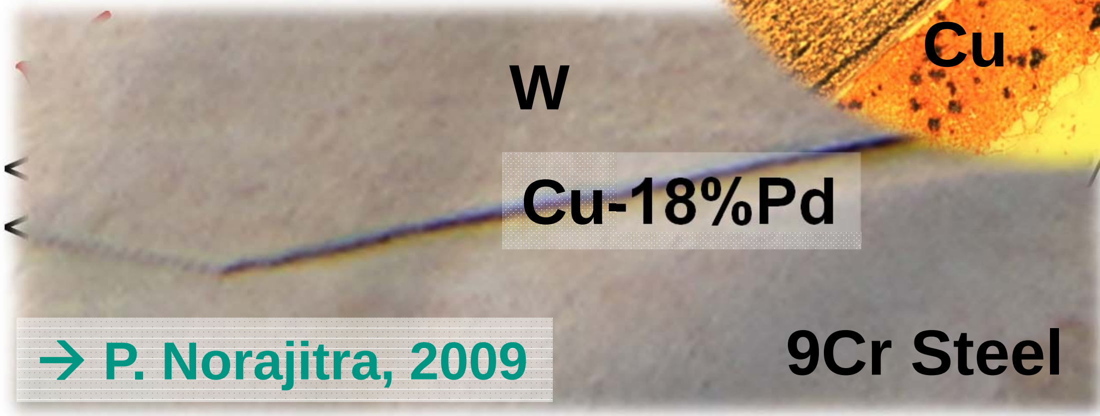


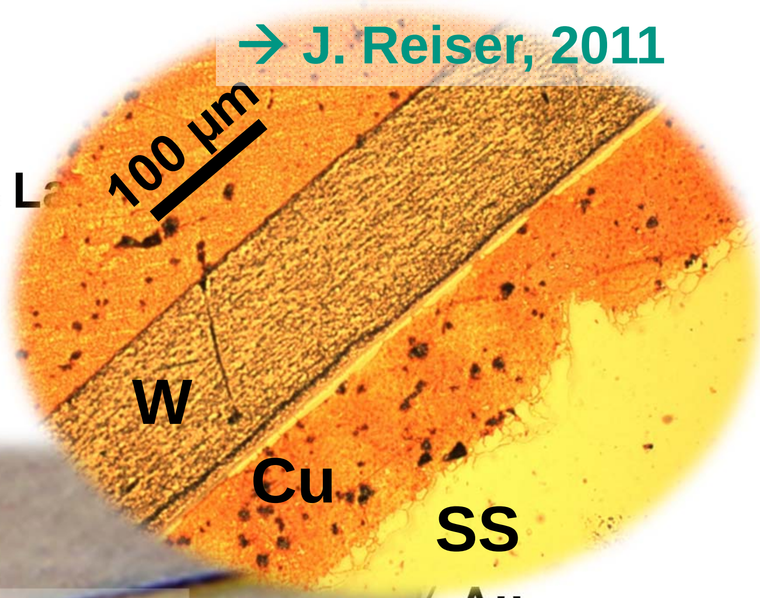
BRAZING W→STEEL



BRAZING MATERIALS, W→STEEL

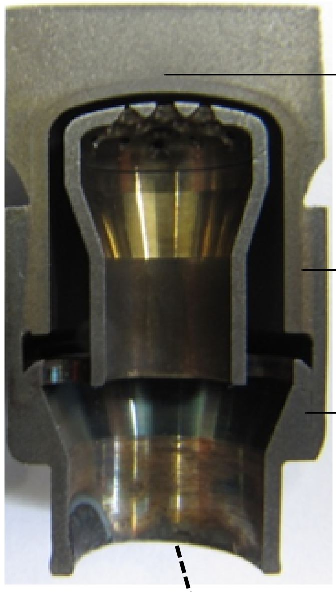
920°C	La	<790°C: eutecticum → 93at.% La
1080°C	Cu	✓ … but strength ???
960°C	Ag	
1060°C	Au	% Au





CONCLUSION: Copper has to be used as sealing rather than as a braze material !!!

ASSEMBLY & TESTING

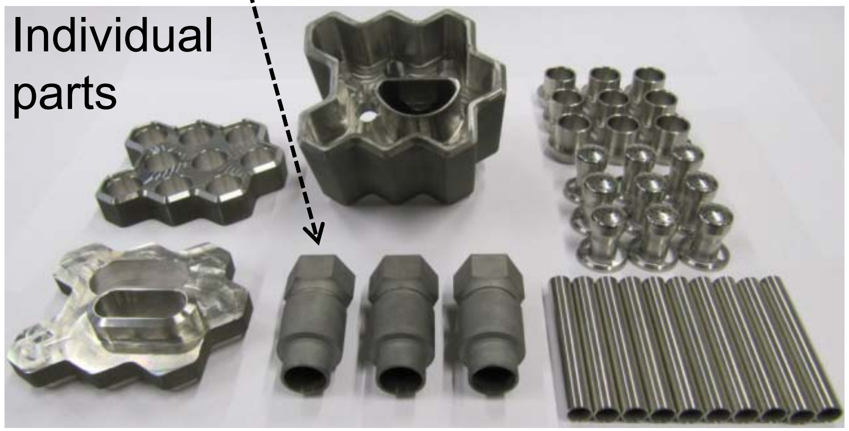


W-WL10 joint brazed with PdNi

WL10-steel joint brazed with CuPd

TIG seal welding (steel-steel joint)

