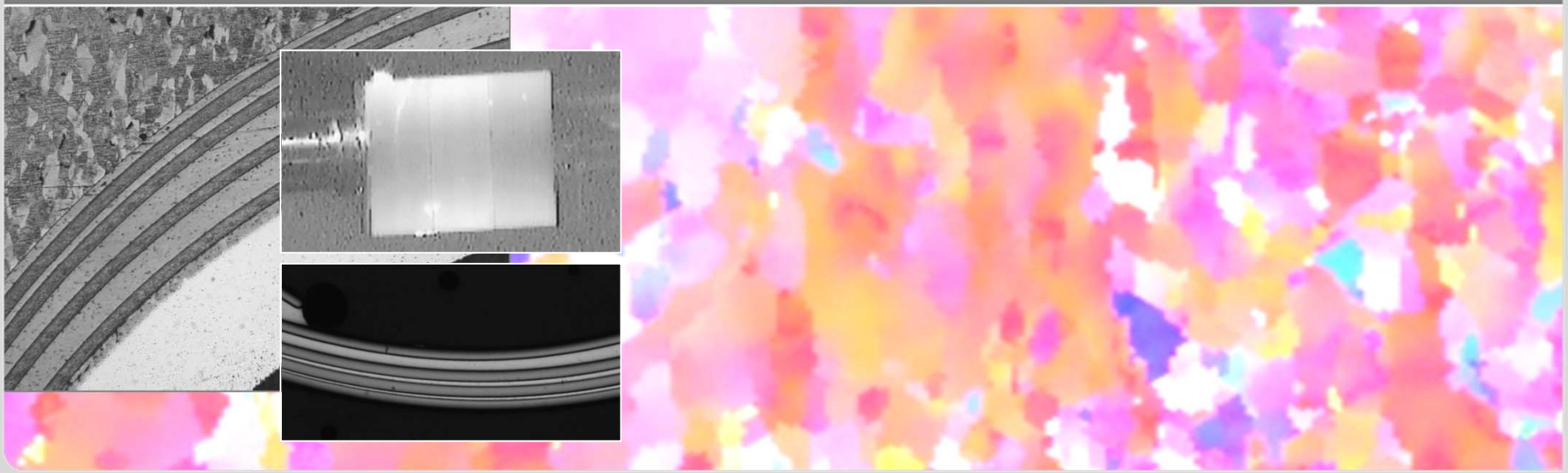
Divertor from the technology perspective

J. Reiser[1], M. Rieth[1], B. Dafferner[1], A. Hoffmann[2]
[1] Karlsruhe Institute of Technology, Institute for Applied Materials, Germany
[2] PLANSEE SE, Reutte, Austria

1st IAEA DEMO program workshop, 15-18 October 2012

INSTITUTE FOR APPLIED MATERIALS, APPLIED MATERIALS PHYSICS

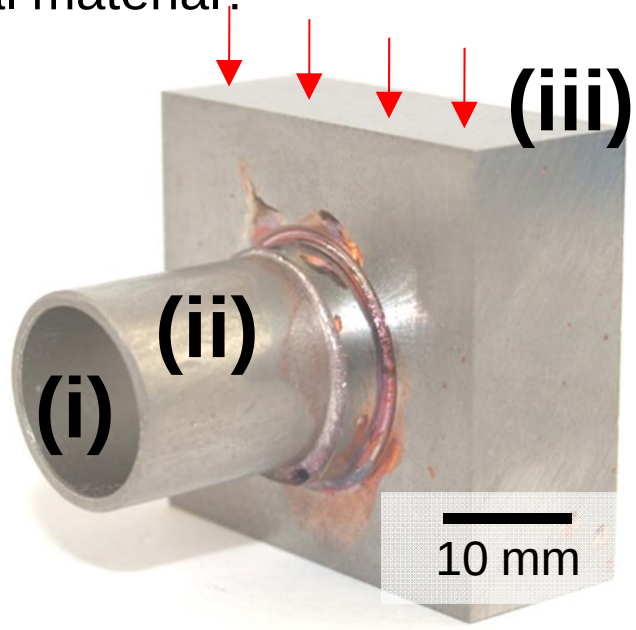


Definition of the “divertor”

- Definition of the divertor: pipe, surrounded by tungsten
  - (i): type of coolant?
  - (ii): structural material for the pipe?
  - (iii): armour material? → tungsten

- Question: What amount of heat can we remove with a specific combination of (i) coolant and (ii) structural material?

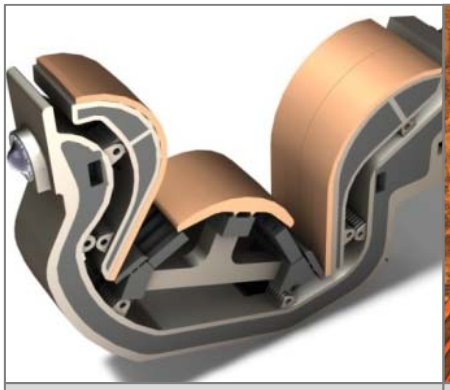
picture: PLANSEE SE



Content

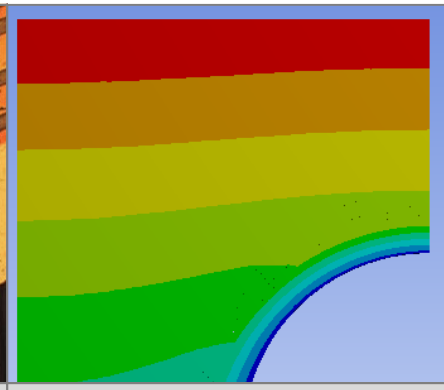
- Introduction
- The tungsten laminate project
- Matrix of coolant and structural material
- Divertor for DEMO: our proposals

- Appendix (material issues)