1-finger modules

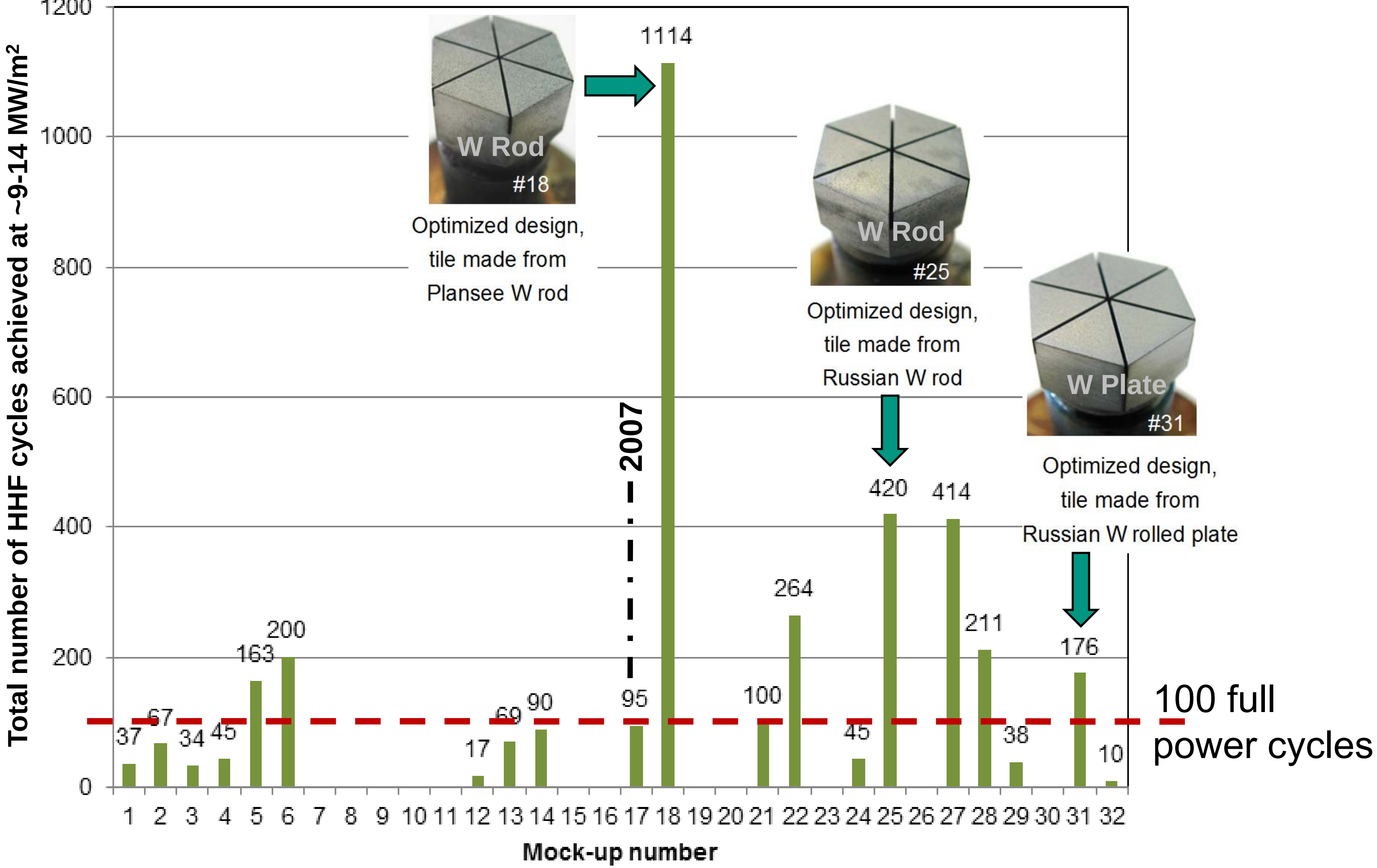


9-finger module (W) for high heat flux (HHF) tests in Efremov

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

P. Norajitra *et al.*

HIGH HEAT FLUX TESTS WITH 1-FINGER MODULES

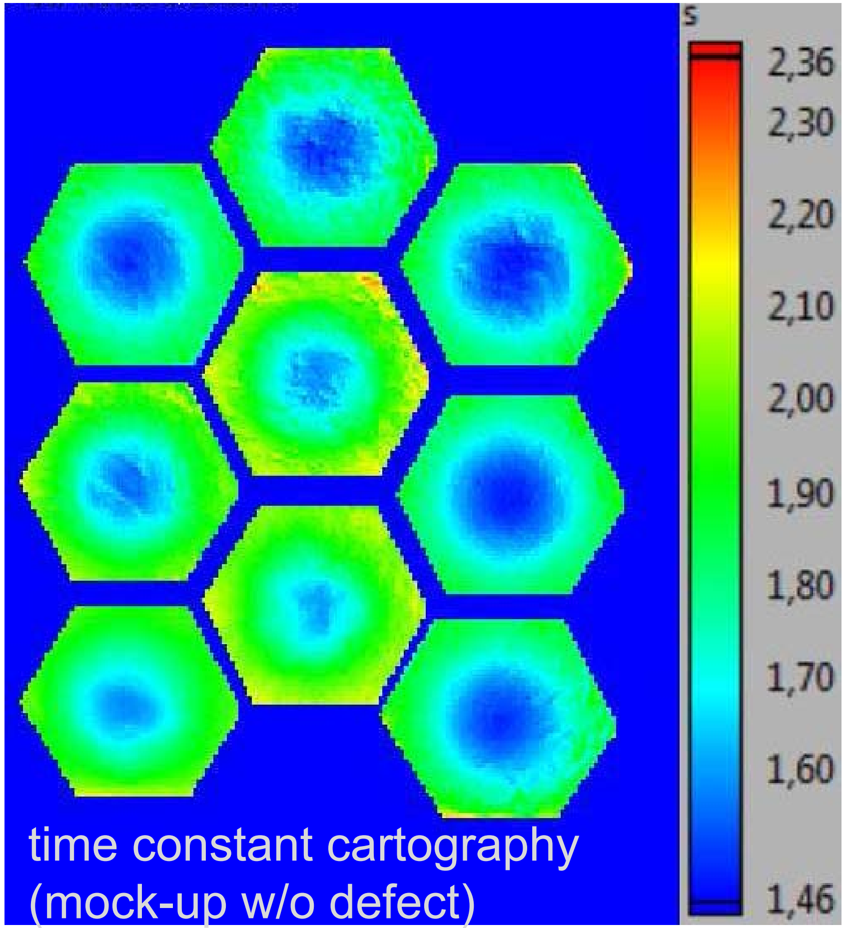


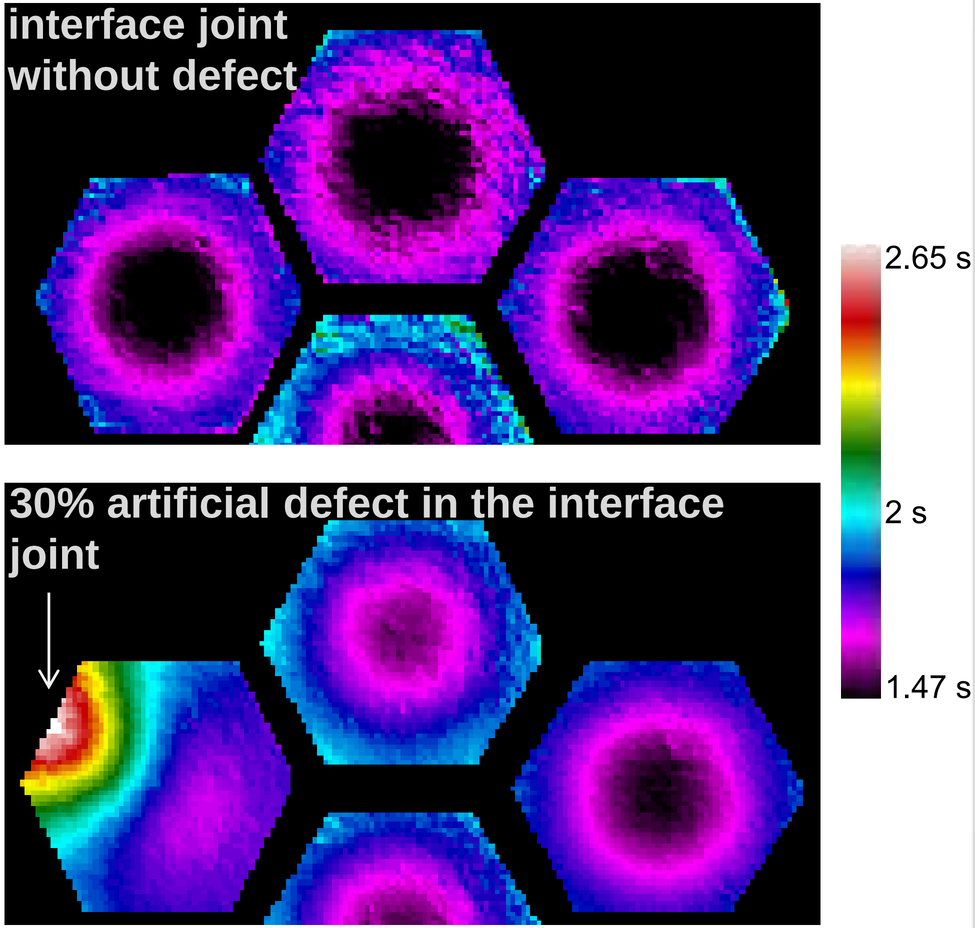
P. Norajitra *et al.*

NON-DESTRUCTIVE EXAMINATION

Karlsruhe Institute of Technology

Infrared thermography in the SATIR facility at CEA





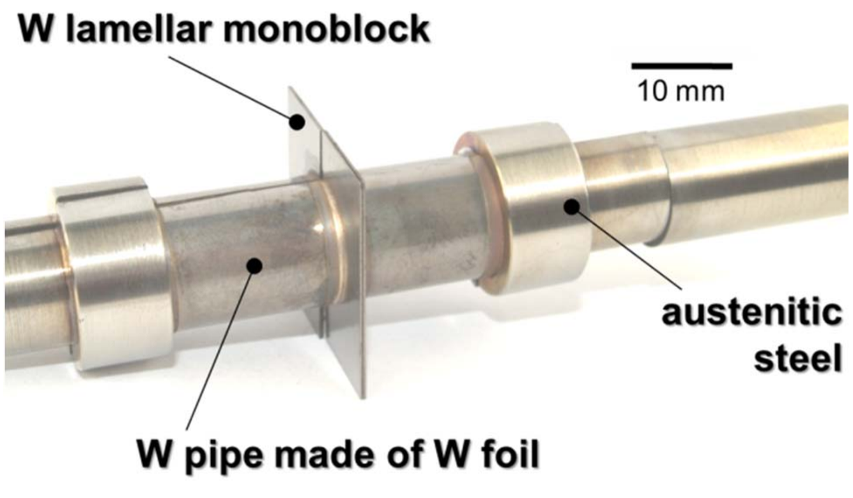
Homogeneous thermal response for each finger and between fingers