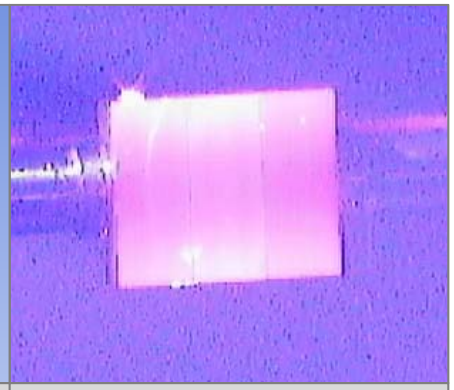


introduction

W-laminate



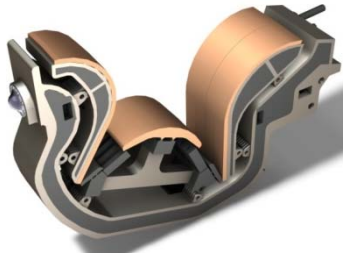
matrix



our proposals

Introduction

- requirements on a DEMO divertor: survive 2 fpy
  - high heat flux:
    - 5 MW/m^2 (plasma physical minimum)
    - 7 MW/m^2 (continuous burning plasma → long term)
    - DEMO: **10 MW/m^2** (pulsed operation → short term) with peaks due to plasma instabilities up to 20 MW/m^2
  - neutron load → structural material
    - W structure: max. 1.9 dpa / fpy [1]
    - steel or Cu cooling structure: max. 5.9 dpa / fpy



picture: ITER

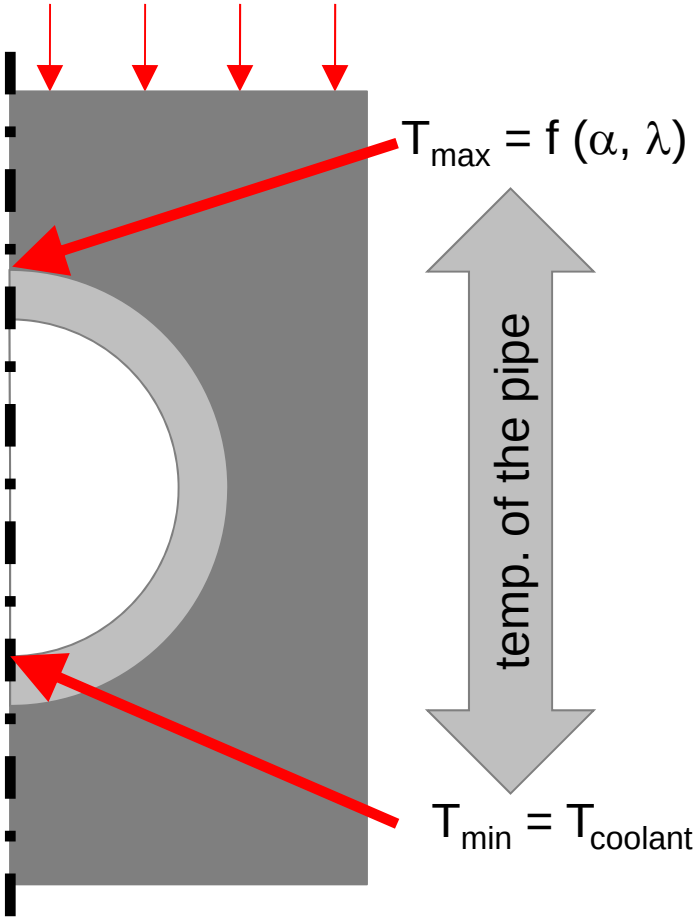
picture: PLANSEE

- References:

[1] M.R. Gilbert, S.L. Dudarev, S. Zheng, L.W. Packer and J.-Ch. Sublet, An integrated model for materials in a fusion power plant: transmutation, gas production, and helium embrittlement under neutron irradiation, Nucl. Fusion 52 (2012).

Introduction

- How to deal with the heat load?



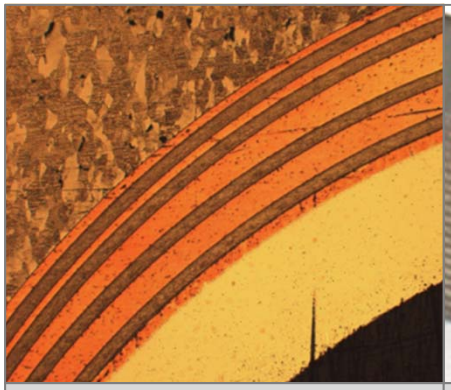
λ: thermal conductivity, [W/(m*K)]	
CuCrZr:	305 (at RT)
austenitic steel, 316Ti:	15 (at RT)
RAFM, Eurofer:	30 (at 500°C)
W:	180 (at RT)

α: heat transfer coefficient, [kW/(m²*K)]		
water:	100	swirl, hypervapotron
helium:	30	jet impingement

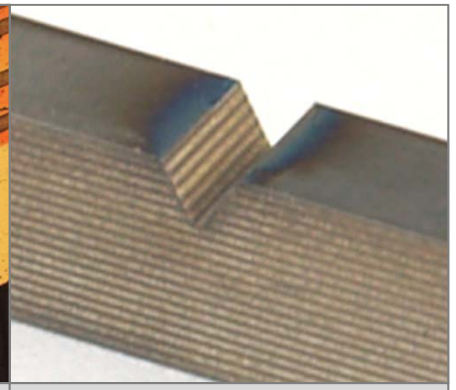
Content

- Introduction
- **The tungsten laminate project**
  - **Interlayer between steel and tungsten**
  - **Structural material**
- Matrix of coolant and structural material
- Divertor for DEMO: our proposals

- Appendix (material issues)



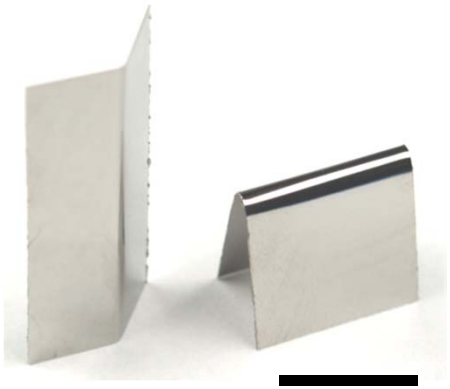
interlayer



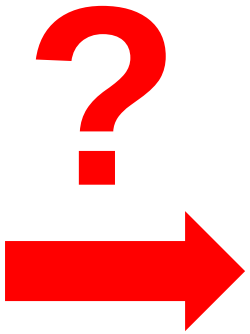
structural material

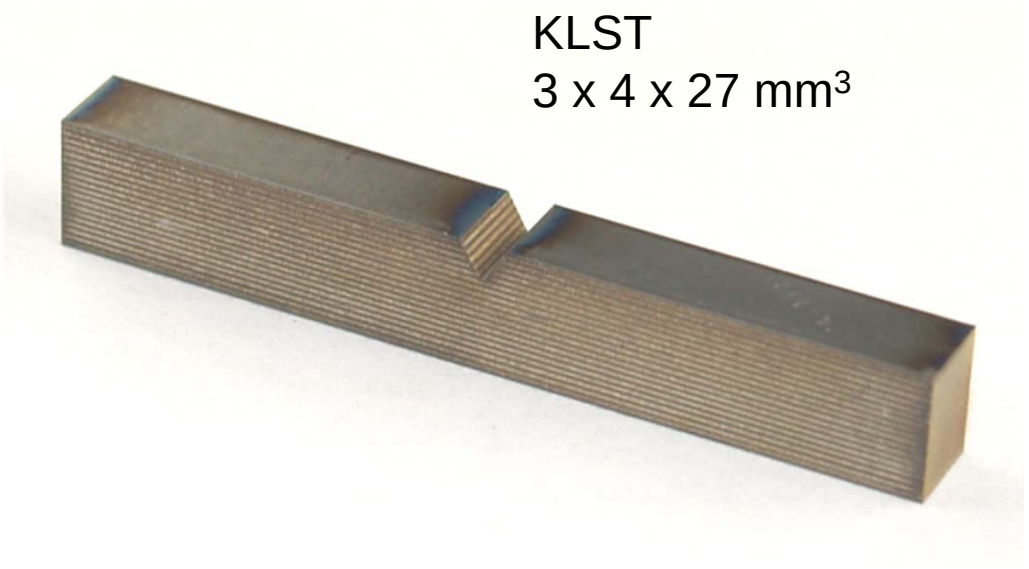
The W-laminate project

- Do we succeed to transfer the ductile properties of a W-foil to the bulk?
- How can W-laminates be used for divertor applications?



10 mm

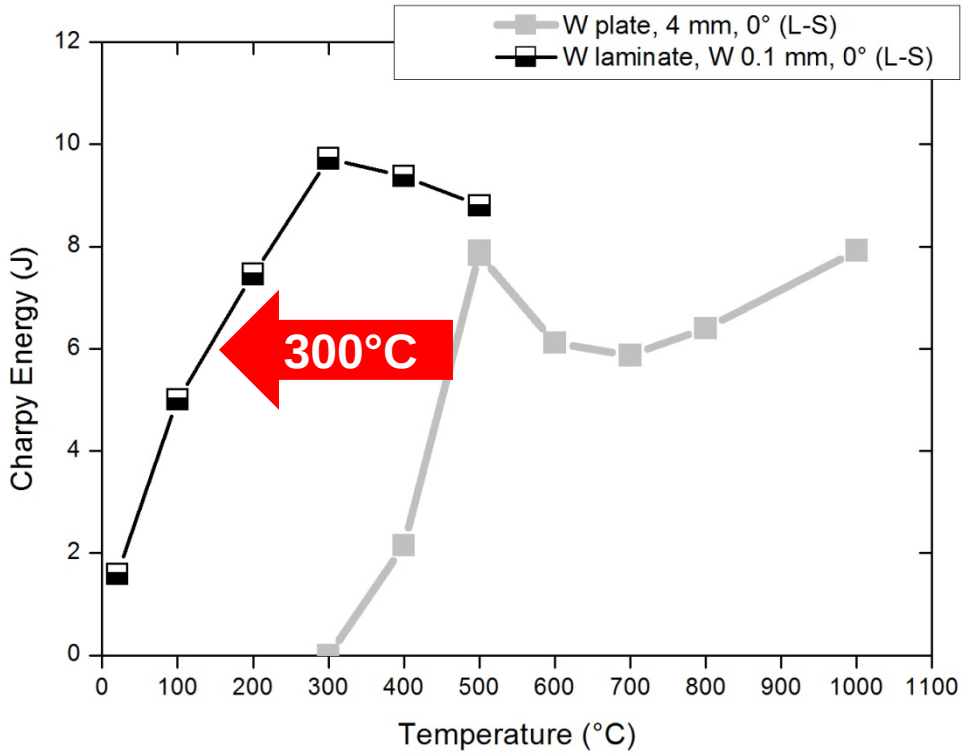




KLST
3 x 4 x 27 mm³

The W-laminate project: Charpy tests

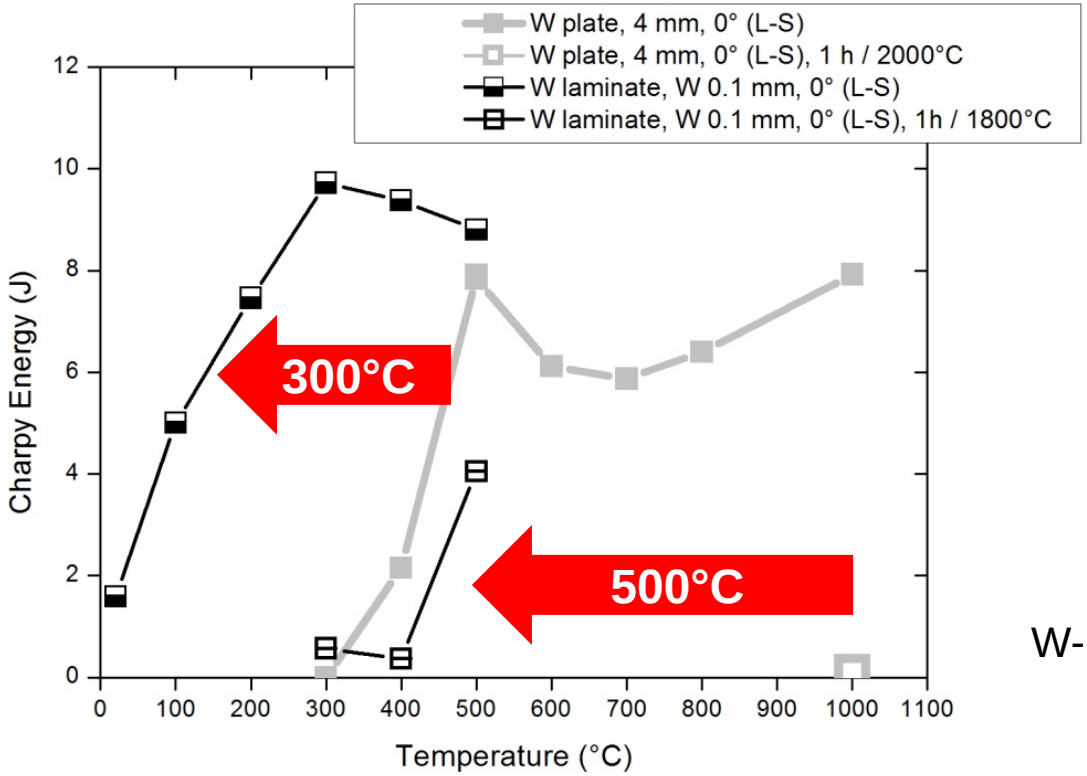
- Can the ductile properties of a foil be transferred to the bulk?
  - as-received condition: improvement of 300°C



W-laminate made of Cu-alloy

The W-laminate project: Charpy tests

- Can the ductile properties of a foil be transferred to the bulk?
  - as-received condition: improvement of 300°C
  - recrystallized condition: improvement of 500°C



W-laminate made of Cu-alloy

The W-laminate project: pipes

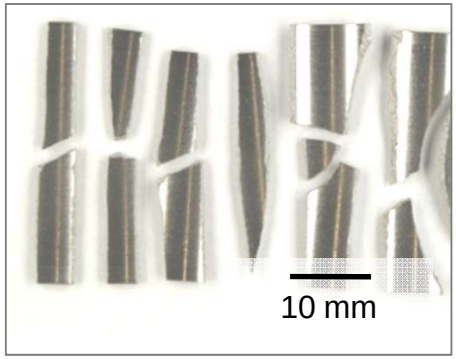
- How can we produce a tungsten pipe?