M. Richou, CEA

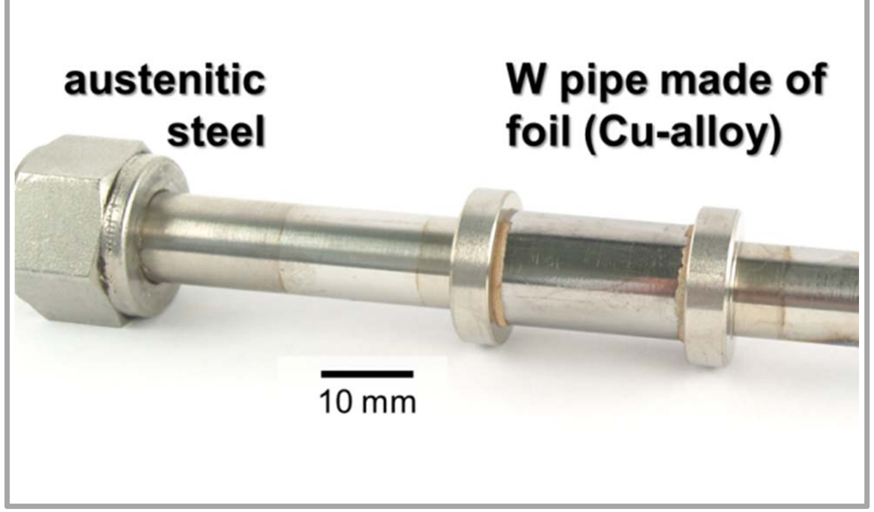
W LAMINATE PIPE TESTING

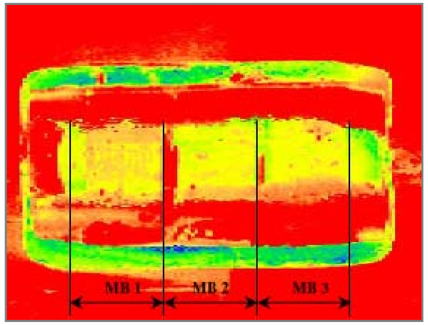
Karlsruhe Institute of Technology

Fabrication studies



Pressurized pipe tests



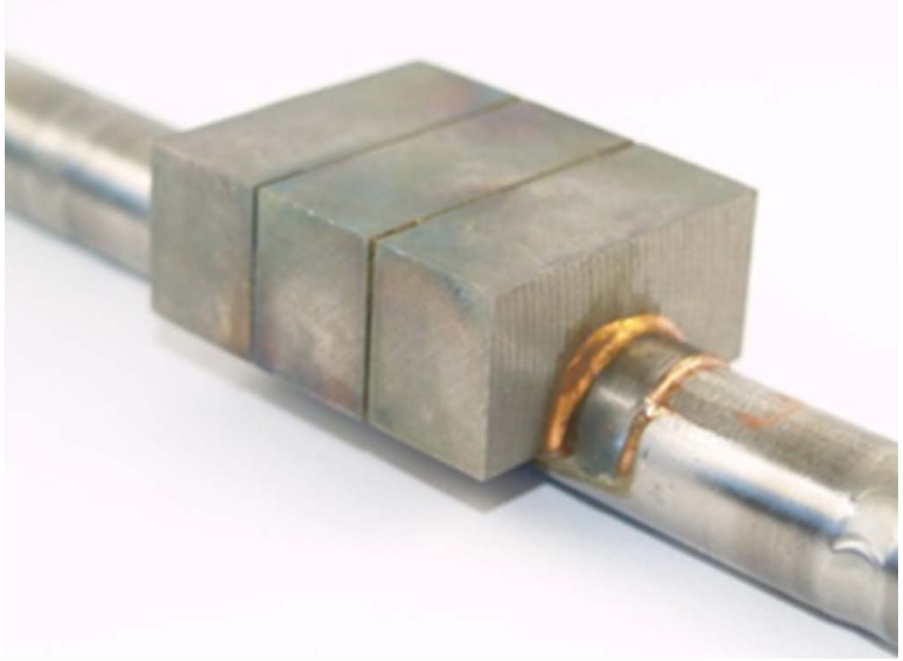


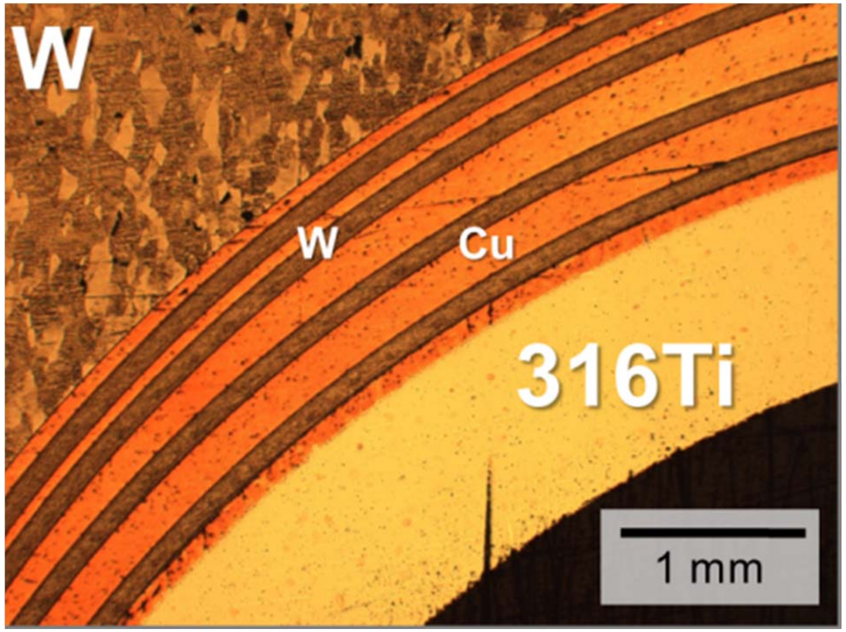
non-destructive testing,
PLANSEE SE

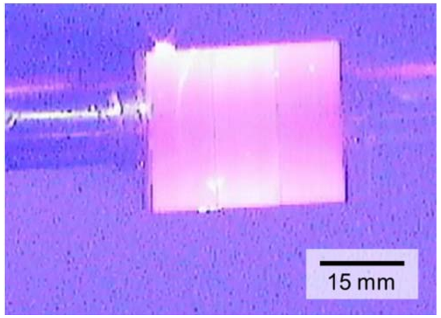
GLADIS, IPP, Garching

KEY EXPERIMENT FOR WATER COOLING

Karlsruhe Institute of Technology



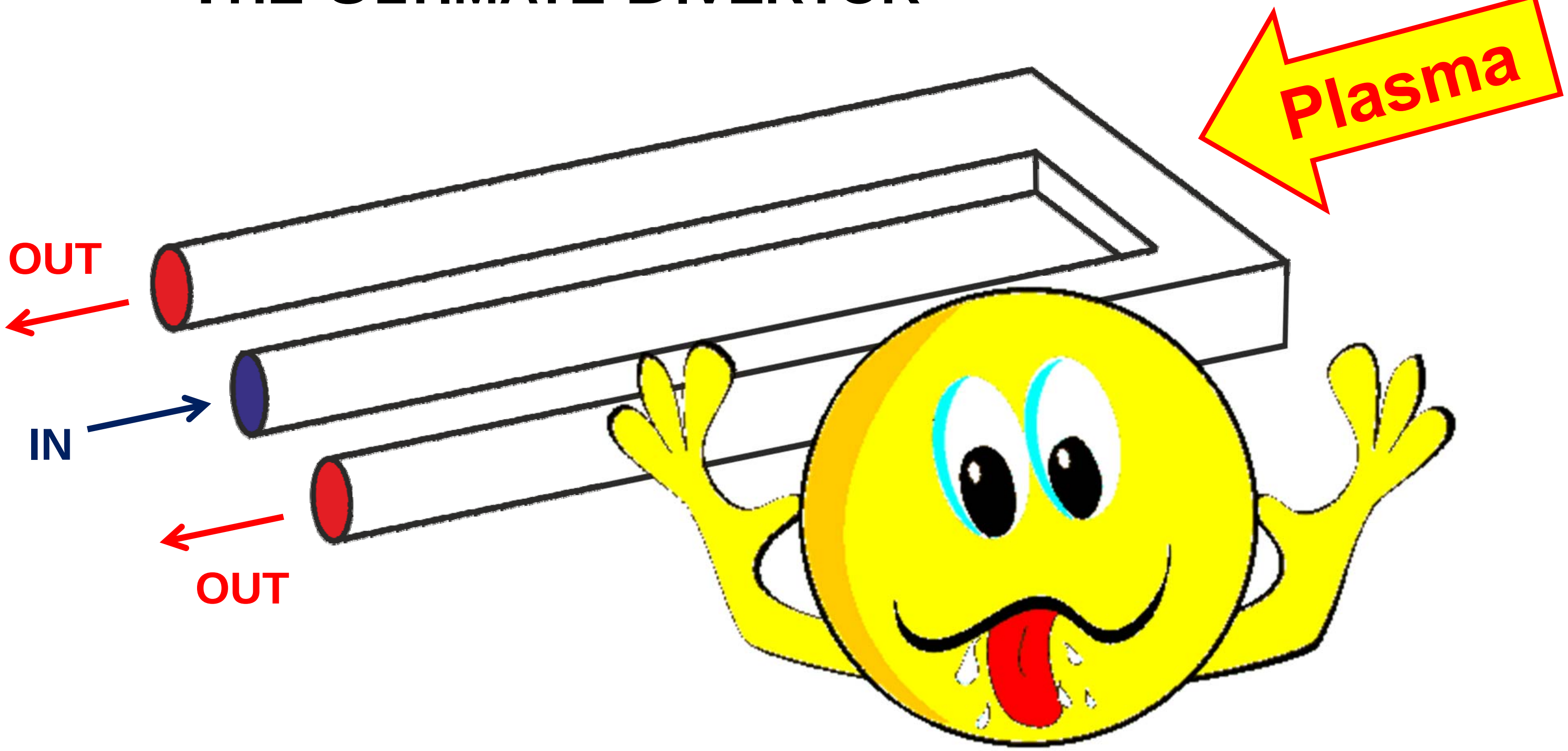




Greuner (IPP), Böswirth (IPP), Reiser (KIT), 2012

- 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**