rod

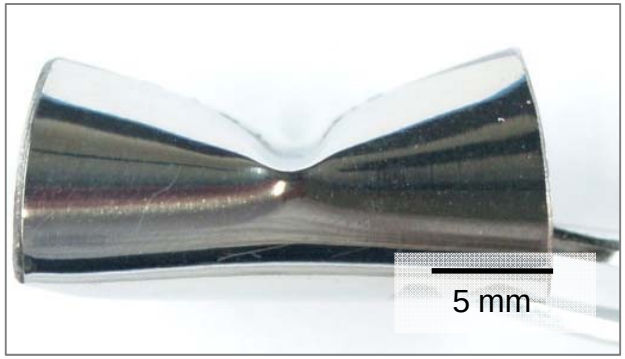
Cu-alloy, 780°C

Cu, 1085°C

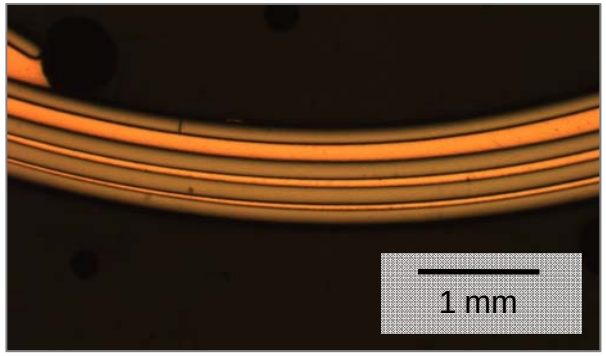
Ti, 1670°C Zr, 1855°C



W rod, Charpy at 300°C



W-laminate-pipe, Charpy at 300°C

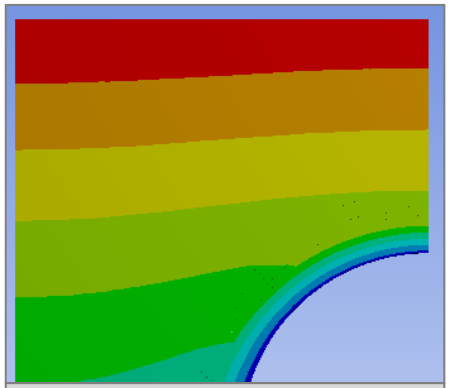


W-laminate-pipe, optical micrograph

Content

- Introduction
- The tungsten laminate project
- **Matrix of coolant and structural material**
  - **What amount of heat can be removed by which combination of (i) structural material and (ii) coolant?**
- Divertor for DEMO: our proposals

- Appendix (material issues)

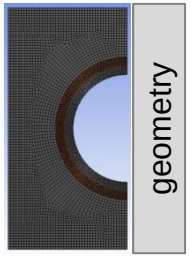


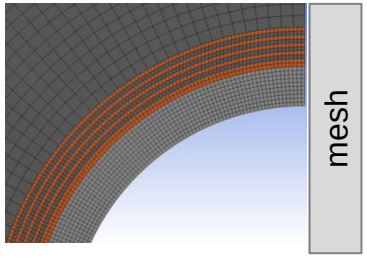
matrix

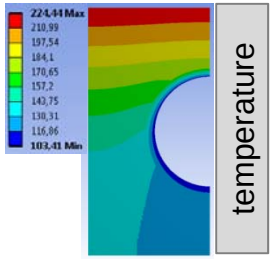
Matrix: material and coolant

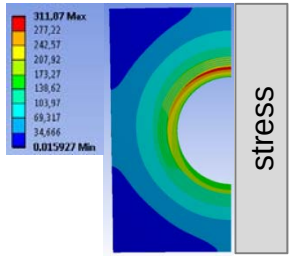
material \ coolant	H_2O, 10 bar RT – 50 °C α = 100 kW/ (m² * K) swirl, hyperv.	H_2O, 100 bar, 100°C – 120 °C α = 100 kW/ (m² * K) swirl, hyperv.	H_2O, 160 bar 275°C – 325°C α = 100 kW/ (m² * K) swirl, hyperv.	He, 100 bar 400°C – 600°C α = 30 kW/ (m² * K) jet impingement
CuCrZr (λ_{RT} = 305 W / (m * K))		20 MW/m²		
steel: Aust. steel, e.g. 316Ti (λ_{RT} = 15 W / (m * K))	5 MW/m²	5 MW/m²	-	-
steel: RAFM, e.g. Eurofer ($\lambda_{500°C}$ = 30 W / (m * K))	-	-	-	1 MW/m²
W*: W-Laminate* (W-Cu) ($\lambda_{RT,L}$ = 240, $\lambda_{RT,II}$ = 285)	-	-	-	10 MW/m²

*: neutrons are not considered





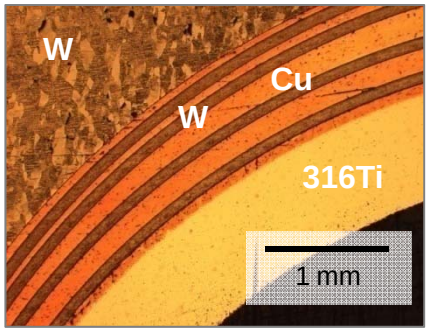


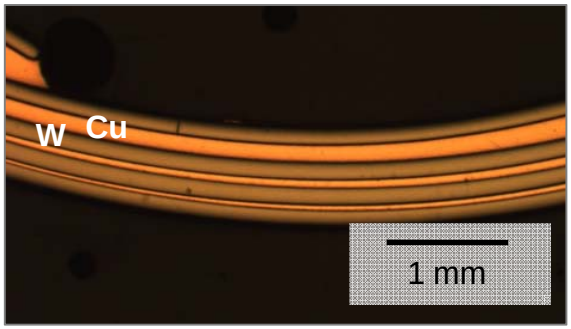


Matrix: material and coolant

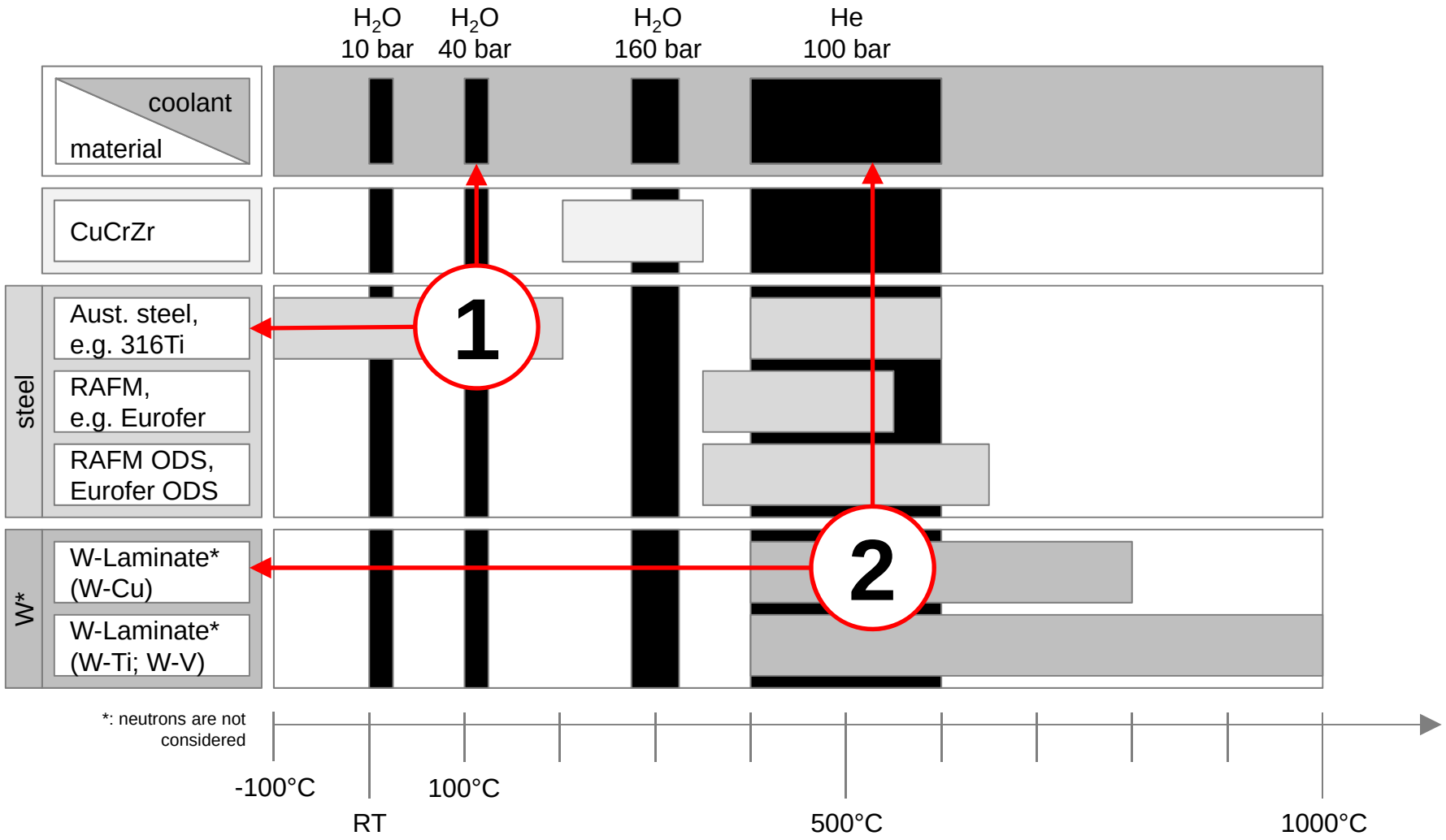
material \ coolant	H_2O, 10 bar RT – 50 °C α = 100 kW/ (m² * K) swirl, hyperv.	H_2O, 100 bar, 100°C – 120 °C α = 100 kW/ (m² * K) swirl, hyperv.	H_2O, 160 bar 275°C – 325°C α = 100 kW/ (m² * K) swirl, hyperv.	He, 100 bar 400°C – 600°C α = 30 kW/ (m² * K) jet impingement
CuCrZr	λ_{RT} = 305 W / (m * K)	20 MW/m²		
steel: Aust. steel, e.g. 316Ti	λ_{RT} = 15 W / (m * K)	**W-laminate** used as **transition piece** between steel pipe and W armour		
steel: RAFM, e.g. Eurofer	$\lambda_{500°C}$ = 30 W / (m * K)			
W*: W-Laminate* (W-Cu)	$\lambda_{RT, L}$ = 240 $\lambda_{RT, II}$ = 285	**W-laminate** used as a **structural material**		