THE ULTIMATE DIVERTOR



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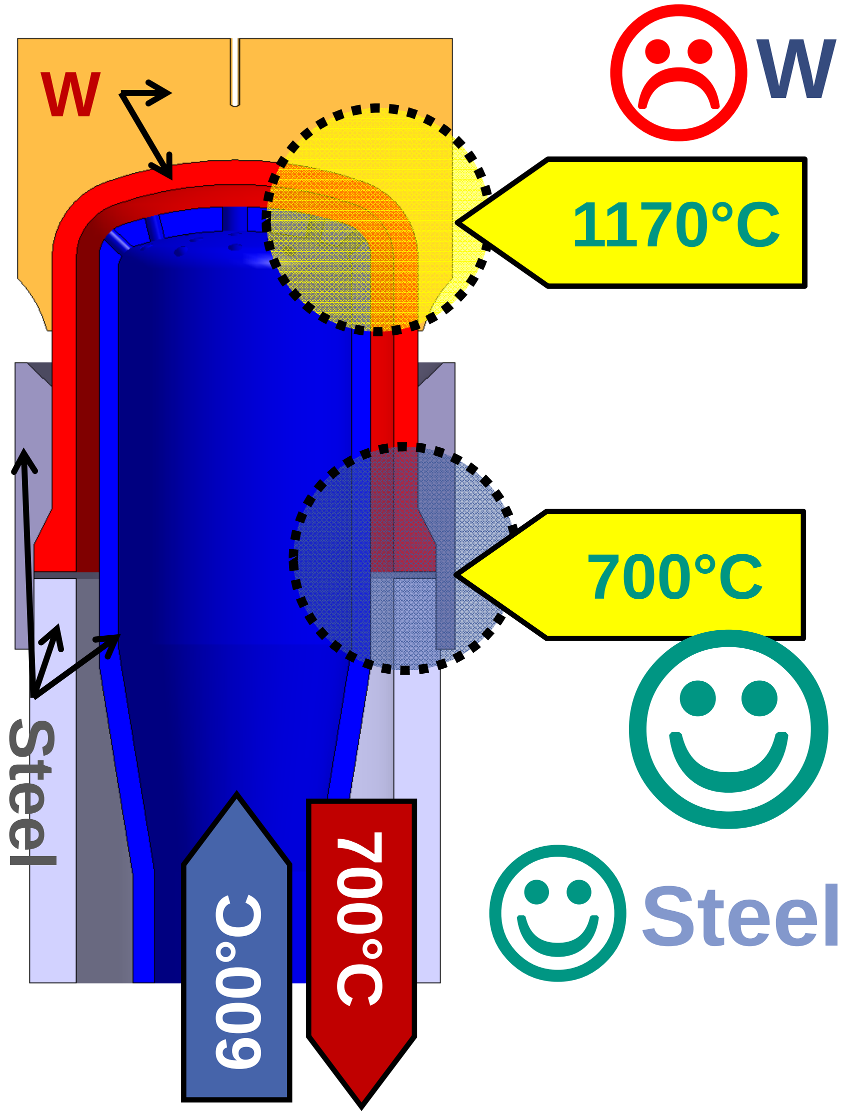
DESIGN ASSESSMENT & CONCLUSIONS

- Assess the three helium cooled divertor concepts (finger, plate, pipe design studies) w.r.t. to swelling, embrittlement, and strength of the used structural materials. Assess also the joints needed in each design.
- Prepare conclusions for the necessary future steps in R&D for each divertor concept.
- Propose possibilities to increase the thermal efficiency of the design used in the “key experiment for a water cooled divertor”. Or propose better WC DEMO divertor concepts.

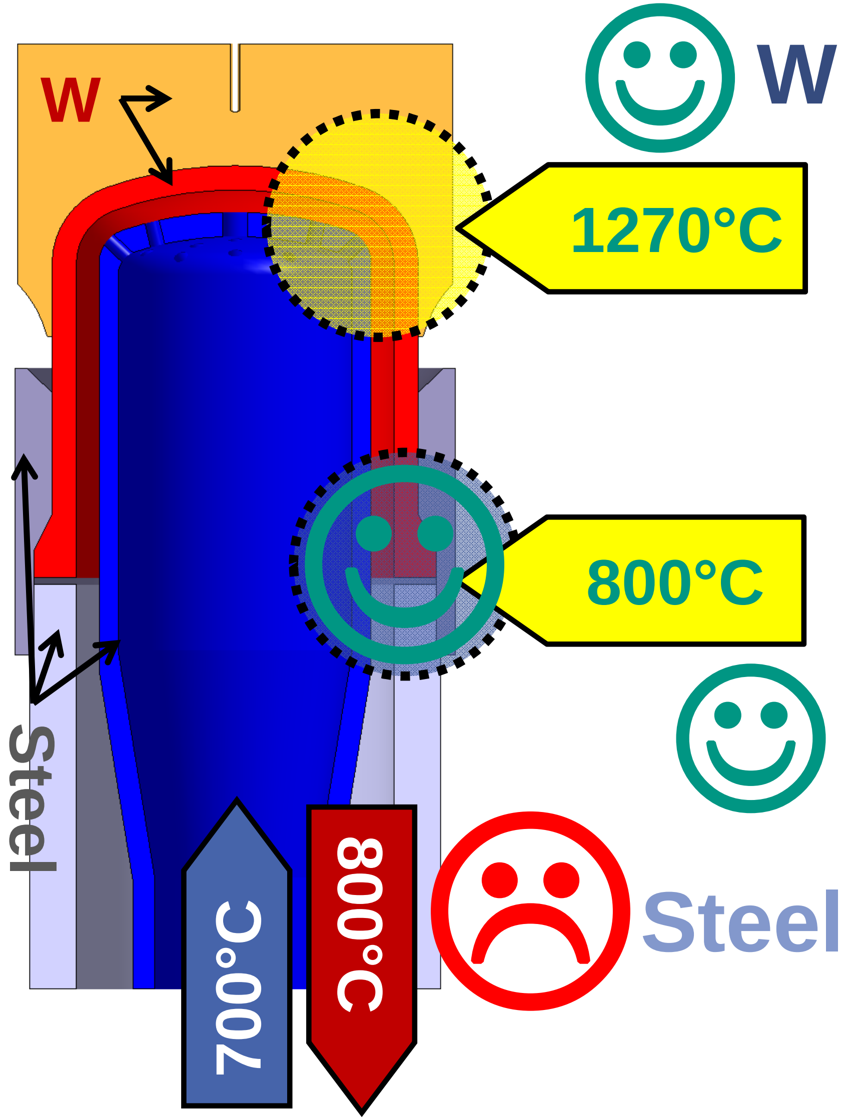
MATERIALS / DESIGN WINDOW → FINGER



Oxidation	→	OK
Swelling ~3%	→	?
Embrittlement	→	OK
Grain Growth	→	? (ODS)

Swelling ~5%	→	?
Embrittlement	→	NO GO (?)
Brazing (Cu)	→	OK (...)
Embrittlement	→	OK
Strength, ...	→	? (ODS)

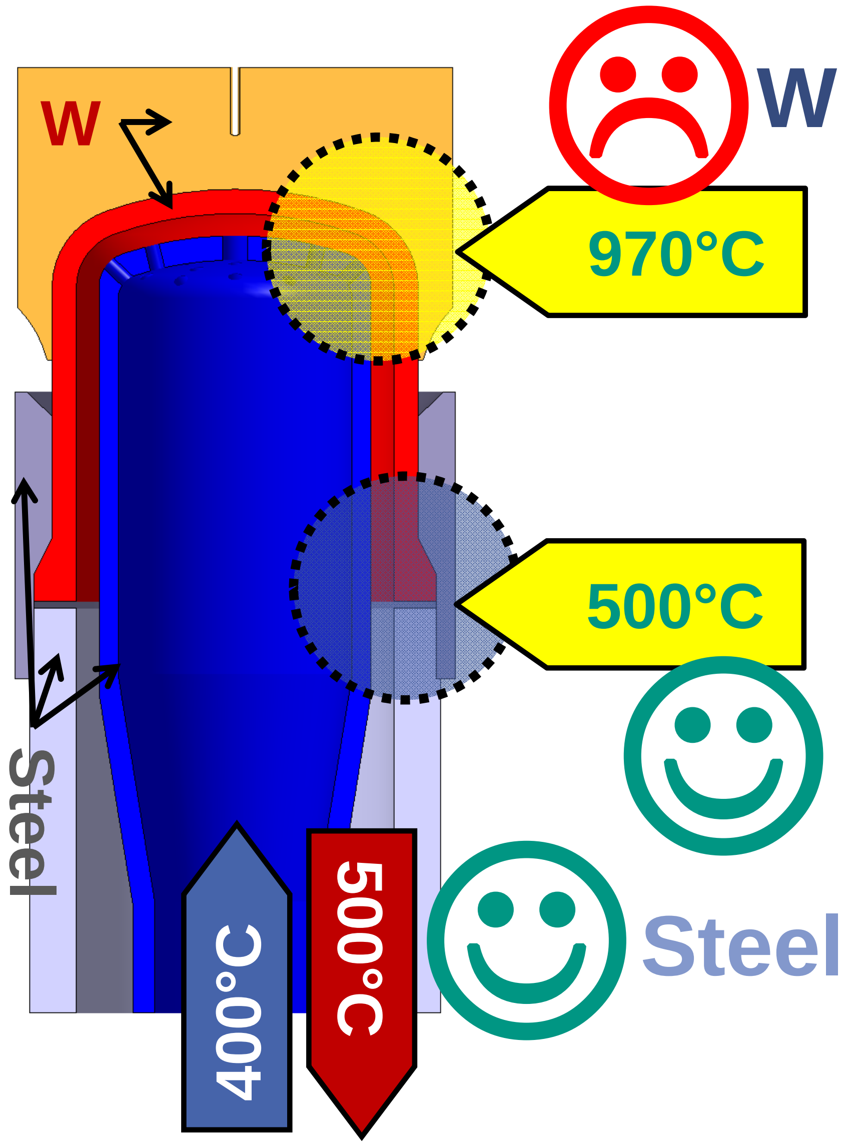
MATERIALS / DESIGN WINDOW → FINGER



Oxidation →	OK
Swelling ~3% →	?
Embrittlement →	OK
Grain Growth →	ODS

Swelling ~5% →	?
Embrittlement →	OK (tbc)
Brazing (Cu) →	OK (…)
Embrittlement →	OK
Strength, … →	ODS ???