*: neutrons are not considered

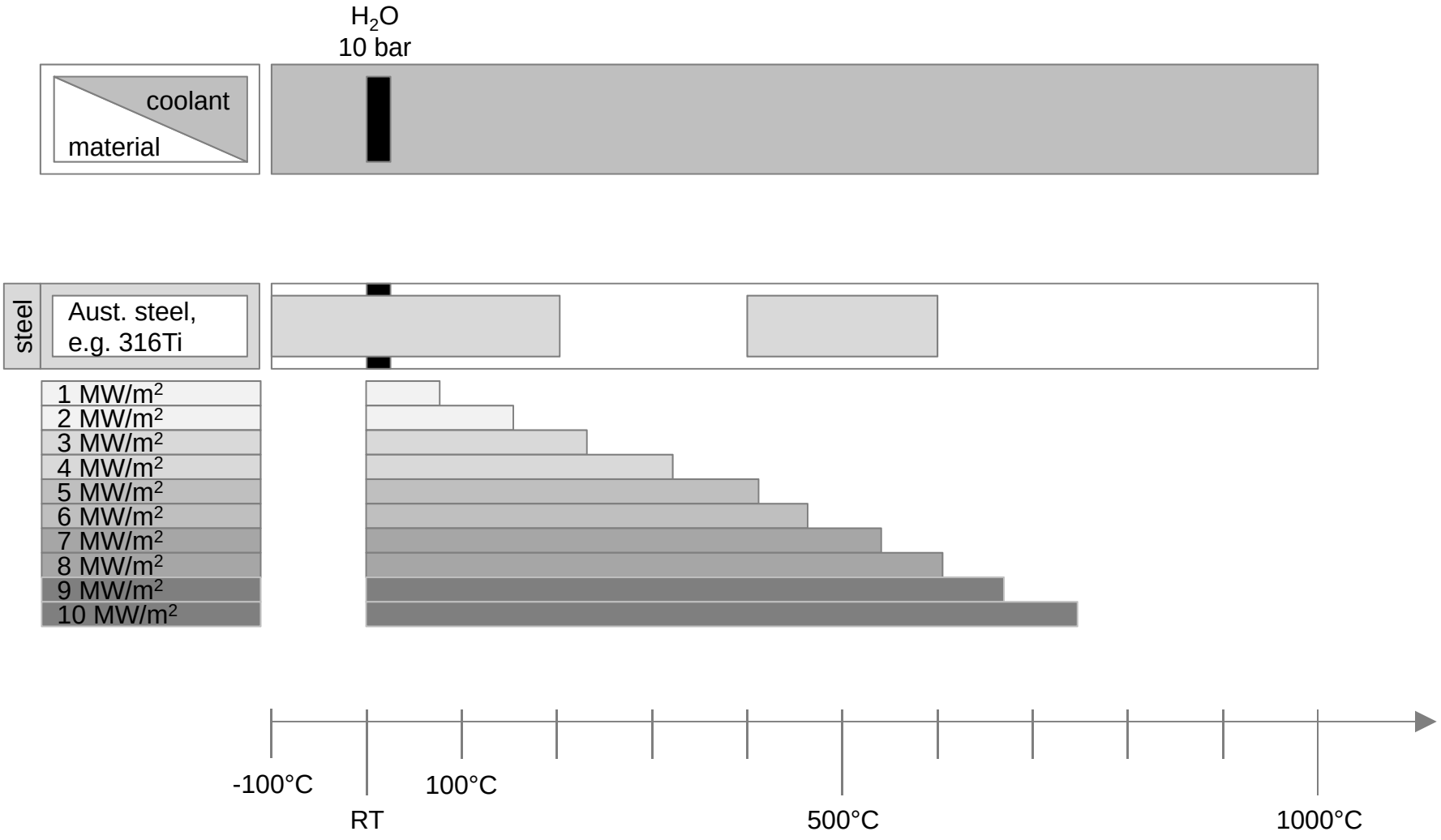




Matrix: material and coolant



Matrix: material and coolant



Content

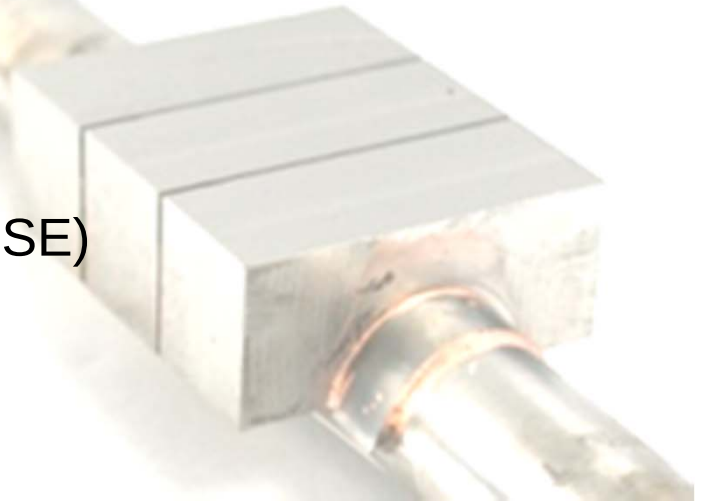
- Introduction
- Matrix of coolant and structural material
- The tungsten laminate project
- **Divertor for DEMO: our proposals**
  - **Austenitic steel – water coolant**
  - **Tungsten laminate – helium coolant**

- Appendix (material issues)

316Ti - water | W-laminate - He

Divertor for DEMO: our proposals 1

- our proposal 1:
  - material: austenitic steel (316Ti)
  - coolant: water (100°C – 120°C, 40 bar)
  - result of simulation: 5 MW/m^2
- state of the art: until now it was not possible to join an austenitic steel pipe with the tungsten armour (different thermal expansion coef. α)
- our idea: use a tungsten laminate as a transition piece

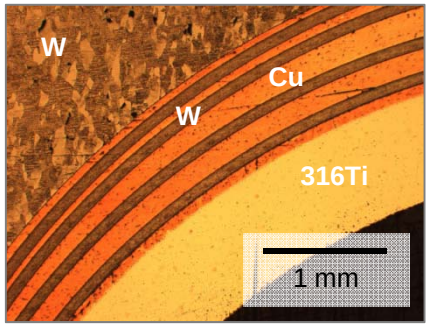


The team:

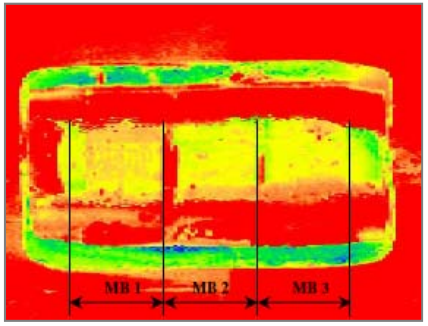
- fabrication Rieth, Reiser (KIT)
- NDT Huber, Zabernig (PLANSEE SE)
- HHF testing Greuner, Böswirth (IPP)
  Pintsuk (FZJ)
  Ghidersa (KIT)

Divertor for DEMO: our proposals 1

- HHF tests, GLADIS, IPP:
  - water, RT, 10 m/s, 1.13 l/s
  - beam 20 s on 40 s off
- **result of test: 100 cycles, 6 MW/m^2, no residual damage**
- next steps:
  - use swirl → improvement of α up to 100 [kW/(m^2*K)]
  - HHF tests at 10 MW/m^2