Materials / Design Window → Finger



Oxidation	→	OK
Swelling <3%	→	OK (?)
Embrittlement	→	OK
Grain Growth	→	OK

Swelling <2%	→	OK (?)
Embrittlement	→	NO GO
Brazing (Cu)	→	OK (…)
Embrittlement	→	OK
Strength, …	→	OK

Lessons learned from the HEMJ development

- 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 an acceptable low thermal stress distribution level.
- Mastering heat fluxes in the order of 10 MW/m² for long periods is only possible by **jet impingement** cooling.
- There is still **no structural W material available** which meets all design requirements. Tungsten composite materials might be the key for alternative designs.
- It is known that all 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.

CONCLUSIONS FOR THE HEMJ DEVELOPMENT

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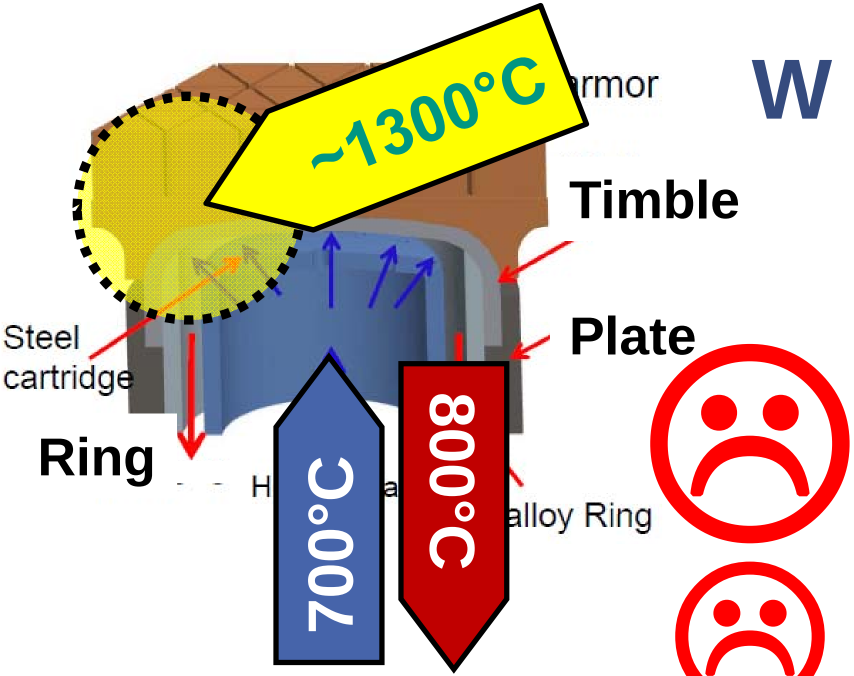
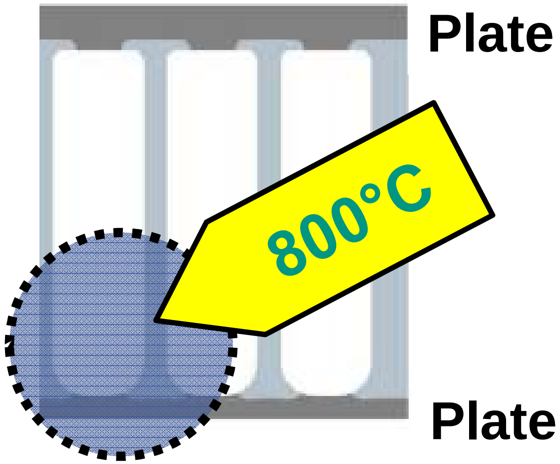
Based on present knowledge on neutron-induced embrittlement of tungsten, an operating temperature of **at least 800 °C** is strongly recommended to mitigate the risk of embrittlement. For the HEMJ concept the upper **limit is 700 °C**, that is, embrittlement of some of the structural subcomponents (e.g. thimbles) has to be partially tolerated.

- Development of design rules for brittle materials
- Risk/failure assessment of multi-component design
- Design studies to reduce risk of leaks and their consequences (e.g. possible use of double walled parts)
- Demonstration of a commercial (mass-) fabrication route
- Determination of the HEMJ performance with a consistent finger test campaign

MATERIALS / DESIGN WINDOW → PLATE





W

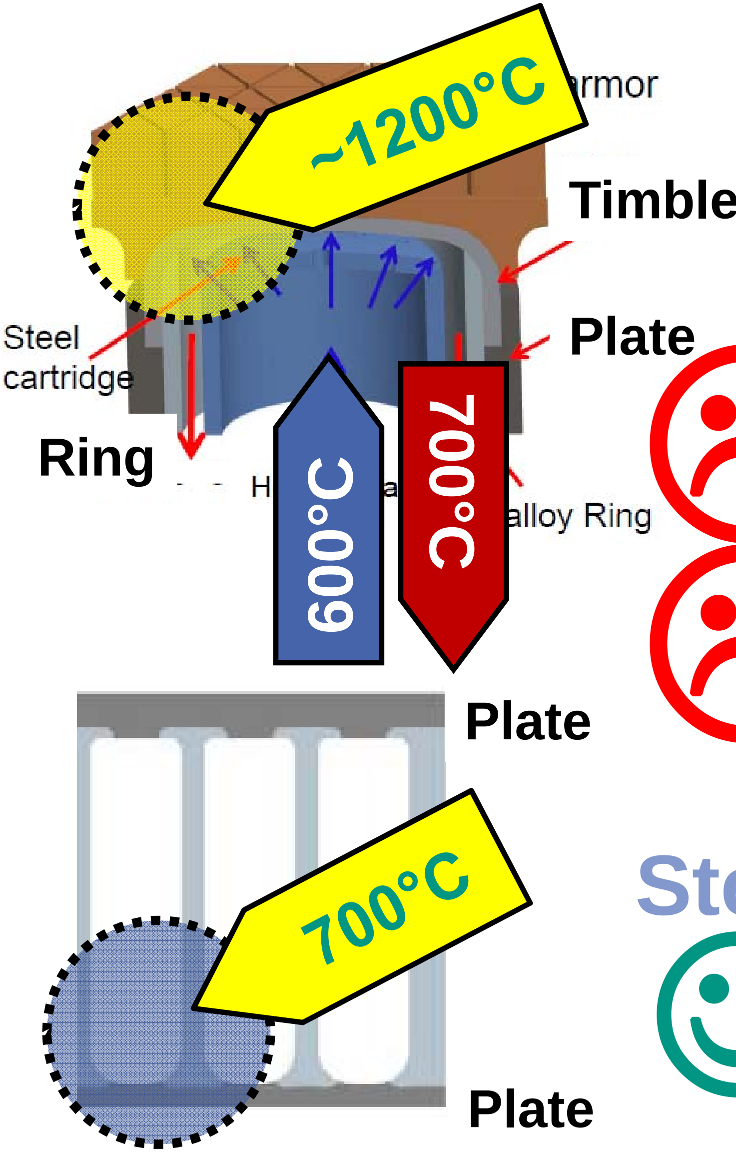
Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	ODS
Brazing W→W →	Pd, Pt ???
Swelling ~5% →	?????
Embrittlement →	OK (tbc)

Steel ☹

Embrittlement →	OK
Strength, … →	(OK)?

MATERIALS / DESIGN WINDOW → PLATE

Karlsruhe Institute of Technology



W

Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	? (ODS)
Brazing W→W →	Pd, Pt ???
Swelling ~5% →	?????
Embrittlement →	NO GO (?)

Steel

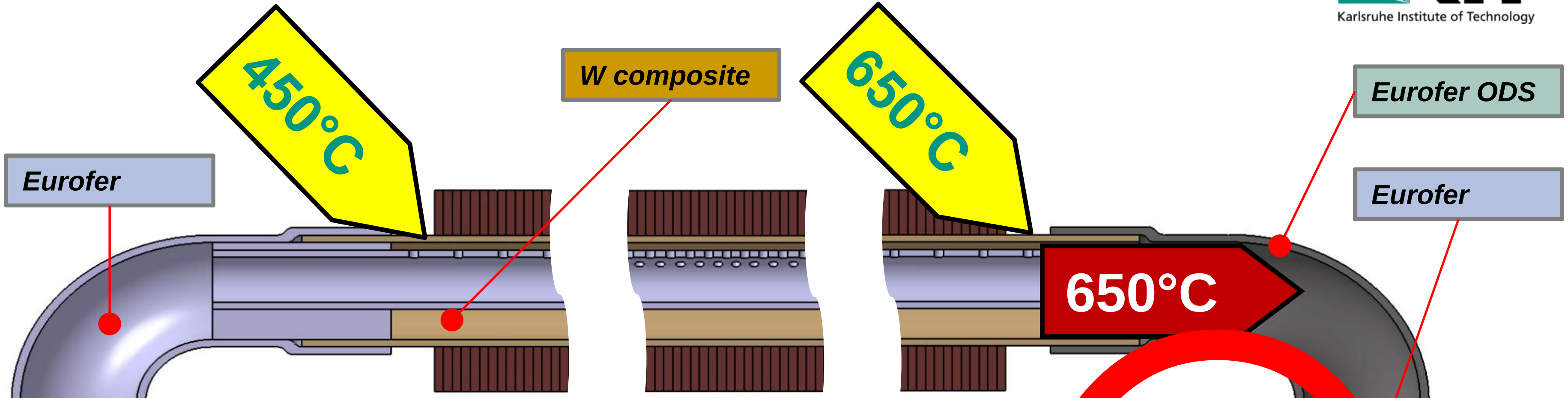
Embrittlement →	OK
Strength, … →	OK

CONCLUSIONS FOR THE PLATE DESIGN

Based on present knowledge on neutron-induced embrittlement of tungsten, an operating temperature of **at least 800 °C** is strongly recommended to mitigate the risk of embrittlement. For this concept there is **no temperature limit**. That is, embrittlement of the structural subcomponents (e.g. thimbles) could (in principle) ruled out.

- Structural integrity of rather long joints (brazing technology)
- Design studies to reduce risk of leaks and their consequences (e.g. possible use of double walled parts)
- The required high temperature cooling loop is a technological challenge!

MATERIALS / DESIGN WINDOW → PIPE



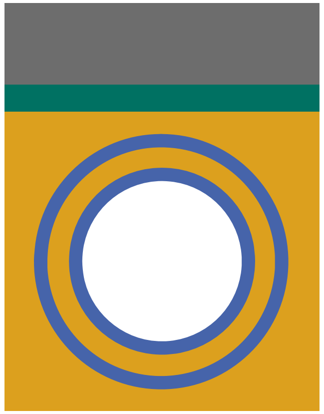
W	Oxidation	→	OK
	Swelling ~4%	→	OK ?
	Embrittlement	→	??? (tbd)
	Grain Growth	→	OK
	Brazing (Cu)	→	OK (…)
Steel	Embrittlement	→	OK
	Strength, …	→	OK

Conclusions for the Pipe Design

Based on present knowledge on neutron-induced embrittlement of tungsten, an operating temperature of **at least 800 °C** is strongly recommended to mitigate the risk of embrittlement. For this concept the upper **limit is 650 °C.**

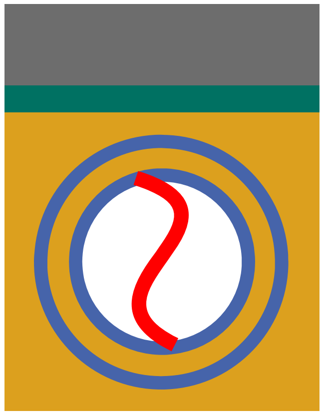
- Irradiation data needed to confirm assumed material behaviour
- Material optimization (laminate components & bonding process)
- Fabrication route for long pipes
- Performance tests under high heat flux

IMPROVEMENT OF THE ITER DIVERTOR



W armour
Cu-W transition
CuCrZr
Stainless Steel,
or other reinforcement
(fibers, meshes, particles)

- De-couple armour and structure
- Reinforce cooling structure
- Double containment



Swirrl or flow promoter
to increase thermal
transfer coefficient