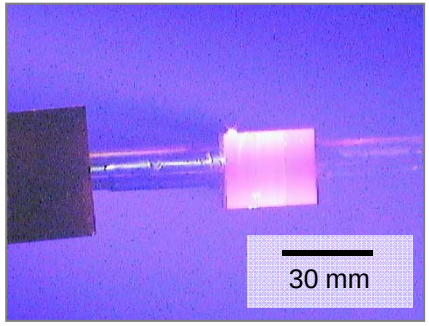


W-laminate as a transition piece



non-destructive testing, PLANSEE SE

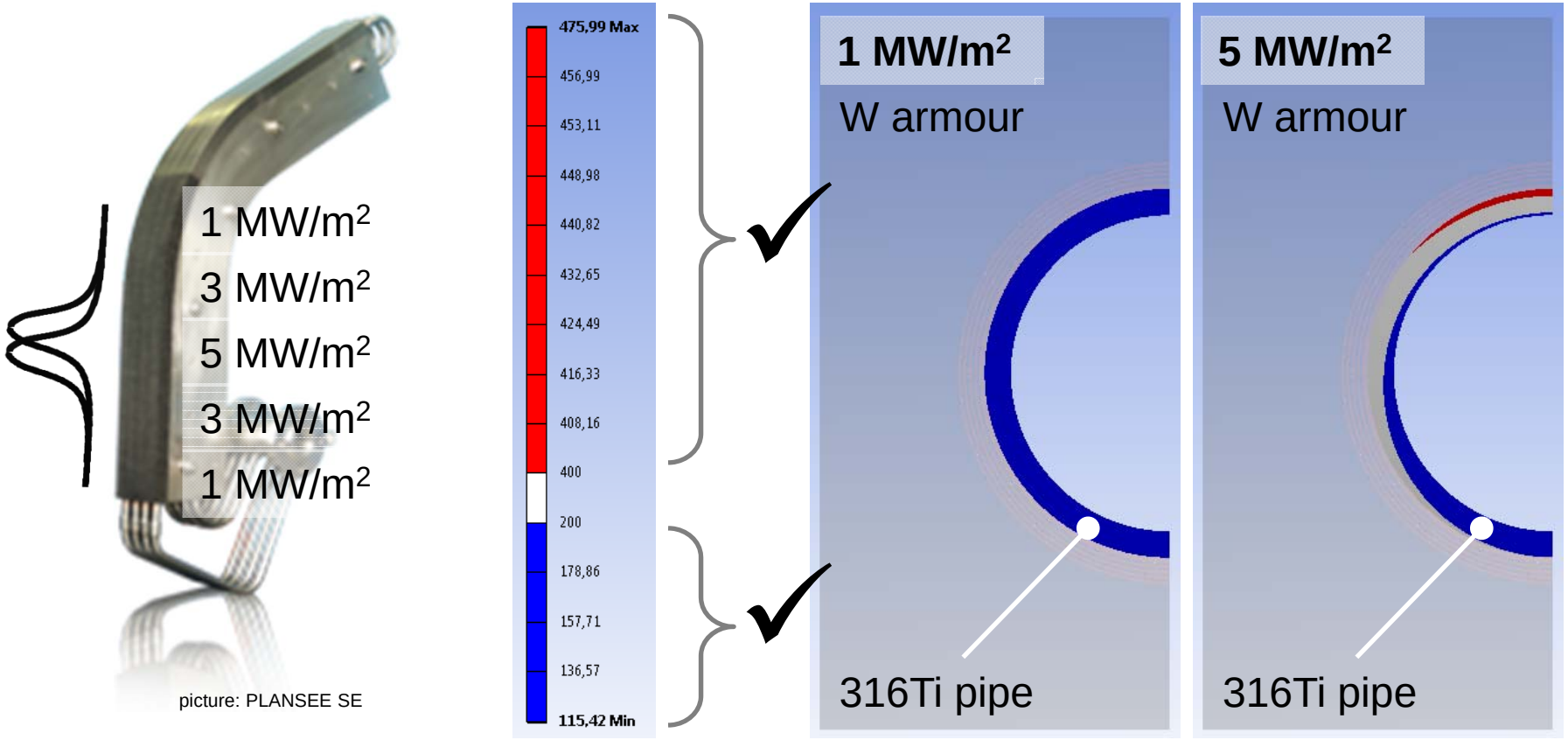
GLADIS, IPP, Garching



Test: 100 Zyklen, 6 MW/m^2

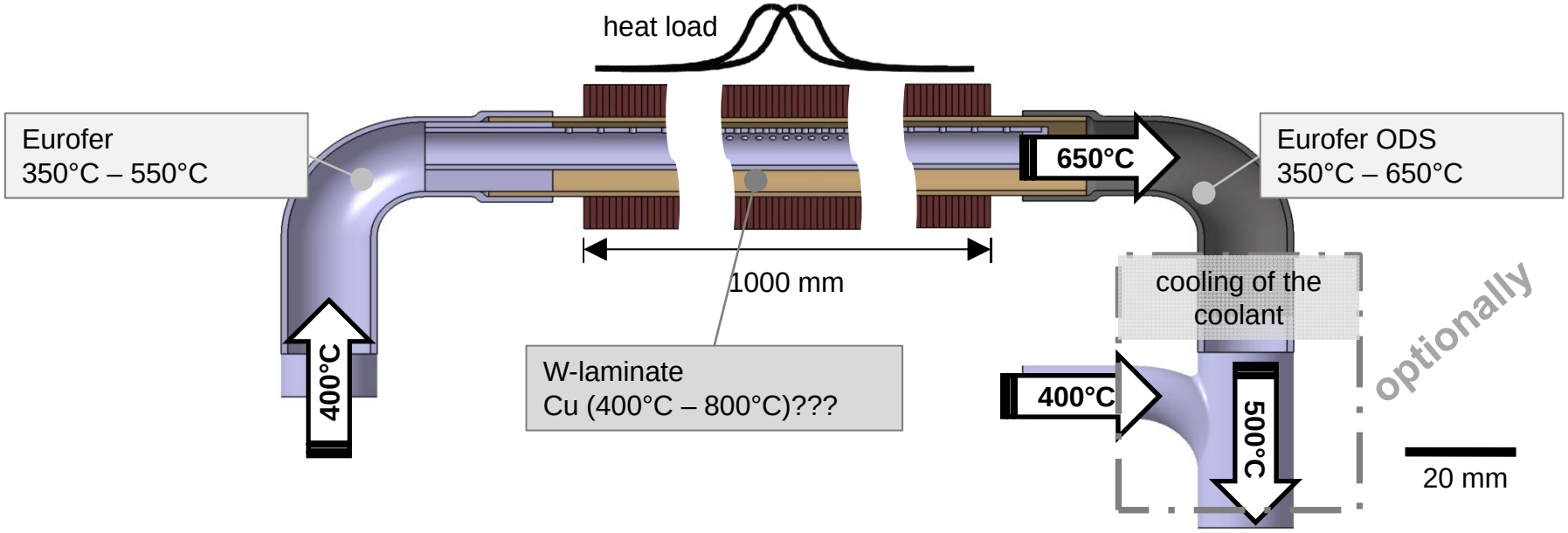
Divertor for DEMO: our proposal 1

- austenitic steel (e.g. 316), coolant: water (100°C – 120°C, 40 bar):
  - operation window: up to 200°C and from 400°C – 600°C

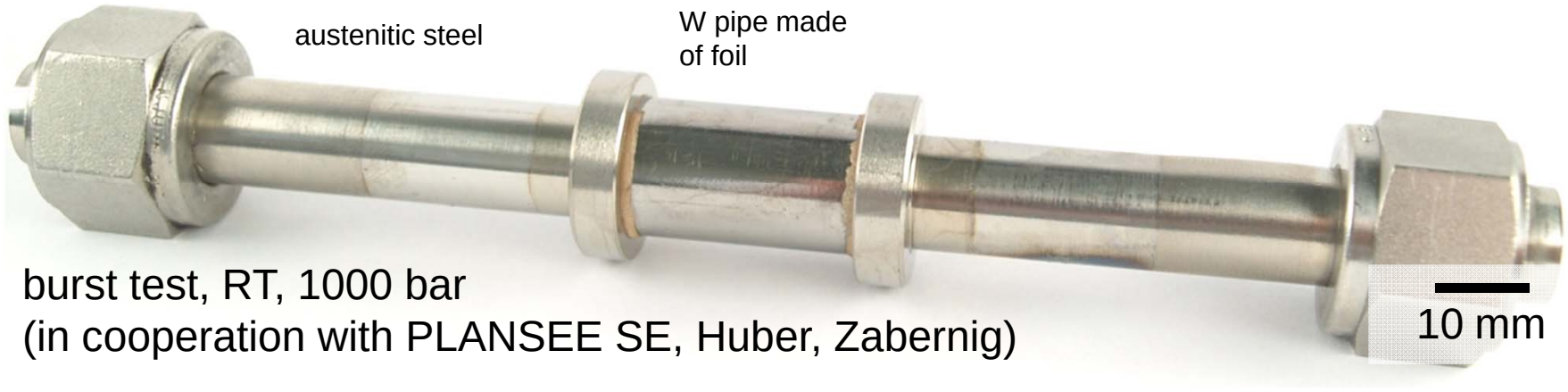


Divertor for DEMO: our proposals 2

- our proposal 2:
  - material: W-laminate pipe (with Cu brazing)
  - coolant: helium (400°C – 600°C, 100 bar)
  - result of simulation: 10 MW/m^2
- state of the art: until now there were no tungsten pipes available
- our idea: use W-laminate pipe as structural material



Divertor for DEMO: our proposals 2



burst test, RT, 1000 bar
(in cooperation with PLANSEE SE, Huber, Zabernig)

Outlook (I/II)

W-laminates

W-foil
1) W
2) WVM (W-0.005 wt.% K)

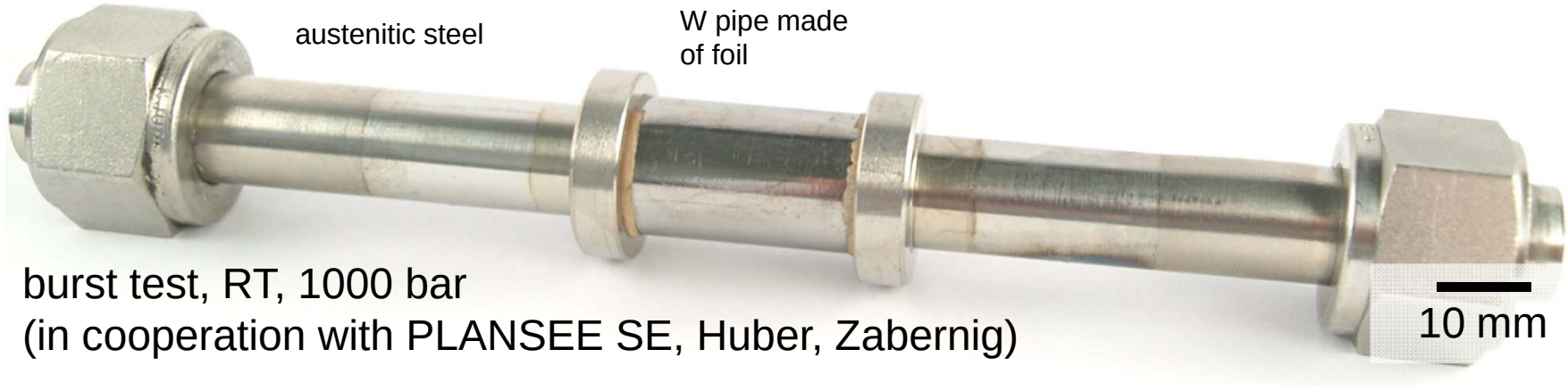
interlayer
1) Cu ($T_{melting}$ = 1085°C)
2) Ti ($T_{melting}$ = 1670°C) → allotropy
3) V, or V4Cr4Ti ($T_{melting}$ = 1910°C) → Kirkendall effect

joining
1) brazing
2) hot pressing / diffusion bonding

Material tests
1) properties after 1000 hours at 1000°C
2) irradiation tests (**ORNL, Oak Ridge, Y. Katoh, L. Snead, *et al.***)

Pipe tests
1) burst tests at 600°C

Joint to steel
1) thermal fatigue tests (RT – 600°C)

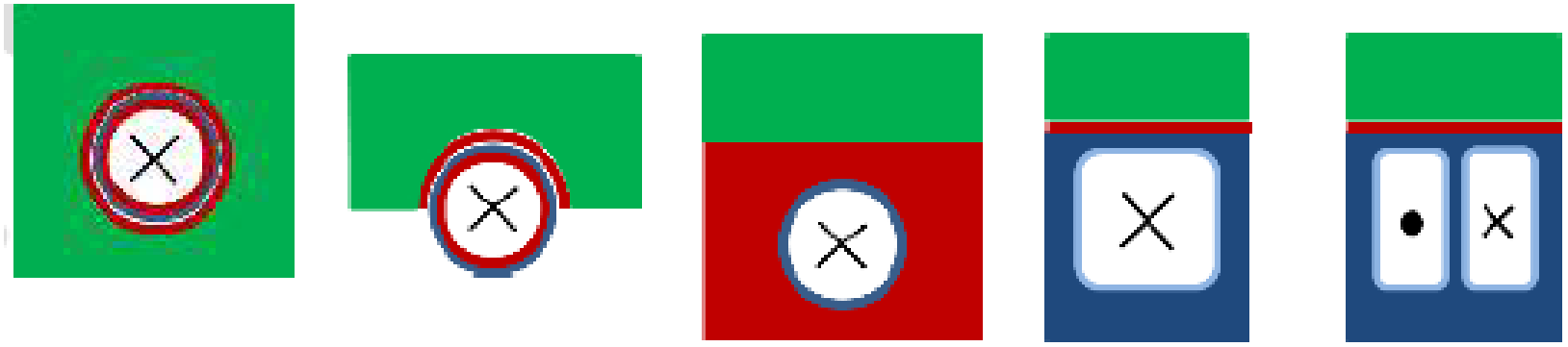


burst test, RT, 1000 bar
(in cooperation with PLANSEE SE, Huber, Zabernig)

Outlook (II/II)

- KIT-CCFE cooperation:

  E. Surrey, T. Barrett, W. Timmis, C. Waldon, M. Porton,…
- Workshop on water cooled divertors:
  - Mai 2012: CCFE
  - August 2012: KIT
  - next: March 2013: CCFE
- Plans and ideas: e.g. double-walled pipes



Summary

- Introduction
  - Requirements for a DEMO divertor
  - Temperature distribution
- The tungsten laminate project
  - Interlayer between steel and tungsten
  - Structural material
- Matrix of coolant and structural material
  - What amount of heat can be removed by which combination of (i) coolant and (ii) structural material?
- Divertor for DEMO: proposals
  - Austenitic steel – water coolant
  - Tungsten laminate – helium coolant
- Appendix (material issues)

Thank you for your attention

The authors are grateful to:

Plansee Metall GmbH,
University of Oxford,
Culham Centre for Fusion Energy,
Oak Ridge National Laboratory, and
our colleagues from IAM (KIT).